Cooperative Game Theoretic Framework for Joint Resource Management in Construction

Sadegh Asgari, S.M.ASCE[1]; Abbas Afshar[2]; and Kaveh Madani, A.M.ASCE[3]

Abstract: Subcontractors have a significant role in the construction industry. Through involvement at different levels, subcontractors may undertake up to 90% of the total value of large construction projects. Due to the lack of systematic relationships and communication among different parties involved in construction projects, many beneficial opportunities such as short-term partnering may stay hidden and unknown during the course of projects. Although partnering is well documented in the literature, quantitative approaches have not been common for determining the value of partnering and developing practical methods for allocation of its benefits. In this study, we discuss how subcontractors can benefit considerably from *joint resource management* in construction projects. We present a short-term partnering case in which subcontractors form an alliance, agreeing to put all or some of their resources in a joint pool for a fixed duration of time and to allocate the group resources using a more cost-effective plan. Cooperative game theory is suggested as the basis for fair and efficient allocation of the incremental benefits of cooperation among the cooperating subcontractors. First, a resource-leveling model is used to build subcontractors' characteristic functions for all possible subcontractors' coalitions. Then, various cooperative game theoretic solution methods are applied for allocation of cooperative gains among the subcontractors. Finally, to ensure that the identified allocation rules are applicable and stable in practice, acceptable allocations are identified using various stability analysis methods. Results show that considerable savings can result from full cooperation among subcontractors based on group rationality as opposed to individual rationality. **DOI: 10.1061/(ASCE)CO.1943-7862.0000818.** *© 2013 American Society of Civil Engineers.*

Author keywords: Game theory; Partnering; Subcontractors; Construction management; Resource management; Optimization; Stability analysis; Cost and schedule.

Introduction

Subcontracting is an important yet disregarded subject in the construction management research. Subcontractors, involved at different levels of a construction project, may account for up to 90% of the total value of the project (Nobbs 1993; Kumaraswamy and Matthews 2000). Due to higher demand fluctuations in construction services, main contractors are more inclined to recruit subcontractors or outsource the project tasks in order to share the project risks and survive in volatile business cycles (Dainty et al. 2001). The increasing complexity and specialization of construction projects are other reasons for general contractors or clients to employ subcontractors. Recent research confirms the increasing trend of employing subcontractors in the U.K. and U.S. since the 1980s (Costantino and Pietroforte 2002; Edwards 2003). As the number of parties involved in a construction project increases, the hidden and unknown beneficial opportunities could increase if different obstacles are resolved. Such obstacles include the problems arising due to the lack of trust and transparency, as well as incomplete flow of information among the parties (Higgin and Jessop 1965; Faulkner and Day 1986).

The existing beneficial opportunities would partially be ignored without investigating their existence and associated benefits. Such opportunities become more valuable in today's severe competitive business environment that makes the marginal benefits narrower than before. In any large construction project, subcontractors may have many relationships within themselves and with other project parties. One type of these relationships is partnering or cooperation. Partnering has been defined by the Construction Industry Institute (CII 1991) as: "... a long-term commitment between two or more organizations for the purpose of achieving specific business objectives by maximizing the effectiveness of each participant's resources." Generally, partnering may be undertaken for a single project based on a short-term agreement (project partnering) or be pursued as a strategy based on long-term agreements concerning a series of projects or transactions (strategic partnering). For a subcontractor, partnering can be considered in two different directions: (1) the vertical direction: partnering with the general contractor or the client; and (2) the horizontal direction: partnering with other subcontractors.

Partnering between general contractors and subcontractors has recently received some attention. Willingness to cooperate is asserted as one of the four criteria considered in the subcontractor selection process by main contractors from Singapore (Hartmann et al. 2009). Cooperative capacity or the extent to which subcontractors fulfill agreements and proactively solve and prevent problems can enhance the relationships established between main contractors and subcontractors. Such relationships can in turn, improve the operational efficiency of construction projects (Humphreys et al. 2003). Case studies suggest that partnering not only results in better performance such as less cost overruns and delays, as well as higher

[1]Ph.D. Candidate, Dept. of Civil Engineering and Engineering Mechanics, Columbia Univ., New York, NY 10027 (corresponding author). E-mail: ma3079@columbia.edu

[2]Professor, Dept. of Civil Engineering, Center of Excellence for Enviro-Hydroinformatics Research, Iran Univ. of Science and Technology, Tehran 16846-13114, Iran. E-mail: a_afshar@iust.ac.ir

[3]Lecturer, Centre for Environmental Policy, Imperial College London, London SW7 2AZ, U.K. E-mail: k.madani@imperial.ac.uk

Note. This manuscript was submitted on July 6, 2013; approved on November 5, 2013; published online on December 26, 2013. Discussion period open until May 26, 2014; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364/04013066(13)/$25.00.

customer satisfaction, but also would lead to faster innovation adaptation (Barlow 2000; DeVilbiss and Leonard 2000). Rahman and Kumaraswamy (2004) suggest that partnering among general contractors and subcontractors develops a potential to avoid short-term opportunistic behavior and encourages cooperation to achieve common goals. By gathering and analyzing empirical data, Eriksson (2007) suggested that to increase incentives for cooperation, clients and contractors should establish long-term working relationships instead of focusing on single projects. Nevertheless, due to the existence of the hold-up risk in project networks, random switching of partners or subcontractors may be required in the period following the introduction of an innovation or organizational change to increase profit (Unsal and Taylor 2011a, b). Based on cooperative game theory concepts, Perng et al. (2005) found that formwork subcontractors may earn more benefits when collaborating with others in a coalition due to the potential for cost reduction under collective actions.

The number and contribution level of subcontractors in a given project depends on the various project characteristics including size, technical complexity, and scattering operations (Kang 2001). Generally, more than a few subcontractors are involved in construction projects, especially in large ones. Main contractors usually split a single project into several subprojects without the awareness of whether this decision is cost effective for subcontractors or not (Kumaraswamy and Matthews 2000; Perng et al. 2005). While in principle, breakdown of a large project into few smaller subprojects should not lead to surplus cost, total costs of the breakdown for subcontractors can be significant. Moreover, as a project gets smaller, the chance of decreasing costs and benefiting from the economies of scale becomes more limited because of having less number of noncritical activities. Larger projects, involving many noncritical activities, have more flexibility in resource scheduling and management, providing a higher chance of saving through comprehensive and systematic decision making that considers the interrelationships of all project tasks.

Subprojects are associated with independent decision making with no consideration of common decision variables. For example, each subcontractor independently performs the site mobilization and removal tasks associated with its subproject. Hence, a subcontractor may keep the unwanted facilities idle before starting the next activity or transferring them to other sites, resulting in unreasonable costs to this subcontractor. Such costs are avoidable if decisions are not made independently. It can be argued that independent planning of subcontractors based on individual rationality results in an overall plan that is inferior to the plan developed by a group of subcontractors based on group rationality. Nevertheless, developing stable cooperative institutions that provide incentives for cooperation to all subcontractors is challenging. Moreover, sometimes forming these institutions may have considerable transaction costs and be infeasible due to physical limitations (e.g., when common facilities and machineries are not used or when subcontractors are spatially dispersed). When such limitations do not exist, joint resource management can be a promising option to increase gains of the parties, participating in a coalition, to use the resources more effectively. Resource management is crucial in the construction industry given its considerable effect on projects' time and costs and on gains of the subcontractors, who are under the clients' pressure to meet the project's expectations and under the market's pressure to remain competitive.

Previous resource management studies have been conducted from the single decision-maker's perspective (Hartmann and Briskorn 2010). Nevertheless, in practice, multiple decision makers may get involved in resource management problems, making single decision-maker models inapplicable. Therefore, to better simulate resource-leveling problems, this study tries to capture the multiple decision makers' aspect of the problem and modeling a case in which multiple decision-makers cooperatively decide on how to share common resources through partnering. The paper focuses on joint resource management as a case of short-term partnering between subcontractors, participating in a coalition and agreeing to put all common resources in a joint pool and employ the collected resources through the most cost-effective plan. Joint resource management seeks cutting subcontractors' superfluous costs by revising their resource planning. Under joint resource management, resources that may remain idle and nonproductive due to undesirable resource fluctuations are shared by subcontractors, providing opportunities for reciprocal exchange of the resources in preplanned periods. Cooperative game theory provides an appropriate basis for developing a subcontractors' partnering model. Hence, within the cooperative game theory framework, this study aims to (1) investigate the maximum obtainable value of joint resource management under all feasible coalitions; (2) identify fair and efficient rules for allocating the incremental benefits of cooperation to the participating subcontractors; and (3) select the allocation rules that are most stable in practice.

The article is organized as follows: the "Game Theory" section reviews the key concepts of cooperative game theory to help with better understanding of the subcontractors' partnering problem. The "Subcontractors' Resource Management Model" section develops a multiresource management model, useful for resource-leveling problems. The developed model is applied to an illustrative example and various mechanisms for allocation of cooperative gains are discussed, their acceptability and stability are examined, and the best allocation scheme is identified. Finally, we conclude with a discussion of the study limitations and provide suggestions for future studies.

Game Theory

Game theory is recognized as the mathematical study of conflict and cooperation between intelligent, rational decision-makers (von Neumann and Morgenstern 1944; Myerson 1991). Decision-makers or players of a game can pursue well-defined objectives and try to outsmart other players by considering their objectives, behavioral characteristics, and possible countermoves (Madani 2010; Madani and Lund 2011, 2012). Noncooperative game theory—one of the two main branches of game theory—can facilitate predicting the likely outcomes and behaviors of decision makers or players of a game who give priority to their own objectives and make strategic decisions based on individual rationality (Madani and Hipel 2011). Players do not always try to maximize their gains through competition. If possible, players may pursue their objectives through cooperation and forming coalitions (Parrachino et al. 2006; Madani and Dinar 2012) and/or linking games (Just and Netanyahu 2004; Madani 2011). Cooperative game theory—the other main branch of game theory—deals with interactions of players who have to cooperatively decide how to fairly and efficiently share the benefits of cooperation. Cooperative game theory provides valuable insights into resource-sharing games in which parties may adopt various strategies for utilization of the shared resource (Parrachino et al. 2006).

Game theory has been identified as a useful framework to investigate various aspects of construction projects (Lazar 2000). Therefore, game theory applications in construction management have increased over the last two decades. Using game theory and negotiation theory, Pena-Mora and Wang (1998) suggested a method for facilitating negotiations and conflict resolution in large-scale civil engineering projects. Ho and Liu (2004) proposed a decision model for analyzing construction claims and examining the existence of opportunistic bidding behavior based on game theory. Ho (2005) applied game theory to analyze the behavioral dynamics of competing bidders and project owners. In another study, Ho (2006) developed a game theoretic model for government rescue dynamics to provide theoretic foundations for examining the quality of public-private partnership policies. Medda (2007) examined the process of risk allocation between public and private sectors in transport infrastructure agreements through a final offer arbitration game to analyze the behavior of the players when faced with opposite objectives in allocation of risks. Shen et al. (2007) and Hanaoka and Palapus (2012) used game theory to identify a reasonable concession period, one of the most important decision variables in arranging a build-operate-transfer (BOT) contract. In a study by Sacks and Harel (2006), game theory was applied to explain the influence of reliability degree of the planned schedule on subcontractors' and project managers' behaviors under traditional unit price contracting. Eriksson (2007) used game theory to explain the lack of cooperation in buyer-supplier relationships within construction and facilities management, and found that long-term contracting provides cooperation incentives. Based on noncooperative game theory concepts and considering the attitudes of parties at two complementary levels of decision making, i.e., strategic and tactical, Yousefi et al. (2010) presented a systematic negotiation method for construction disputes. Unsal and Taylor (2011a) integrated an agent-based simulation model with game theory to examine the hold-up problem in project networks. While the aforementioned studies have mostly focused on noncooperative game theory concepts, a limited number of studies have applied cooperative game theory in construction management. Perng et al. (2005) investigated the possibility of improving profitability through coalition formation by independent subcontractors; and recently, Hsueh and Yan (2011) used cooperative game theory to allocate joint venture profits among its members with respect to their contributions.

Cooperative game theory provides an appropriate framework for studying joint resource management through partnering during construction projects. Based on cooperative game theory solution methods one can (1) identify the possible coalitions that can be formed among the cooperative parties to increase their benefits and (2) decide how to fairly and efficiently divide the benefits of cooperation among the coalition members.

If N represents the grand coalition that includes all players (subcontractors), subset S ($S \subseteq N$) represents a possible coalition of players or a possible alliance formed by subcontractors. v can be defined as the characteristic function that assigns a *worth* or *value* $v(S)$ to each coalition S (e.g., the total benefit of S). In this study, we assume that joint resource management is a cooperative game with transferrable utility. Transferable utility implies that the total utility of the coalition is constant, irrespective of how the coalitional payoff is divided between the coalition members. In an n-player cooperative game, solution concepts propose one or more allocations $[x(1), x(2), \ldots, x(i), \ldots, x(n)]$ to fairly and efficiently divide the total value of the coalition among players, where $x(i)$ represents player i's payoff. An appropriate cooperative solution satisfies the following three principles [Eqs. (1)–(3)]

$$\sum_{i \in N} x(i) = v(N) \tag{1}$$

$$x(i) \geq v(i), \quad \forall\ i \in N \tag{2}$$

$$\sum_{i \in S} x(i) \geq v(S), \quad \forall\ S \subseteq N \tag{3}$$

The efficiency principle (Eq. 1) will be satisfied when $v(N)$, the total value of the grand coalition, is fully divided among players. The individual rationality principle [Eq. (2)], requires that the payoff allocated to any player i, $x(i)$, to be greater than the amount that it can attain on his own, $v(i)$. The coalitional rationality principle [Eq. (3)] requires that the sum of cooperative allocations to any coalition S, $\sum_{i \in S} x(i) = x(S)$, to be greater than the total obtainable gains under any coalition that includes the same players [$v(S)$].

The core of the game $C(v)$, introduced by Gillies (1959), is established based on Eqs. (1)–(3) and represents a set of players' collaborative payoffs (allocations under cooperation) that are not dominated by any other allocation set

$$C(v){:}\left\{x \in R^n \middle| \sum_{i \in N} x(i) = v(N), \text{and} \sum_{i \in S} x(i) \geq v(S), \forall\ S \subset N \right\} \tag{4}$$

Allocations that do not belong to the core are potentially not acceptable by players or coalitions. If the core of a cooperative game is nonempty, there is a potential for cooperation. When the core exists, the challenge is to identify the fairest allocation among all possible allocations in the core. Based on different notions of fairness, various cooperative game theory solutions have been proposed that select a specific allocation as the fairest solution. If the identified solution belongs to the core, it automatically satisfies the individual and group rationality as well as the efficiency criteria.

Nash-Harsanyi Bargaining Solution (Harsanyi 1959, 1963)

This solution, which is the generalized version of the Nash bargaining solution for two-player bargaining games (Nash 1953), finds the cooperative allocation solution based on the following mathematical model

$$\Omega = \max \prod_{i=1}^{n} [x(i) - v(i)] \tag{5}$$

Subject to Eqs. (1)–(3)

Given the constraints of this model, the Nash-Harsanyi solution always belongs to the nonempty core.

Nucleolus (Schmeidler 1969)

The Nucleolus is based on the idea of the excess. The excess of the coalition S associated with x is

$$e(S, x) = v(S) - \sum_{i \in S} x(i) = v(S) - x(S) \tag{6}$$

where $e(S, x)$ can be interpreted as a tax imposed to or dissatisfaction of coalition S. Now, consider vector $E(x)$ whose components are the excesses of the all possible subsets of N except Ø; and N, arranged in a decreasing order. The Nucleolus is a unique allocation that minimizes $E(x)$ in a lexicographic order (Schmeidler 1969). In other words, the Nucleolus minimizes the dissatisfaction of the dissatisfied coalitions gradually (starting from the highest dissatisfaction and getting to the lowest dissatisfaction). The Nucleolus allocation is a unique solution to the following linear programming problem

$$\min \varepsilon \tag{7}$$

subject to

$$e(S, x) \leq \varepsilon \quad \forall\ S \subset N \tag{8}$$

Eq. (1)

$$\varepsilon\text{:free}$$

where ε is the tax imposed on every coalition to eliminate the tendency for leaving the grand coalition.

The above linear programming may or may not result in a unique allocation. In that case, to find the Nucleolus the taxing process should be continued by minimizing the second-highest excess, then the third-highest excess, and so on to the last one (the lowest excess). The Nucleolus solution belongs to the core if the core is nonempty.

Shapley Value (Shapley 1953)

The marginal contribution of player i to coalition S is defined as the value added to this coalition by player i's arrival to the coalition

$$M(i,S) = v(S\cup i) - v(S), \quad \forall\ S \subseteq N \setminus \{i\} \tag{9}$$

Shapley (1953) suggested that the average of the marginal contributions of player i to all possible coalitions and sequences as the fair and efficient allocation to this player

$$x(i) = \sum_{S\subseteq N\setminus\{i\}} \frac{s!(n-s-1)!}{n!} M(i,S), \qquad s = |S| \tag{10}$$

The Shapley value is a unique allocation, which is always in the core if the game is convex. A convex game is defined as the game in which

$$v(S\cup T) + v(S\cap T) \geq v(S) + v(T), \quad \forall\ S,T \subseteq N \tag{11}$$

where S and T are two possible coalitions.

τ-Value (Tijs 1981)

The τ-value is a feasible compromise between two vectors of UB and LB that are the marginal vector (Utopia vector) and the minimum right vector, respectively. For player i, UB_i, the upper bound, and LB_i, the lower bound, are defined as

$$UB_i = v(N) - v(N\setminus\{i\}), \quad \forall\ i \in N \tag{12}$$

$$LB_i = \max_{S:i\in S}\left(v(S) - \sum_{j\in S\setminus\{i\}} UB_j\right), \quad \forall\ i\in N \tag{13}$$

There is a unique allocation that lies in the hyperplane of the efficiency and on the line segment $[LB(v), UB(v)]$. This allocation can be calculated as

$$x(i) = LB_i + \alpha(UB_i - LB_i) \tag{14}$$

where

$$\alpha = \begin{cases} 0 & \text{if } UB_i = LB_i \\ \frac{v(N)-\sum_{i\in N} LB_i}{\sum_{i\in N} UB_i - \sum_{i\in N} LB_i} & \text{otherwise} \end{cases} \tag{15}$$

Similar to the Shapley value, the τ-value may not be always in the core.

The introduced methods for allocating incremental benefits of cooperation can be used in cost allocation problems in which the incremental benefit of cooperation is equal to the total reduced cost under cooperation. In that case, if $c(i)$ and $c(S)$ represent the cost of player i and the total cost of coalition S, respectively, $v(S)$ can be calculated as

$$v(S) = \sum_{i\in S} c(i) - c(S) \tag{16}$$

Then, the allocated cost to each player, $x_c(i)$, is

$$x_c(i) = c(i) - x(i) \tag{17}$$

Subcontractors' Resource Management Model

In this section, we introduce a multiresource management model for subcontractors. The suggested model is used to construct the payoff functions of subcontractors in their short-term partnering game. It is noteworthy that any resource management model could be employed as long as it provides realistic estimation of subcontractors' payoffs under noncooperation (status quo) and for any possible coalition among subcontractors. One can mathematically prove that the choice of the model and its assumptions will not affect the main message of this study, which is that joint resource management is superior to individual resource management. However, the value of cooperation cannot be determined in the general case and a certain payoff function has to be selected to determine the value of cooperation. Aligned with the main objective of a resource-leveling problem (Koulinas and Anagnostopoulos 2012), we need a model that helps us develop meaningful payoff functions for subcontractors who manage their resources to meet project objectives and requirements, including completing their tasks before the designated finish date. Hariga and El-Sayegh's (2011) resource leveling formulation is employed here as the basis of the introduced model. They developed an integer-linear optimization model of multiresource leveling with continuous and intermittent activities. To our knowledge, it is one of the few models that consider cost of splitting, hiring, and firing. Generally, the aim of resource leveling is to minimize the peak demand and undesirable fluctuation of resources. In order to achieve an optimal solution to a resource-leveling problem, various techniques have been employed based on different assumptions for different project networks. The ability of Hariga and El-Sayegh's simple model to find optimal solutions makes it a desirable model for application in subcontractors' network activities problems that are usually small to middle sized.

To develop a multiresource management model, we first need to categorize the construction resources as each resource category has specific cost characteristics. Resource categorization will help us define the cost functions for subcontractors in single and coalitional forms, $c(i)$ and $c(S)$, respectively.

Resources Categorization

Here, we assume that subcontractors have access to the following categories of resources:

1. Constant resources: Many subcontractors have constant crews and equipment. Subcontractors prefer to use the constant resources according to the peak demand, resulting in uniform resource histograms. Regarding human resources, they almost count on a fixed set of staff such as high-quality skilled workers and engineers who are considered to be assets for subcontractors. It is believed that firing surplus workers destroys workers' morale, does not promote loyalty, and does not capture the benefits of learning/training acquired by workers after being on site for some time (Senouci and Eldin 2004). Besides, hiring and firing workers for short periods might be costly in some countries due to work regulations and laws. This assumption is valid for some equipment usage, too. A uniform rectangular resource histogram is more desirable (Mattila and Abraham 1998) for constant resources. One reason is to avoid

the considerable transportation, mobilization, and removal costs of construction equipment (Karra and Nasr 1986). The other reason is that the crew reaches its highest productivity when its size remains almost constant during construction activities. As a result, the subcontractors prefer to mobilize the construction site according to the peak demand of each constant resource. They employ this category of resources through a long-term contract that includes a number of projects.

2. Temporary resources: Subcontractors hire or procure some temporary resources like open shop workers, who are available at any time. Some equipment falls in this category when it is convenient and economic for subcontractors to rent them for short periods of time even in an irregular manner. The important point about this resource category is that subcontractors generally prefer the least number of hire-fire processes, the least number of setting up-removal rounds, the least cost for transportation between sites, and the least fluctuations of these resources between consecutive days to avoid low productivity and extra cost due to additional orientations or mobilization. This category of resources is normally hired for a short time through a temporary contract.

Model Formulation in a Single Form

First, we develop a resource management model for each individual subcontractor i (for $i = 1, \ldots, N$). Later, we extend the single form models to the coalitional form. Assume that the CPM (critical path method) scheduling of critical and noncritical activities has been established for each subcontractor's network. Based on logical relationships between m activities of the project with total duration T, for each activity j $(j = 1, \ldots, m)$ the earliest start time ES_j, the earliest finish time EF_j, the latest start time LS_j, the latest finish time LF_j, and total float TF_j can be calculated. For running the project activities subcontractor i requires P different resource types, belonging to different categories (e.g., two different machines and one type of skilled workers as constant resources and the general open shop workers as a temporary resource), at different rates over the duration of activities. To treat constant resources and temporary resources differently in the model, they are put into two independent complement sets, called as CR and TR, respectively. In other words, the union of these two sets includes all resource types and their intersection is an empty set ($\mathrm{CR} \cap \mathrm{TR} = \oslash$).

The following sets of constraints should be considered for the optimization model.

Resource balance constraints: Eq. (18) determines the resource requirement for both critical and noncritical activities in each period t:

$$R_{tp} = \sum_{u=1}^{nc} r_{\mathrm{up}}.z_{tu} + \sum_{j=1}^{nn} r_{jp}.y_{tj}, \qquad t = 1, 2, \ldots, T \quad \text{and}$$
$$p = 1, 2, \ldots, P \quad \text{or} \quad p \in (CR \cup TR) \tag{18}$$

where R_{tp} = requirement for resource type p in period t; r_{up} = number of units of resource type p needed to run critical activity i; z_{tu} = binary parameter equal to one when critical activity u is active (running) from period ES_i to period EF_i and zero otherwise; r_{jp} = number of units of resource type p needed to run noncritical activity j; and y_{tj} = binary variable equal to one when noncritical activity j is active during period t and zero otherwise.

Eq. (19), suggested by Hariga and El-Sayegh (2011), guarantees that for each temporary resource type p, the number of required units in period t in addition to the number of acquired units in period t have to be equal to sum of the number of released units in period t and the number of required units in the period $t - 1$.

$$\begin{aligned} &R_{tp} - R_{(t-1)p} + H_{tp} - F_{tp} = 0, \quad t = 1, 2, \ldots, T \quad \text{and} \\ &p \in TR \qquad H_{tp} \geq 0, \quad t = 1, 2, \ldots, T \quad \text{and} \\ &p \in TR \qquad F_{tp} \geq 0, \quad t = 1, 2, \ldots, T \quad \text{and} \\ &p \in TR \qquad R_{0p} = 0, \quad p \in TR \end{aligned} \tag{19}$$

where H_{tp} = number of units of resource type p acquired during period t and F_{tp} = number of units of temporary resource type p released during period t.

Since Hariga and El-Sayegh's model aims to minimize costs of hiring/firing processes and splitting activities, their model is only applicable to problems that include temporary resources. Indeed, its objective implicitly considers all resources as temporary resources based on our resource categorization. For applicability to all resource categories (both constant and temporary resources), we extend their model by adding another constraint to address constant resources

$$\begin{aligned} &R_{tp} - A_{tp} + I_{tp} = R\mathrm{max}_p, \quad t = 1, 2, \ldots, T \quad \text{and} \\ &p \in CR \qquad I_{tp} \geq 0, \quad t = 1, 2, \ldots, T \quad \text{and} \quad p \in CR \end{aligned} \tag{20}$$

where $R\mathrm{max}_p$ = maximum number of units of constant resource type p required for the total project duration in addition to the available units of constant resource type p; A_{tp} = number of units of constant resource type p available during t; and I_{tp} = number of units of constant resource type p that remain idle during t.

Here, we assume that subcontractors may have some units of constant resources already available. They just need to employ $R\mathrm{max}_p$ for total project duration from the beginning of the project. For example, for a subcontractor that already has two skilled workers in its team from the beginning of a five-day project ($A_{tp} = 2$ for $t = 1, \ldots, 5$) and needs 2, 1, 2, 4, and 3 skilled workers in days 1 to 5, respectively, the minimum possible $R\mathrm{max}_p$ will be 2 units. Thus, the number of idle skilled workers (I_{tp}) for days 1 to 5 will be 2, 3, 2, 0, and 1, respectively.

Duration constraint: Since noncritical activities can be split, a duration constraint is needed to guarantee that for each noncritical activity, number of active periods is equal to the activity duration

$$\sum_{t=ESj}^{EFj} y_{tj} = T_j, j = 1, 2, \ldots, nn \tag{21}$$

Network logic constraints: The precedence relationships among noncritical activities have to be ensured by the following constraints

$$S_j + (T + 1 - t).y_{tj} \leq T + 1, \qquad t = ES_j, \ldots, LS_j \tag{22}$$

$$F_j - t.y_{tj} \geq 0, \qquad t = EF_j, \ldots, LF_j \tag{23}$$

$$S_k \geq F_j + 1, \quad \forall\ k \in \ \text{Successor}\ (j), \quad j = 1, 2, \ldots, nn \tag{24}$$

Splitting constraints: Eqs. (25) and (26) are to determine the number of times a noncritical intermittent activity is split. For each activity, L_{tj} will be equal to one if the continuation of the activity is stopped and zero otherwise. NS_j accounts for the number of required noncritical splits and will be used in the objective function of the resource management model. The splitting constraints are as follows:

$$L_{tj} - (y_{ti} - y_{(t+1)i}) \geq 0, \quad j = 1, 2, \ldots, nn, \quad t = ES_j, \ldots, LF_j \tag{25}$$

$$NS_j = \begin{cases} \sum_{t=ES_j}^{LF_j} L_{tj} - 1 & \text{for all intermittent noncritical activities} \\ 0 & \text{for all continuous noncritical activities} \end{cases}$$

$$y_{tj} \in \{0,1\}, \quad j = 1,2,\ldots,nn, \quad t = ES_j,\ldots,LF_j$$

$$L_{tj} \geq 0, \quad j = 1,2,\ldots,nn, \quad t = ES_j,\ldots,LF_j \tag{26}$$

where S_j = start time of noncritical activity j; F_j = finish time of noncritical activity j; L_{tj} = nonnegative variable to determine whether noncritical activity j is split in period $t+1$; and NS_j = number of times noncritical activity j is split through the course of project.

For a detailed illustration on the above constraints [except for Eq. (20)], see Hariga and El-Sayegh (2011).

Objective function: In developing a resource management plan, subcontractors try to minimize the total costs of employing different resources types through shifting and splitting noncritical activities. Therefore, we consider net cost minimization as the objective of our resource management model. The net cost minimization objective function of the model is comprised of the following five components:

1. Constant resource cost: As discussed earlier, subcontractors prefer to have access to constant resources in a regular and steady manner. These resources are sometimes active and other times idle in the construction site. Nevertheless, in both modes these resources have costs to the subcontractors. For this resource category, the resource management model tries to minimize the demand peak in order to reduce the total time of having these resources in the idle mode. Therefore, the following cost component is used to represent the cost of employing a fixed number of constant resource units during the project

$$(PF - PS + 1)\sum_{p\in CR} R\max_p . CC_p \tag{27}$$

where PS = project start date; PF = project finish date; and CC_p = cost of employing one unit of constant resource type p in period t.

2. Idle resource returns: Constant resources cost differently to the subcontractors in the active and idle modes. Idle mode is associated with savings in equipment repair and maintenance costs. Equipment can be even leased to other projects for short periods. Similarly, engineers and skilled workers can be temporarily assigned to other subcontractors' projects. The following term represents the total idle resource returns

$$\sum_{p\in CR}\left[IR_p \sum_{t=1}^{T} I_{tp}\right] \tag{28}$$

where IR_p = expected returns of one unit of constant resource type p in period t. For simplicity, the expected cost savings and returns could be considered as a percentage of constant resource cost (say, $IR_p = 0.2CC_p$).

3. Temporary resource cost: Subcontractors have to pay for temporary resources only when they are active as these resources can be employed (hired-fired) anytime. The total cost of employing temporary resources is

$$\sum_{p\in TR}\left[CT_p \sum_{t=1}^{T} R_{tp}\right] \tag{29}$$

where CT_p = cost of employing one unit of temporary resource type p in period t.

4. Acquiring/releasing cost: This cost component, suggested by Hariga and El-Sayegh (2011), reflects the cost of acquiring and releasing temporary resources

$$\sum_{p\in TR}\left[CF_p \sum_{t=1}^{T} F_{tp} + CH_p \sum_{t=1}^{T} H_{tp}\right] \tag{30}$$

where CH_p = total cost of acquiring one unit of resource type p (costs of reorientation, setting up, etc.) and CF_p = total cost of releasing one unit of resource type p (costs of firing, removal, etc.).

5. Splitting cost: This cost component, also suggested by Hariga and El-Sayegh (2011), represents the cost of splitting noncritical activities

$$\sum_{j=1}^{nn} CS_j . NS_j \tag{31}$$

where CS_j = cost of splitting noncritical activity j.

The objective function of the resource management model for a single subcontractor is the sum of the costs of employing constant and temporary resources, fluctuations in resource usage, and splitting noncritical activities, written as:

$$Z = (PF - PS + 1)\sum_{p\in CR} R\max_p . CC_p - \sum_{p\in CR}\left[IR_p \sum_{t=1}^{T} I_{tp}\right] + \sum_{p\in TR}\left[CT_p \sum_{t=1}^{T} R_{tp}\right] + \sum_{p\in TR}\left[CF_p \sum_{t=1}^{T} F_{tp} + CH_p \sum_{t=1}^{T} H_{tp}\right] + \sum_{j=1}^{nn} CS_j . NS_j \tag{32}$$

Model Formulation in a Coalitional Form

In case of cooperation between subcontractors (partnering), the proposed model must be solved for the overall project network, consisting of linked subprojects. This network is managed by the subcontractors' coalition. While all decisions are made by the coalition on a cooperative basis, the maximum number of different resources required by each subcontractor in addition to the available resources ($R\max_p$) should be still managed by each subcontractor independently. In other words, each subcontractor $i(i = 1,\ldots,N)$ participating in the coalition determines its own $R\max_{pi}$ and employs $p(p = 1,2,\ldots,P)$ different resources for its own project duration.

For example, consider subcontractors 1 and 2 with the project timelines shown in Fig. 1. When the two subcontractors participate in the two-subcontractor coalition $\{1,2\}$, subcontractor 1 is responsible to acquire $R\max_{1p}$ for its own project duration, including the uncommon duration of $T(1 \setminus 2)$ and common duration of $T(1 \cap 2)$, while subcontractor 2 is responsible to provide $R\max_{2p}$ for the uncommon duration of $T(2 \setminus 1)$ and common duration of $T(1 \cap 2)$. Therefore, the following constraint must substitute Eq. (20)

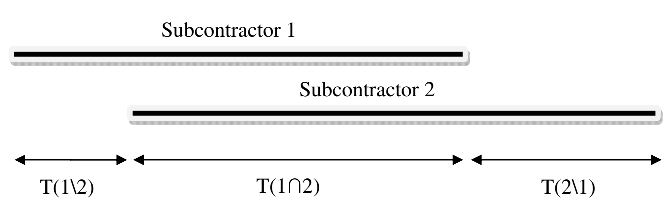

Fig. 1. Project timelines for subcontractors 1 and 2

$$R_{tp} - A_{tp} + I_{tp} = \sum_{s:PS_i \leq t \leq PF_i} R\max_{ip}, \quad t = 1, 2, \ldots, T \quad \text{and} \quad p = 1, 2, \ldots, P \tag{33}$$

And in the objective function, the constant resource costs component [Eq. (27)] should be replaced by

$$\sum_{i=1}^{N} (PF_i - PS_i + 1) \sum_{p=1}^{P} R\max_{ip}.CC_p \tag{34}$$

where PS_i = project start date for subcontractor i and PF_i = project finish date for subcontractor i. $y_{ti}, S_j, F_j, L_{tj}, NS_j, R_{tp}, H_{tp}, F_{tp}, I_{tp}$, and $R\max_{ip}$ are the decision variables of the developed resource management model.

Illustrative Example

For better illustration of the utility of the developed model, consider a large construction project in which three subcontractors are in charge of accomplishing three different subprojects in one site. Fig. 2 and Table 1 present the subprojects' bar charts and network information. Among all resources used by subcontractors, three machine types (M1, M2, and M3), and two types of human resources, i.e., skilled worker (SW) and open shop worker (OW), are in common. Resources M1, M2, and SW are the constant resources while resources M3 and OW are temporary resources. Tables 2 and 3 indicate the daily resources costs and the available resources units in different periods, respectively. In the idle mode, machines M1 and M2 cost 20% less. Skilled workers cost 33% less in the inactive mode.

To calculate the fair and efficient cost shares of the coalition members based on different cooperative game theory concepts in this super-additive nonconvex problem, we first need to calculate the costs of all possible coalitions. Therefore, we solve the formulated optimization model for singleton coalitions ({1}, {2}, {3}), two-member coalitions ({1, 2}, {1, 3}, {2, 3}), as well as the grand coalition ({1, 2, 3}). In the noncooperative mode (singleton coalitions) each subcontractor tries to level its own resource usage individually. The resulting bar charts for single subcontractors are presented in Fig. 2.

Table 4 shows the values of the five components of the objective function for all seven possible coalitions. Comparison of the objective values under full noncooperation and the objective values under partial or full cooperation suggests that cooperation can provide cost-saving opportunities. The bar chart for the grand coalition is presented in Fig. 3. This figure shows whether a given activity is ongoing in a given period of time or not.

Discussion

In a multiresource-leveling problem, the leveling is done based on priorities, which specifically come from the considered resource costs in our model. The model starts moving and splitting noncritical activities to level more costly resources and minimize their peak demands as well as the number of hire-fire processes. Activity splitting, as a technique for obtaining more flexibility in activities network, has been applied and often has resulted in more cost-effective plans (Karaa and Nasr 1986; Son and Mattila 2004; Hariga and El-Sayegh 2011). However, the model cannot come up with a desirable leveling for most of resources, especially for small networks such as subcontractors' individual networks even when splitting some activities is allowed. Therefore, there is a considerable cost return potential for subcontractors through leveling common resources by cooperation and use idle resources of each other instead of employing more constant resources from the beginning of their subprojects. A large number of resource idling periods are observable during each subcontractor's subproject (Fig. 4), indicating the inefficiency of individual resource management (status quo). Comparison of M1 profiles under individual and collective resource management, presented in Fig. 4, underlines the value of partnering. Moreover, the zero splitting cost for all subcontractors in status quo (Table 4) indicates the inefficiency of activity splitting in single forms and the higher suitability of coalitions for taking advantage of network flexibilities.

	Period (day)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Subcontractor 1	A1	1	1	1	1	0	0	0	0	0																
	B1	1	1	1	1	1	1																			
	C1	0	0	1	1	1	1	1	1	1	1	0	0	0												
	D1					1	1	1	0	0	0	0	0													
	E1							1	1	1	1															
	F1									0	0	1	1	0	0	0										
	G1											1	1	1	1	1										
	H1								1	1	1	0	0	0	0	0										
Subcontractor 2	A2				1	1	1	1	1																	
	B2									1	1	1	1	1												
	C2				0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1			
	D2														1	1	1	1	0	0	0	0	0			
	E2																		0	0	0	0	0	1	1	1
	F2														1	1	1	1	1	1	1	1	1	1	1	1
Subcontractor 3	A3						1	1	1	1	1															
	B3											1	1	1	1	1	1	1	1	1	1					
	C3						0	0	0	0	0	0	0	1	1	1	1	1	1	1	0					
	D3						0	1	1	1	1	1	1	0	0											
	E3												0	1	1	1	1	1	1	0	0					

: Critical activity   : Noncritical activity   1,0 : Activity is working or not in a given period

Fig. 2. Status quo Gantt charts of subcontractors (individual leveling)

Table 1. Network Information

	Network								Resource rates (r_{ip} and r_{ip})				
Activity	Duration (days)	ES	EF	LS	LF	TF (day)	Type of activity	CSj	M1	M2	M3	SW	OW
Subcontractor 1													
A1	4	1	4	6	9	5	Intermittent	$100	1	1	0	2	4
B1	6	1	6	1	6	0			0	1	1	1	5
C1	8	1	8	6	13	5	Intermittent	$200	1	0	0	3	5
D1	3	5	7	10	12	5	Intermittent	$100	0	1	1	1	8
E1	4	7	10	7	10	0			1	0	0	2	6
F1	2	9	10	14	15	5	Continuous	—	0	0	0	2	7
G1	5	11	15	11	15	0			0	1	0	1	9
H1	3	8	10	13	15	5	Continuous	—	0	2	2	1	6
Subcontractor 2													
A2	5	4	8	4	8	0			0	1	1	3	7
B2	5	9	13	9	13	0			0	1	0	3	5
C2	5	4	8	18	22	14	Intermittent	$200	0	2	2	2	10
D2	4	14	17	19	22	5	Intermittent	$100	0	1	0	2	8
E2	3	18	20	23	25	5	Continuous	—	0	0	1	1	4
F2	12	14	25	14	25	0			0	1	2	1	6
Subcontractor 3													
A3	5	6	10	6	10	0			1	0	1	2	4
B3	10	11	20	11	20	0			1	0	2	3	5
C3	7	6	12	14	20	8	Intermittent	$160	2	0	1	1	3
D3	6	6	11	9	14	3	Intermittent	$120	1	0	2	1	5
E3	6	12	17	15	20	3	Intermittent	$120	0	0	0	2	5

Table 2. Daily Resource Costs and Idle Resource Returns

	Resources				
Parameter	M1	M2	M3	SW	OW
CC	$1,000	$800	—	$300	—
CT	—	—	$500	—	$150
CI	—	—	$100	—	$25
CD	—	—	$100	—	$75
IR	$200	$160	—	$100	—

As Table 4 suggests, participation of subcontractor 1 in all possible coalitions ({1,2}, {1,3}, and {1,2,3}) is more valuable than other subcontractors in terms of the resulting cost savings. Thus, this subcontractor may claim for a higher share from the incremental benefits of cooperation (cost reduction). Although the period of time that subcontractor 1's network overlaps networks of subcontractors 2 and 3 is the shortest (12 + 10 = 22 days according to Table 3), this subcontractor can benefit the most from cooperation because of having more resources in common with other subcontractors and having more flexibility in its network. Due to having less common resources and less flexibility in their networks, partnering of subcontractors 2 and 3 would not result in considerable benefits, even though the two subcontractors have the longest overlap (15 days).

Allocation of Cooperative Gains

While partnering can result in major cost savings, the main challenge is how to share the benefits (savings) on a fair and efficient basis among the cooperating parties. We use cooperative game theory concepts to determine the fair and efficient share of the subcontractors such that they have no motivation to leave the grand

Table 3. Subcontractors' Available Resources and Overlapping Periods

							Overlapped period with Subcontractor			Sum of
Subcontractor	Availability period	M1	M2	M3	SW	OW	1 (days)	2 (days)	3 (days)	overlapped period (days)
1	day 1–day 15	1	1	0	4	0	—	12	10	22
2	day 4–day 25	0	3	0	2	0	12	—	15	27
3	day 6–day 20	1	1	0	1	0	10	15	—	25

Table 4. Values of the Objective Function and Its Components for All Possible Coalitions ($)

	Coalition						
Objective function component	{1}	{2}	{3}	{1, 2}	{1, 3}	{2, 3}	{1, 2, 3}
Constant resources cost	36,000	6,600	52,500	30,600	60,000	54,600	52,500
Idle resources returns	6,660	5,100	6,900	10,140	6,060	10,500	8,060
Temporary resource costs	39,150	54,900	44,650	94,050	83,800	99,550	13,8700
Acquiring/releasing costs	2,500	2,800	2,100	4,400	4,700	4,900	6,900
Splitting costs	0	0	0	200	220	160	940
Total cost	70,990	59,200	92,350	119,110	142,660	148,710	190,980
Incremental benefit of cooperation	0	0	0	11,080	20,680	2,840	31,560

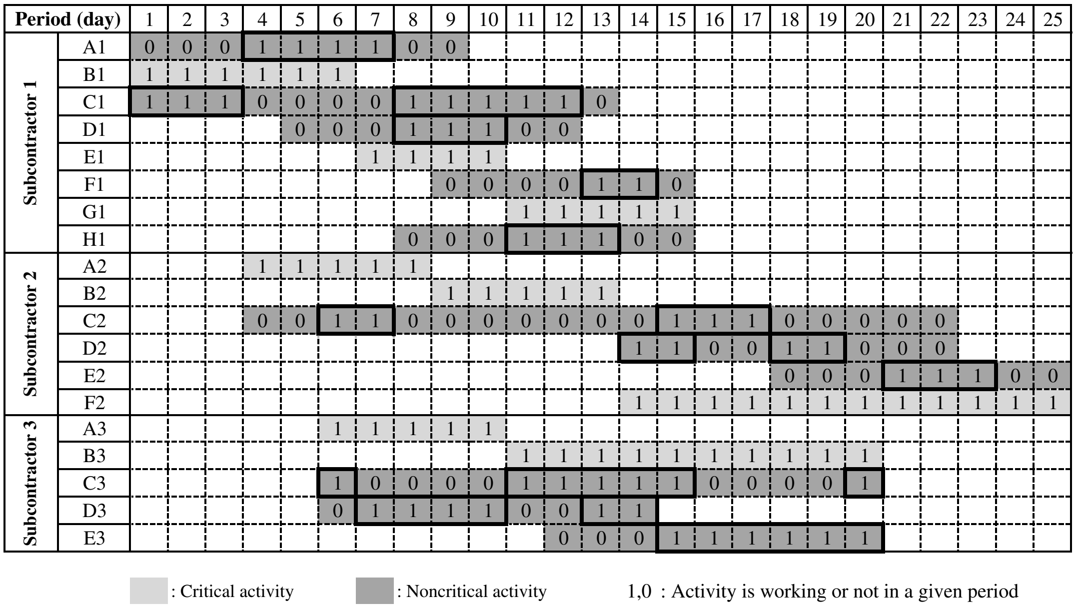

Fig. 3. Cooperative Gantt chart of subcontractors (leveling by grand coalition)

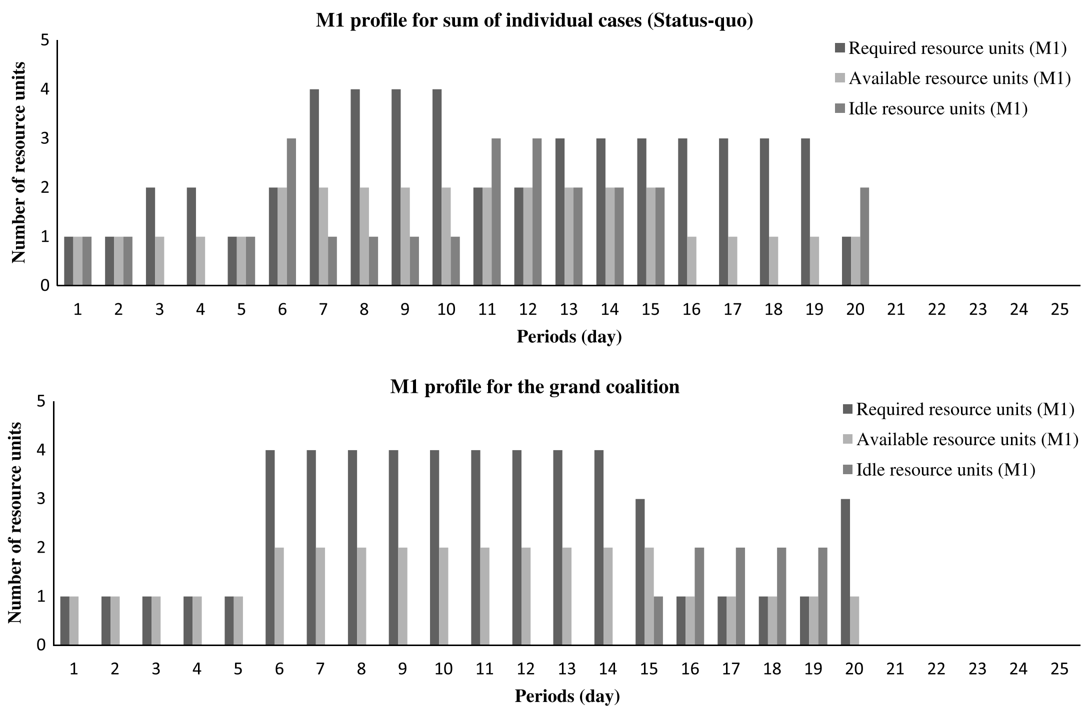

Fig. 4. Comparison of M1 profiles under individual and collective resource management

coalition. Fig. 5 shows the core space of three-subcontractor partnering example inside a simplex in R^3, with vertexes $[v(1,2,3) = 31560, 0, 0]$, (0,31560, 0), (0,0,31560), that represents the set of all possible allocations. The inequality constraints have been calculated based on Eqs. (2)–(3), using the data from Table 4. There are infinite potentially acceptable solutions in the core. Based on different notions of fairness, the four introduced cooperative solution concepts select for unique solutions out of all possible solutions as the best allocation solution (Table 5). It is noteworthy that here we are calculating the values of partial and full coalitions based on the transferrable utility assumption. Under this assumption, side payments are allowed; subcontractors cooperatively provide the required resources, and share the total cost of cooperation. In this case, parties can benefit from the Pareto-optimal social planner solution, yielding the highest level of cost saving. When utility is not transferrable, parties cannot benefit from the social planner solution and the overall savings will not be Pareto-optimal (although sometimes more practical). In that case, the problem finds a different structure and should be solved differently [e.g., Madani (2011)]. Construction partnering with nontransferrable utilities may only involve sharing the common resources and no cost sharing. Future studies can focus on nontransferrable utility partnering problems.

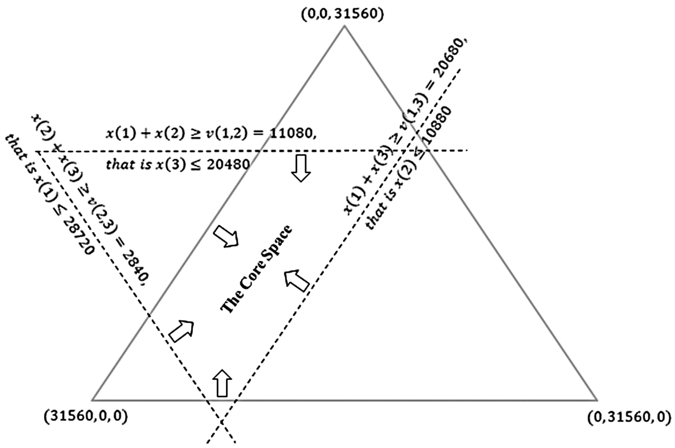

Fig. 5. Core space for the illustrative example

Table 5. Allocation of Cooperative Gains Based on the Four Cooperative Game Theory Solutions

		Solution			
Subcontractor	Cooperation Results	Nash-Harsanyi	Nucleolus	Shapley value	τ-value
1	Allocated cost ($)	60,470	59,910	56,123	55,854
	Cost difference with respect to the non-cooperative case (%)	15%	16%	21%	21%
	Resulted benefits ($)	10,520	11,080	14,867	15,136
2	Allocated cost ($)	48,680	53,760	53,253	53,502
	Cost difference with respect to the non-cooperative case (%)	18%	9%	10%	10%
	Resulted benefits ($)	10,520	5,440	5,947	5,698
3	Allocated cost ($)	81,830	77,310	81,603	81,624
	Cost difference with respect to the non-cooperative case (%)	11%	16%	12%	12%
	Resulted benefits ($)	10,520	15,040	10,747	10,726

Solution Acceptability and Stability

While all the core solutions, including the four selected solutions based on cooperative game theory solution methods, are potentially acceptable based on mathematical calculations, parties may find many of them unfair in practice. Parties who find an allocation solution unfair have motivations for leaving the grand coalition and forming partial coalitions or act individually, making the grand coalition unstable. For instance, in this example the shape of the core (Fig. 5) implicitly suggests the final allocation should follow the $x(1) > x(3) > x(2)$ order. Therefore, although Nucleolus has been proposed as an acceptable and efficient solution to cooperative game theory problems, Nucleolus allocation might not be a fair solution in the example problem.

Stability of cooperative allocation solutions must be acceptable as evaluated to ensure their feasibility. A simple approach to identify the most stable solution is to use social choice rules or voting theory methods (Sheikhmohammady and Madani 2008; Shalikarian et al. 2011). Plurality rule is one of the social choice rules, commonly used to simply identify the most popular allocation solution (Dinar and Howitt 1997; Madani and Dinar 2012). Plurality rule chooses the most preferred solution by the most number of users. Table 6 shows how the subcontractors rank the four

Table 6. Preference Orders of the Subcontractors over the Four Cooperative Game Theory Solutions

	Solution			
Subcontractor	Nash-Harsanyi	Nucleolus	Shapley value	τ-value
1	1	2	3	4
2	4	1	3	2
3	1	4	3	2
Total score	6	7	9	8

Table 7. Propensity to Disrupt of the Subcontractors under the Four Cooperative Game Theory Solutions

	Solution			
Subcontractor	Nash-Harsanyi	Nucleolus	Shapley value	τ-value
1	1.73	1.59	0.93	0.90
2	0.03	1.00	0.83	0.91
3	0.95	0.36	0.91	0.91
Maximum propensity to disrupt	1.73	1.59	0.93	0.91

cooperative game theory solutions. In Table 6, rank 4 belongs to the most-preferred allocation by the subcontractor and rank 1 belongs to the least-preferred allocation. Based on the plurality rule, the Shapley allocation and then the τ-value allocation are the best solutions, acceptable by the majority.

While application of social choice rules is straightforward, due to their qualitative nature, social choice rules sometimes fail to identify the most stable solution correctly. Thus, quantitative stability evaluation methods are believed to be more appropriate for selecting the most stable solution and for providing useful stability assessment information (Madani and Dinar 2012). The *propensity to disrupt* method (Gately 1974) is one of the quantitative stability evaluation methods used in the cooperative game theory literature. Basically, this method determines the most stable solution with respect to the players' powers in the grand coalition. Player i's propensity to disrupt (PTD_i) is defined as (Gately 1974; Straffin and Heaney 1981)

$$\mathrm{PTD}_i = \frac{\sum_{j \neq i} x(i) - v(N \setminus i)}{x(i) - v(i)} \tag{35}$$

As an indicator of player i's power, PTD_i is essentially the ratio of what the other players ($N \setminus i$) will lose if player i refuses to cooperate and leaves the grand coalition, to what player i will lose by leaving the grand coalition. The higher the propensity to disrupt of a player, the higher his negotiation power. Generally, a low PTD_i reflects a high enthusiasm for cooperation and staying the grand coalition. On the other hand, a player with a high PTD_i is not as enthusiastic about staying in the coalition and his high level of contribution to the grand coalition gives him a great negotiation power. This player can potentially use this power and threaten the other players that he will leave the grand coalition so that he can obtain a higher share.

Table 7 shows the propensity to disrupt (PTD) of the subcontractors for the four different game theory solutions. According to this table, the τ-value solution is the most stable solution as under the τ-value allocation method all subcontractors have the same power. Furthermore, this method yields the lowest maximum PTD (0.91). The Shapley solution is the second best allocation solution based on the players' PTD. The other two cooperative game theory solutions are not stable in practice, as they do not distribute negotiation powers equally.

Although both stability evaluation methods (plurality rule and PTD) selected the same allocation methods (τ-value and Shapley value) in this case, application of a quantitative method was necessary to obtain detailed information about the general quality of the solutions and the power distributions under each method. Having access to such information is more critical in cooperative game theory problems involving more players.

Conclusions

This article suggested cooperative game theory as an appropriate framework for analyzing joint resource management in construction. Under this framework, aligned with CII's fundamental definition of partnering (CII 1991), an alliance (a coalition) is formed by subcontractors for cooperative management of the construction resources, resulting in incremental benefits for the participating subcontractors. The suggested analysis framework can help determining the maximum total obtainable values by subcontractors partnering in resource management under each feasible coalition. As indicated through a numerical example, cooperative game theory methods help design fair, efficient, and stable schemes for sharing the benefits of cooperation. For partnering to be feasible and profitable, the partners' roles and responsibilities should be clearly determined in advance. In case of partnering, the plan under the grand coalition of subcontractors reflects the optimal road map for partners and determines which resources have to be shared and when.

To facilitate joint resource management in construction, this study generalized the single-decision-maker resource-leveling model to a multiple decision-makers' resource-leveling model. The suggested model can be used by partnering subcontractors to manage construction resources more efficiently on a cooperative basis, resulting in considerable cost savings. Partnering makes the feasible solution space of the resource-leveling problem larger, with the potential to improve the Pareto-optimal solution. From the game theoretic perspective, partnering can be considered as linking games, generally resulting in expansion of the solution space and opportunities for finding win-win solutions (Madani 2011), associated with cost reductions. Results from applying the suggested model to a theoretical example indicate that having more resources in common and more flexibility in the activities' network makes short-term partnering more valuable while those flexibilities may remain unused under individually-based resource management. Moreover, while the idea of project breakdown into several subprojects helps a general contractor benefit from different subcontractors' specialization and experience, the idea of considering horizontal partnering among subcontractors can lead to a more cost-effective resource management. This underlines the need for reconsideration of the current project management practices focusing on task breakdown within individual planning boundaries.

While potentially all parties can benefit from cooperation, enforcing cooperation may be challenging in practice due to several reasons, including, but not limited to, lack of trust and information, lack of monitoring and information sharing mechanisms, high transaction costs, involvement of too many parties, diversity of needs, different scopes of work and work schedules, legal issues, unpredictable changes, different subcontractor sizes/powers (company size, capital, etc.), and desire for competition. Discussion on possible impacts of each of these factors on forming cooperative mechanisms needs further investigation. In-depth interviews and surveys might be conducted in future studies with both general contractors and subcontractors in order to get insights from different aspects and to design effective procedures to overcome different barriers for implementing the proposed framework in practice. Nevertheless, cooperation among smaller contractors seems promising due to the significant potential for incremental benefits and because of their less complex and shorter schedules. Different measures such as binding agreements and various supervising mechanisms may be applied to enforce and sustain the cooperation. It might be argued that considerable cooperative gains cannot provide sufficient motivation in forming coalitions when subcontractors are competitors in the local market. However, experience shows that cooperation can be implemented in practice even when it involves big companies in fiercely competitive industries such as the automobile industry (Brandenburger and Nalebuff 1996).

This study considered the critical aspects of real-world construction management problems. However, modeling often differs from practice, as it always involves simplifying assumptions that should not be ignored when interpreting results to advise policy making (Madani 2013). These simplifications, which might be addressed in future studies, include (1) having the same objective and strategy for resource management on a short-term basis for all subcontractors, assuming that they are all interested in minimizing resource management costs using a resource leveling model; (2) categorizing all resources into constant resources and temporary resources based on subcontractors, resource usage behavior; (3) assuming that subcontractors keep the same set of resources on site when they are idle; (4) assuming that subcontractors incur extra cost for hiring/firing processes; and (5) assuming that the problem is a transferable utility game and common resources are equally valued by partnering subcontractors.

A balance was struck between the need to keep the model simple and understandable and the need to provide a reasonable and plausible representation of the real problem. Future modeling efforts may capture other aspects of construction problems (e.g., budget limitations, timing issues), consider transaction costs of cooperation, and evaluate the sensitivity of critical parameters on feasibility of cooperation and stability of solutions.

References

Barlow, J. (2000). "Innovation and learning in complex offshore construction projects." *Research policy*, 29(7–8), 973–989.

Brandenburger, A. M., and Nalebuff, B. J. (1996). *Co-opetition*. Currency, New York.

Construction Industry Institute (CII). (1991). "In search of partnering excellence." *Special Publication No. 17-1, Rep.*, Partnering Task Force of CII, Austin, TX.

Costantino, N., and Pietroforte, R. (2002). "Subcontracting practices in USA homebuilding—an empirical verification of Eccles's findings 20 years later." *Eur. J. Purch. Supply Manage.*, 8(1), 15–23.

Dainty, A. R. J., Briscoe, G. H., and Millett, S. J. (2001). "Subcontractor perspectives on supply chain alliances." *Constr. Manage. Econ.*, 19(8), 841–848.

DeVilbiss, C. E., and Leonard, P. (2000). "Partnering is the foundation of a learning organization." *J. Manage. Eng.*, 10.1061/(ASCE)0742-597X(2000)16:4(47), 47–57.

Dinar, A., and Howitt, R. E. (1997). "Mechanisms for allocation of environmental control cost: Empirical tests of acceptability and stability." *J. Environ. Manage.*, 49(2), 183–203.

Edwards, D. J. (2003). "Accident trends involving construction plant: an exploratory analysis." *J. Constr. Res.*, 4(2), 161–173.

Eriksson, P. E. (2007). "Cooperation and partnering in facilities construction—empirical application of prisoner's dilemma." *Facilities*, 25(1/2), 7–19.

Faulkner, A. C., and Day, A. K. (1986). "Images of status and performance in building team occupations." *Constr. Manage. Econ*, 4(3), 245–260.

Gately, D. (1974). "Sharing the gains from regional cooperation: a game theoretic application to planning investment in electric power." *Int. Econ. Rev.*, 15(1), 195–208.
Gillies, D. B. (1959). "Solutions to general non-zero-sum games." *Contributions to the theory of games*, A. W. Tucker, and D. R. Luce eds., Princeton University Press, Princeton, NJ, 47–85.
Hanaoka, S., and Palapus, H. P. (2012). "Reasonable concession period for build-operate-transfer road projects in the Philippines" *Int. J. Proj. Manage.*, 30(8), 938–949.
Hariga, M., and El-Sayegh, S. M. (2011). "Cost optimization model for the multiresource leveling problem with allowed activity splitting." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000251, 56–64.
Harsanyi, J. C. (1959). "A bargaining model for the cooperative n-person game." *Contributions to the theory of games*, A. W. Tucker, and D. R. Luce, eds., Princeton University Press, Princeton, NJ, 324–356.
Harsanyi, J. C. (1963). "A simplified bargaining model for the n-person game." *Int. Econ. Rev.*, 4(2), 194–220.
Hartmann, S., and Briskorn, D. (2010). "A survey of variants and extensions of the resource-constrained project scheduling problem." *Eur. J. Oper. Res.*, 207(1), 1–14.
Hartmann, A., Ling, F., and Tan, J. (2009). "Relative importance of subcontractor selection criteria evidence from Singapore." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2009)135:9(826), 826.
Higgin, G., and Jessop, N. (1965). *Communications in the building industry*, 2nd Ed., Tavistock, London.
Ho, S. P. (2005). "Bid compensation decision model for projects with costly bid preparation." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2005)131:2(151), 151–159.
Ho, S. P. (2006). "Model for financial renegotiation in public-private partnership projects and its policy implications: game theoretic view." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2006)132:7(678), 678–688.
Ho, S. P., and Liu, L. Y. (2004). "Analytical model for analyzing construction claims and opportunistic bidding." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2004)130:1(94), 94–104.
Hsueh, S. L., and Yan, M.-R. (2011). "Contribution-based profit-sharing scheme for joint ventures." *Technol. Econ. Dev. Econ.*, 17(3), 445–458.
Humphreys, P., Matthews, J., and Kumaraswamy, M. (2003). "Preconstruction project partnering: From adversarial to collaborative relationships." *Supply Chain Manage. Int. J.*, 8(2), 166–178.
Just, R. E., and Netanyahu, S. (2004). "Implications of 'victim pays' infeasibilities for interconnected games with an illustration for aquifer sharing under unequal access costs." *Water Resour. Res.*, W05S02, 1–11.
Kang, L. S. (2001). "Optimal schedule planning for multiple, repetitive construction process." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2001)127:5(382), 382–390.
Karaa, F., and Nasr, A. (1986). "Resource management in construction." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)0733-9364(1986)112:3(346), 346–357.
Koulinas, G., and Anagnostopoulos, K. (2012). "Construction resource allocation and leveling using a threshold accepting–Based hyperheuristic algorithm." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000492, 854–863.
Kumaraswamy, M. M., and Matthews, J. D. (2000). "Improved subcontractor selection employing partnering principles." *J. Manage. Eng.*, 10.1061/(ASCE)0742-597X(2000)16:3(47), 47–57.
Lazar, F. D. (2000). "Project partnering: improving the likelihood of win/win outcomes." *J. Manage. Eng.*, 10.1061/(ASCE)0742-597X(2000)16:2(71), 71–83.
Madani, K. (2010). "Game theory and water resources." *J. Hydrol.*, 381(3–4), 225–238.
Madani, K. (2011). "Hydropower licensing and climate change: Insights from cooperative game theory." *Adv. Water Resour.*, 34(2), 174–183.
Madani, K. (2013). "Modeling international climate change negotiations more responsibly: Can highly simplified game theory models provide reliable policy insights?" *Ecol. Econ.*, 90, 68–76.
Madani, K., and Dinar, A. (2012). "Cooperative institutions for sustainable common pool resource management: Application to groundwater." *Water Resour. Res.*, 48(9).
Madani, K., and Hipel, K. W. (2011). "Non-cooperative stability definitions for strategic analysis of generic water resources conflicts." *Water Res. Manage.*, 25(8), 1949–1977.
Madani, K., and Lund, J. R. (2011). "California's Sacramento-San Joaquin delta conflict: From cooperation to chicken." *Water Res. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000164, 90–99.
Madani, K., and Lund, J. R. (2012). "A Monte-Carlo game theoretic approach for multi-criteria decision making under uncertainty." *Adv. Water Resour.*, 35(5), 607–616.
Mattila, K., and Abraham, D. (1998). "Resource leveling of linear schedules using integer linear programming." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)0733-9364(1998)124:3(232), 232–244.
Medda, F. (2007). "A game theory approach for the allocation of risks in transport public private partnerships." *Int. J. Proj. Manage.*, 25(3), 213–218.
Myerson, R. B. (1991). *Game theory: Analysis of conflict*, Harvard University Press, Cambridge, MA.
Nash, J. (1953). "Two-person cooperative games." *Econometrica: J. Econometric Soc.*, 21(1), 128–140.
Nobbs, H. (1993). *Future role of construction specialists*, The Business Round Table, London.
Parrachino, I., Zara, S., and Patrone, F. (2006). "Cooperative game theory and its application to natural, environmental, and water resource issues: 1. Basic theory." *World Bank Policy Research Working Paper 4072*, World Bank.
Pena-Mora, F., and Wang, C. Y. (1998). "Computer-supported collaborative negotiation methodology." *J. Comput. Civ. Eng.*, 10.1061/(ASCE)0887-3801(1998)12:2(64), 64–81.
Perng, Y.-H., Chen, S.-J., and Lu, H.-J. (2005). "Potential benefits for collaborating formwork subcontractors based on co-operative game theory." *Build. Environ.*, 40(2), 239–244.
Rahman, M. M., and Kumaraswamy, M. M. (2004). "Contracting relationship trends and transitions." *J. Manage. Eng.*, 10.1061/(ASCE)0742-597X(2004)20:4(147), 147–161.
Sacks, R., and Harel, M. (2006). "An economic game theory model of subcontractor resource allocation behavior." *Constr. Manage. Econ*, 24(8), 869–881.
Schmeidler, D. (1969). "The nucleolus of a characteristic function game." *SIAM J. Appl. Math.*, 17(6), 1163–1170.
Senouci, A. B., and Eldin, N. N. (2004). "Use of genetic algorithms in resource scheduling of construction projects." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2004)130:6(869), 869–877.
Shalikarian, L., Madani, K., and Naeeni, S. T. O. (2011). "Finding the socially optimal solution for California's sacramento-san joaquin delta problem." *Proc., 2011 World Environmental and Water Resources Congress*, R. E. Beighley, and M. W. Kilgore, eds., ASCE, Palm Springs, CA, 3190–3197.
Shapley, L. S. (1953). "A value for n-Person games." *Contributions to the theory of games*, H. W. Kuhn, and A. W. Tucker, eds., Princeton University Press, Princeton, NJ, 307–317.
Sheikhmohammady, M., and Madani, K. (2008). "Sharing a multi-national resource through bankruptcy procedures." *Proc., 2008 World Environmental and Water Resources Congress*, R. W. Babcock, and R. Walton, eds., ASCE, Reston, VA.
Shen, L. Y., Bao, H. J., Wu, Y. Z., and Lu, W. S. (2007). "Using bargaining-game theory for negotiating concession period for BOT-type contract." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2007)133:5(385), 385–392.
Son, J., and Mattila, K. (2004). "Binary resource leveling model: Activity splitting allowed." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2004)130:6(887), 887–894.
Straffin, P. D., and Heaney, J. P. (1981). "Game theory and the Tennessee Valley authority." *Int. J. Game Theor.*, 10(1), 35–43.
Tijs, S. H. (1981). "Bounds for the core of a game and the τ-value." *Game theory and mathematical economics*, O. Moeschlin, and D. Pallaschke. eds., North-Holland, Amsterdam, 123–132.

Unsal, H. I., and Taylor, J. E. (2011a). "Modeling interfirm dependency: Game theoretic simulation to examine the holdup problem in project networks." *J. Construct. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000286, 284–293.

Unsal, H. I., and Taylor, J. E. (2011b). "An empirical investigation of opportunistic behaviour in project networks and its impact on market efficiency." *Eng. Proj. Organ. J.*, 1(2), 95–106.

von Neumann, J., and Morgenstern, O. (1944). *Theory of games and economic behavior*, Princeton University Press, Princeton, NJ.

Yousefi, S., Hipel, K. W., and Hegazy, T. (2010). "Attitude-based negotiation methodology for the management of construction disputes." *J. Manage. Eng.*, 10.1061/(ASCE)ME.1943-5479.0000013, 114–122.

J. Constr. Eng. Manage.