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Application of Game Theory in Studying Subcontractors' Cooperation in Construction Projects - Joint Resource Management

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ABSTRACT

Resource management is one of the most significant roles of every project manager in today's highly competitive construction industry. One solution to reduce costs of resources is to manage them jointly. Joint resource management is based on cooperation between subcontractors who are seeking a win-win resolution. It is an attempt to schedule the project tasks, enabling subcontractors to optimally utilize resources and minimize their idle times.

Cooperative game theory, describing a series of moves leading to an integrative conclusion, is a powerful tool for studying cooperation between subcontractors. Construction projects are not too different from real games. By using game theoretic language, a construction project is defined as a "game" in which subcontractors are considered as game "players" and are able to manage their own resources to maximize their "profit". Talking of cooperative game theory, these players develop strategies to maximize the overall profit of project based on the fact that these strategies would bring more profit to each player too. Cooperative game theory is used to analyze interactions between subcontractors to allocate the game profit among the players. In order to achieve this, subcontractors should have a clear understanding of cooperation and understand mutual objectives to provide a sound basis for a synergetic climate in joint resource management.

One key point in understanding cooperation is trust. Trust is known as one of the fundamental principles of cooperation. It can lead to a cooperative behavior between subcontractors and act as the glue holding subcontractors together. Trust is defined as a psychological state comprising the intention to accept vulnerability based upon positive expectations of the intentions or

behavior of another. “Trust” game (also known as “stag hunt”) as well as “Prisoner’s Dilemma”, have been used to represent trust and cooperation problem in the game theoretic framework. Compared to what has been done in other areas, less attention has been given to trust in construction projects.

With all these in mind, the main purpose of this study is to study the cooperation between subcontractors employing cooperative game theory. After reviewing the theoretical foundations of game theory and in light of previous studies done, a model is constructed with the aim of optimizing common resources. The gains of joint resource management are analyzed and allocated by applying the cooperative game solution. A case study is also used to analyze the problem and illustrate the model’s practical contribution to construction projects. Last but not least, the cooperation game is studied utilizing the stag-hunt game, and a set of strategies to achieve the best outcomes in cooperation is offered.

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Joint Resource Management

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To

All those who have a blue bird in their hearts

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Chapter 1 Introduction

Introduction

Resource management is one of the most significant roles of every project manager in today's highly competitive construction industry. To meet this goal, costs of equipment and labor should be controlled and optimized. Managing equipment in construction projects, especially in heavy projects, is a big issue for contractors, since an inefficient resource allocation causes in greater idle times for equipment and a larger amount of costs. Equipment refers to all the equipment, tools, and apparatus necessary for the proper construction and acceptable completion of a project. Some equipment has shared use by all subcontractors on the construction site. These pieces of equipment are kept on the site over a longer period, throughout almost the entire construction phase. Some examples of general use equipment include: cranes, air compressors, light towers, forklifts and pumps.

Subcontracting is defined as outsourcing the tasks of a project and award them to companies named subcontractors, which offer labor, material and equipment needed for the execution of project (Tam, 2011).The main contractors transfers the risks of project to subcontractors. Moreover, subcontracting allows the main contractor to use the subcontractors' expertise and experience and increase the efficiency of work (Choudhry, 2012). In other words, subcontractors have a great advantage in their expertise areas of undertaking subprojects with main contractors (Yik, 2008).These benefits encourage the contractors to sublet work to subcontractors, making subcontracting a worldwide practice. The contribution of subcontractors to construction process can account for as much as 90% of the total value of the project (Kumaraswamy M. M., 2000). Since the majority of construction work is done by subcontractors, cooperation between them has significant effect on projects' success. While subcontracting can cause obstacles due to lack of cooperation, good management can lead it towards cooperation and increase the potential opportunities.

One solution to cut costs of resources is to manage them jointly. Joint resource management is based on cooperation between subcontractors who are seeking win-win resolution. It is an attempt to schedule the project tasks, enabling subcontractors to optimally utilize resources and reduce the idle time of them. Due to several reasons, subcontractors are not able to employ/release resources on a daily manner. Thus they define a minimum period for different resources they need and hire/release the resources at the beginning of each period. This makes them to employ the maximum number of resources needed in each time intervals and some of resources remain idle during the project. For this reason, joint resource management is a helpful solution to optimize the idle resources and consequently optimize the resources costs.

The main question is how joint resource management is applicable in scheduling the project activities. It might be possible to do the optimization manually for a really small project however it is definitely impossible to optimize resources in a real project having reasonable numbers of activities. Computer programming automates this procedure by using different algorithms. In this study, Genetic Algorithm is used to solve the optimization problem and coding is done in Visual Basic language. Thesis structure, besides the nominal definitions, is introduced in this chapter.

Research Problem

Although establishing cooperation between subcontractors strengthens their competitiveness in winning construction projects, there has been little research on this topic. This research aims to study the joint resource management, a cooperation between subcontractors to increase the efficiency of common resources, using game theory. Game theory offers a set of profit allocation as a solution of the cooperation game. In this study, different solutions are compared to each other and based on the designed criteria, these solutions are ranked.

Nominal Definitions

a. Subcontractor

Subcontractor is an individual or business firm contracting to perform part or all of another's contract. Subcontractors often specialize in one specific area of construction and try to network with contractors who negotiate for larger jobs that include this area of specialty. The key point about subcontractors is that they form agreements with the contractor, not with the owner. Usually, subcontractors perform 80-90 percent of construction work.

b. Joint Resource Management

On the contrary of having single decision maker in resource management process, there is another solution named joint resource management. Joint resource management is based on cooperation between different subcontractors involved in a construction project, managing the common resources together as a pool of resources to achieve the most efficient resource employment. The main objective of this collaboration is to optimize costs of resources by decreasing their idle time and lower the total cost for resources.

c. Cooperation

Cooperation is defined as short or long-term commitment between two individuals or firms who work together with the purpose of achieving specific business objectives like a lower project cost. One solution in cooperation is to maximize the effectiveness of each partner's resources and minimize the cost of resources. By cooperation, subcontractors are able to save 5 to 30 percent of project costs.

d. Trust

A psychological state comprising the intention to accept vulnerability based upon positive expectations of the intentions or behavior of another. Trust is known as one of the fundamental principles of cooperation. It can lead to a cooperative behavior between subcontractors and acts as the glue holding subcontractors together. Reduced project time and cost and improved productivity of project, are achievable through trust-based relationships.

e. Prisoner's Dilemma

Originally formed by M. Flood and M. Dresher and formalized by A. W. Tucker 40 years later, prisoner's dilemma is an example of games in which perfect rationality will not result in the best solution for a game. This game can be used as a model to study real-world dilemmas and will be explained in the third chapter.

f. Stag Hunt Game

Also named as "trust" or "cooperation" game, stag hunt game is an example to describe social cooperation and trust. Although most researchers focus on prisoner's dilemma as an example describing cooperation, some others believe that stag hunt game is a better tool to model social cooperation. This game will be explained in details in the third chapter and will also be used to study the cooperation between subcontractors.

Thesis Structure

This thesis is written in six chapters. The first chapter is the introductory chapter which provides the background to the topic, stating the research problem and the aim of the research. Some basic definitions are also included in the first chapter to clarify the main concepts used. The second chapter is allocated to game theory and literature review. The main purpose is to evaluate the previous works done and highlight what this study tries to fill. The previous works done are categorized into three groups and several papers are studied in each group. The third chapter outlines the model and goes into the details of game solutions. In the fourth chapter, an example is used to illustrate the cooperation game. The fifth chapter is where the case studies are analyzed using the model introduced in the former chapter. More comments on the results and their interpretation are presented in the fifth chapter and also an explanation for any unexpected results is provided. The last chapter is the concluding chapter where the research problem and solution are emphasized. Also, some suggestions for future research are noted as well as the research limitations. At the end, the bibliography contains the reference material for this study and the appendix includes the code written to run the model and data exported from it.

Chapter 2 Theory and Literature Review

Introduction

While there are several definitions for game theory, the most common definition introduces game theory as “study of mathematical models of conflicts and cooperation between rational players” (Rapoport, 1960). Although the first applications of this theory to political science and philosophy occurred during the 1950s, it is applicable in a wide range of areas, from biology to computer science and psychology to economics and management. For instance, game theory is used in natural resource management and resource allocation mechanisms like international fisheries management as a new powerful management tool. Changes in the nature of problems researchers are facing, and the recent shift to issues in economics and management field might be one of the significant reasons for increased implementation of game theory in last ten years.

There are two approaches to utilize game theory in addressing different problems; first, it might be used as a normative exercise to investigate how decisions *should* be made based on the perfect rationality of players. Second is to investigate how decisions *are* made. It is important to distinguish which approach is taken in this study. Sadly, the literature has been silent on studying game theoretic behaviors in cooperation problem, thus there is no data available to study how players behave in the construction industry. Consequently, this study aims to investigate how players *should* make decisions, not how they make decisions in real-life projects.

Game theory has known as a positive exercise, providing the framework to study the subcontractors’ strategic interactions. The cooperation between subcontractors in a construction project is studied through the framework of game theory, focusing on how player should form coalitions, which coalitions are made, how the profits of working in coalitions are calculated, the game solutions to allocate this profit to coalition members, and tools to measure the satisfaction of players in each coalition. The following sections give insight into the theoretical foundations of game theory and the earlier studies done on cooperation and application of game theory in construction problems.

Theoretical Foundations

Game Theory

Game theory can be defined as the logical analysis of the conflict between two or more individuals or agents in any situation. It provides a mathematical technique to analyze situations in which an individual's decision influences the others' welfare. "Conflict analysis" or "interactive decision theory" are more accurate names for this subject, but the name "game theory" seems to be here to stay (Myerson, 1991). Due to its position in providing the mathematical foundation for different branches of social sciences, game theory is appealing for scientists. In the language of game theory, a "game" refers to any social situation involving two or more individuals. Each game consists of three important components:

1. There are at least two individuals (or agents) called players.
2. Each player has a set of actions which he/she may follow. These courses of actions are named strategies.
3. The outcome of each strategy is determined and associated with each outcome there is a value named payoff for each player.

Game theory is the study of players' rational decisions in order to get a larger payoff. In game theory, it is assumed that each player is intelligent and rational, that is, he or she always takes actions in a way to maximize her own objectives. To measure these objectives, an expected value named "payoff" is defined and players' objectives are calculated in units of this payoff. The modern idea of rational decision-maker is justified by von Neumann and Mongenstern (1947), however, it goes back to Bernoulli (1738) for the first time. This concept is the base for "expected utility-maximization" theorem, explaining how a rational individual behaves, choosing the possible outcome. This maximizing behavior is also derived from evolutionary selection models, mostly used in biology. As Maynard Smith (1982) argues about evolutionary selection, individuals (and other complex organisms) may tend to maximize their general survival/reproductive fitness measure.

It should be emphasized that each player has some control over the outcome since he or she can take different strategies. However because of interactions between different strategies taken, none of the players have a complete control over the ultimate outcome. These interactions of different strategies make each game a "mathematical model" of conflict between players. Correspondingly, game theory offers ideas to resolve conflicts in a rational framework.

Conflict modeling in a game-theoretic framework faces several obstacles. First, any real conflict is complex, making it difficult to identify all of the players, possible strategies, and outcomes of strategies. Second, in some situations of real-world, not all players are rational. In explaining rational behavior there are arguments between mathematicians. Since rationality is a significant issue, this concept will be discussed in a separate subchapter. The third obstacle is that for players not having completely opposing interests, game theory does not come up with a single solution. In most situations, it offers a variety of suggestions for players (Straffin, 1993).

Utility

Utility is an economic concept and an important underpinning of the rationality and game theory. Economists use utility to measure the preference of any service or good over another service or good. In game theory, this concept is used to measure the satisfaction of players in a game. It also reflects the motivations of players by assigning a number for every outcome of the game.

Since utility values are not necessarily measured in monetary terms, utility payoff is not same as the monetary payoff. For many decision-makers, the utility is a nonlinear function of monetary worth. A poor individual may get more incremental utility from an extra dollar than the rich individual gets from the same amount. Many variables other than an individual's monetary worth affects his/her utility payoff, like the other players' utility payoff and the sympathy/antipathy she feels.

In game theory, utility is divided into two main groups, transferable utility, and non-transferable utility. In games with transferable utility, utility acts like "money" and can be transferred among game players. In the transferable utility games, numerous game-theoretic solutions exist and are used to allocate the utility among players. These solutions are introduced in the third chapter. Transferable utility is a basic assumption in studying cooperative games. Cooperative games are a category of games and are presented in the following section.

Cooperative Game Theory

Although almost every game has an element of cooperation and every cooperation has an element of conflict (Mesterton-Gibbons, 2000), games are traditionally classified into cooperative and noncooperative. These two categories define how the interaction between players is formalized. While noncooperative game theory describes the actions that are available for players to be taken separately, cooperative game theory focuses on outcomes when players come together. Since this study is on cooperation, cooperative game theory and its characteristics should be defined first. Cooperative game theory studies the strategies and payoffs of coalitions. Every coalitional game consists of a finite set of players and a characteristic function. Formally, let $N = \{1, 2, ..., n\}$ be the finite set of players and $i = \{1, 2, ..., n\}$ the index of different members of N. The characteristic function, denoted v that specifies the value created by different subsets of N is $v : 2^N \rightarrow R$ that satisfies $v(\phi) = 0$. Characteristic function describes the collective payoff each coalition of players can gain through the game. This payoff helps the players to choose which coalitions to form, in order to gain the best result. A coalition, S, is defined as any subset of N, $S \subset N$. The set N is called grand coalition and ϕ the empty coalition. For N players, the set of coalitions has 2n elements. V(S) is a real number for each coalition, $S \subset N$, which can be considered as the value of coalition when members of S work together as a unit.

The coalitional form of an n-person game is given by the pair (N, v) and satisfies following conditions:

1. $v(\phi) = 0$;

2. For every disjoint coalitions S and T $(S \cap T = \phi)$, $v(S \cup T) \geq v(S) + v(T)$;

Condition 1 says that empty coalition has zero value and condition 2 says that two disjoint coalitions will have more value when acting together than when they work apart.

Trust

In order to answer the question "What is the game theory?" one might state "Game theory is a tool to study the conflict between rationale players". Although, this definition might be misunderstood, categorizing the game theory as a concept in psychology, game theory is a branch of mathematics where perfect rationality exists. Von Neumann, one of the pioneers of game theory, explains a game as a state of conflict between two or more players who are able to make decisions and these decisions together make the ultimate result of the game. It should be taken into account that the possible results are known but not final unless the game is done. He adds game theory is studying the conflict between rational but pessimistic players. The source for Von Neumann's opinion about games is the Poker game where a player needs to guess the other players' moves and this is the main difference between game theory and probability theory. In a research done in 1944 and named "game theory and economic behavior", Von Neumann and Morgenstern introduced game theory as a mathematical foundation for studying economic behavior. Two bidders in a bidding game can be considered as two players of a game, in which they must try to understand the other player's behavior in order to win the game.

The main assumption in game theory is that players are perfectly rational and interested in winning the game. It is possible to study the interaction between two or more rational players through game theory. In every game, each player has several strategies and is aware of the outcomes and also trying the gain as much as possible. The outcome can be stated as utility or amount of money as the utility of the game.

While John Nash, an American mathematician and one of the pioneers of game theory, was studying non-cooperative game theory; Von Neumann and Morgenstern were interested in N-player games in which players cooperated with each other. Cooperative games are a group of games where players are able to form coalitions in order to gain higher utilities. This approach was taken in order to find a solution for n-player economic conflicts. In this type of games where the interests of players are not completely in contradiction with each other, finding a solution is more difficult. The most important question to answer is how to share the utility between players of a coalition when they work together.

Rationality

While game theory is based on the assumption of "rationality", it is unable to predict irrational players' behavior. This assumption is the necessary condition to find out the equilibrium while it also creates great tension. Players choose their strategies because of what happens if they did not choose it. In other words, the problem is to suggest how players should play if their peer does not play in accordance with her/his equilibrium strategy. These counterfactual hypothesis are studied by Lewis (Lewis, 1976) in terms of "possible worlds" in which that player's strategy is indeed an equilibrium. These other worlds must be considered in studying equilibriums and our task is to understand which world is closest to each player. An equilibrium is a collection of optimal strategies in the closest possible world. The original game is replaced with new game matching the original one, while with small probability it is different. The reason for this different behavior of players might be their imperfect rationality or their mistakes, which result in changed beliefs and preferences of players.

Assumption about rationality is changeable from perfect rational players to players who sometimes make decisions by rules of thumb or other simple systems like analogies with similar situations or more complicated ones like social norms or convocations.

Prisoner's Dilemma

Prisoner's dilemma is an example to illustrate why two rational players do not cooperate in some games although by cooperation both of them gain the highest utility. Tucker (1992) formalized what Dresher and Flood (1950) first had presented and named it "prisoner's dilemma". Imagine two criminals are arrested and kept in solitary not communicating with each other. Each prisoner is offered two options; first to stay silent and second to betray the other prisoner by confessing that he has done the crime. The prosecutors will operate as follows:

1. If both of prisoners confess against the other, each will be sent to prison each for two years.
2. If one confesses but the other stays silent, the one who confesses is set free and the other person serves 3 years in prison.
3. If both of them stay silent, they are only prisoned for one year.

The payoff for prisoner's dilemma is summarized in table 2.1.

Table 2-1Payoff Matrix for Prisoner's Dilemma

B A	Silent	Betray
Silent	(-1, -1)	(-3, 0)
Betray	(0, -3)	(-2, -2)

Assuming that betraying the other person has no effect on the betrayer's future reputation, the perfect rational strategy for each player is to betray, because by betraying he will get a greater payoff. The conclusion is that the dominant strategy for this game is having two betrayers. The first and most important question is that while the prisoners would get a better outcome if both stay silent, why they do not cooperate and get it? What is the reason for this bias seen in social games which leads rational self-interested people to not work together? While the only Nash equilibrium for this game is to betray (-2, -2), it is not Pareto efficient and cooperation results in a better outcome (-1, -1) for players. In other words, the overall years in prison in case of cooperation, 2, is less than 4 years of prison in Pareto efficient solution for the game. An important assumption leading us to choose (-1, -1) as the solution for this game is that players choose their strategies independently and they have no opportunities to communicate before choosing their strategies in the game; while the approach that does not use this assumption is valuable too and leads us to greater outcomes. In effect, the concept of Nash equilibrium imposes a constraint on social behavior theorists making it difficult for them to prescribe nonequilibrium behaviors.

A generalized form is shown in table 2.2. C stands for the cooperation (both stay silent) while N is the payoff when none of the players cooperate (both betray). In case one does not cooperate (betrays) and the other one cooperates (stays silent) the payoff for betrayer is shown by N' and for the cooperator by C'. The conditions for a prisoner's dilemma: $N' > C > N > C'$.

Table 2-2 Generalized Payoff Matrix for Prisoner's Dilemma

B A	Cooperate	Not Cooperate
Cooperate	(C, C)	(C', N')
Not Cooperate	(N', C')	(N, N)

Stag Hunt Game

Although prisoner's dilemma is an example of cooperation, some game theorists believe that stag hunt game is the best example to study the cooperation between players. Some variants for this game include "coordination game", "trust game" and "assurance game". Rousseau explains this game including two hunters. These hunters either can work together and hunt a large stag or work individually and kill the hare which is easy to catch. While killing the stag needs patience, the hare is present and one can sacrifice the other player and hunt the hare when the other hunter wastes the time and starves. The payoff matrix for this game is presented in table 2.3.

Table 2-3 Payoff Matrix for Stag Hunt Game

B A	Stag	Hare
Stag	(2 2)	(0, 1)
Hare	(1, 0)	(1, 1)

This game has two pure Nash equilibria. When both players cooperate, it is a risk dominant strategy and when both of them do not cooperate, (1,1), it is a payoff dominant one. A payoff dominant Nash equilibrium is Pareto superior to all other Nash equilibria. In such cases, having multiple equilibria, any one of these equilibria could become a self-fulfilling prophecy, therefore the constraint imposed by Nash equilibrium does cause less difficulties for social behavior theorists. The most important question arising here is that what might make players to implement a specific equilibrium. Schelling (Schelling, 1960) introduces "focal-point effect" that is an equilibrium that has some property that conspicuously distinguishes it from all other equilibria. According to this effect, if there is one focal equilibrium in a game, then we should expect to observe that equilibrium. The focal-point effect enables a mathematician to predict people's behavior in real conflict situations considering social psychology and anthropology. Equity and efficiency are two welfare properties to determine the focal equilibrium in a game. In games having more than one Nash equilibrium, psychology and cultural background of the society and players is an important reference to determine which equilibrium would be focused on. Traditional modes of behavior, as well as cultural norms, can lead players to play the game in a way resulting in a specific equilibrium.

Preplay communication is also another possible way to focus on one equilibrium in this kind of games. There might be an individual suggesting game players a focal equilibrium to implement, whom we call "focal arbitrator". To make it clear the outcome of this communication is an agreement on how the game should be played while it is not binding for any of the players. While the arbitrator's suggestion is normally considered to be accepted by players, the arbitrator is not willing to suggest a non-equilibrium solution.

The payoff matrix at table 2.4 illustrates the generic form of stag hunt game, where:

$C > N' \geq N > C'$.

Table 2-4 Generalized Payoff Matrix for Stag Hunt Game

B A	Cooperate	Not Cooperate
Cooperate	(C, C)	(C', N')
Not Cooperate	(N', C')	(N, N)

In real-world games, prisoner's dilemma is changeable to stag hunt if not cooperating results in a negative effect on the result. For example, suppose that a non-cooperator is punished and this punishment is equivalent to 2 years in prison. Therefore the payoff matrix for this game is illustrated as shown in table 2.5. Since this game satisfies the inequity $-1 > -2 \geq -2 > -3$, this punishment has turned it into stag hunt game.

Table 2-5 Prisoner's Dilemma Considering Punishment for Non-Cooperator Party

B A	Silent	Betray
Silent	(-1, -1)	(-3, -2)
Betray	(-2, -3)	(-2, -2)

Evolution

While the ultimate purpose of game theory is to find an equilibrium and present it as the solution of the game, many games have more than one equilibrium and solving this problem by illustrating a single equilibrium is considered as the success of the game theory in some cases. This problem is described as a separate question, named "equilibrium selection" in evolutionary game theory. For instance, consider the stag-hunt game. This game has two pure-strategy Nash equilibria. To answer the question "which equilibrium should be chosen" classical game theory does not offer an answer. Evolutionary game theory is found to be helpful in answering this question.

Maynard Smith and Axelrod were among first researchers who tried to combine the evolutionary criterion in biology with game theory concept and find a simulation of people's behavior in a conflict (Maynard-Smith, 1973). Evolutionary game theory has taken its name from studies in biology (Axelrod & Hamilton, 1981). In its biological application, genes are the players of the games, which endow their host organism. The payoff for each parent gene is the number of their children carrying the same gene (Samuelson, 1997). Axelrod tried to use this phenomenon to model players' behavior in repeated tournaments of prisoner's dilemma. By constructing a dynamic model and simulating the players' strategies, he concluded that the winner of the prisoner's dilemma is a strategy called "Tit for Tat". Tit for Tat was the evolutionary answer presented by Axelrod, in which the player begins the game by cooperating and after her first move, she makes each move mimicking the other player's last move. This strategy is discussed thoroughly in the fourth chapter.

Literature Review

This study is based on extensive research in game theory and related topics. To make it organized, the main references are categorized into two main groups and summarized in following sub-chapters as cooperation, and game theory and its contribution to civil engineering problems. Majority of the reference papers are published in well-known international journals like Construction Engineering and Management, Construction Management and Economics, Economic Behavior and Organization, Games and Economic Behavior, Water Resource Planning and Management, Conflict Resolution and Experimental Economics. In addition, several books published by Harvard University Press, The MIT Press, Princeton University Press and American Mathematical Society and a couple of thesis works are the strong support for this study. To gain a clear understanding of what has been done in past in the field of this study, some of the significant previous studies are summarized in following sections.

Cooperation

In this section, different types of cooperation between people involved in a project are studied and different models are fitted to them. In addition, the key factors for building this cooperative relationship and their success factors are investigated. Table 2.6 presents the main studies summarized in this section.

Partnering is now a well-known contracting approach in the USA and a great amount of research is done demonstrating the benefits of partnering. Even so, the empirical studies on actual partnering practices are limited. There are often a considerable amount of guidelines that merely offer tested principles of partnering. In real industry cases, complicated relationships between project parties exist and this causes failure to address the partnering issues with means of theoretical studies which stand far away from practical contributions. Having these in mind, Bresnen and Marshall studied “Building Partnership” including nine case studies from medium to large scale projects, selected from across the industry (Bresnen, Building partnerships: case studies of client/contractor collaboration in the UK construction industry, 2000). Throughout these case studies, which all were in the UK, they examined the collaboration from different viewpoints. These viewpoints from clients, contractors, designers, and subcontractors provided the practical information to analyze the limitations and paradoxes of cooperation.

They begin with the definition of partnering presented by CII[1] (1991) in which partnering is defined as commitments by organizations to cooperate to achieve common business objectives. There is much case study evidence that partnering has shown performance benefits, however, there are some cases in which partnering has failed to meet performance expectations. Their research had objectives including types of collaborative approaches, the factors promoting or inhibiting collaboration between partners and investigating the effect of this collaboration on project performance in terms of cost, quality, time, buildability, and client satisfaction.

The research is based on 9 case studies and 158 interviews (18 per case, on average) with different departments and team members and subcontractors' representatives. These case studies included oil and gas projects, building projects and process plants. In all projects, collaboration is known as an important factor affecting team culture development and the support of senior management is vital for building collaboration between project partners. One of the common practices is the existence of joint target cost setting. Across these 9 cases, respondents believed that collaboration between subcontractors is important, however, this rarely happened in their projects.

[1] Construction Industry Institute

As a conclusion, Bresnen and Marshall state that the most beneficial factors in cooperation are indirect factors such as the willingness of contractors to absorb the extra cost. Their research suggests that formal mechanisms like financial incentives are not efficient as tools motivating cooperation between project partners. People and relationships are at the heart of collaboration and continued relationships secure the benefits of cooperation.

Based on the assumption that partnering still has a need for more in-depth research, Bresnen and Marshall have published issues, problems and dilemmas of partnership in Construction Management and Economics journal as a separate paper, exploring the link between partnering and culture at organizational and inter-organizational levels (Brresnen.M. and Marshall, 2000) . They put more emphasis on social science concepts and organizational theory. In this study, authors agree with definition suggested by CII to use "partnering" to refer generically to all collaborative approaches. If these collaborative approaches are adopted, the performance of project will be improved. Although partnering is the term used to address the cooperation and collaborative behavior in a project, Holti and Standing state that partnering and collaboration are better understood as a result of several interrelated individual and organization initiatives (Holti, 1996).

As could be seen, construction reports show an evident reduction in costs by 30% when partnering is applied. Authors state that reduced costs and improved productivity are two main incentives for engaging in cooperation. They agree that cultural alignment is a prerequisite for partnering. The culture that is "a set of shared meanings and mutual values", is known as a complex and multi-faceted phenomenon that develops through social interactions. Having this in mind, implementing effective partnership, requires set of techniques and more important the top management commitment. Ultimately, formal partnering arrangements are completely different from real operational level behaviors and to achieve a successful partnering, decentralized and flexible structures must be defined in the project.

Table 2-6 Summarized Papers' Detailed List

C ategory	Title	Authors	ear
C ooper ation	Building partnerships: case studies of client and contractor collaboration in the UK construction industry	Bresnen, M. and Marshall, N.	000
	Partnering in construction: a critical review of issues, problems and dilemmas	Bresnen, M. and Marshall, N.	000
	Development of a Practical Model of Partnering for Construction Projects	Cheng, E. W. L. and Li, H.	003
	Exploring Critical Success Factors for Partnering in Construction Projects	Chan, A. P. C. et al.	004
	Reconstructing relationally Integrated Teams	Kumaraswamy, M. M. et al.	005
	Conceptual model of partnering and alliancing	Anvuur, A. M., and Kumaraswamy, M. M.	007
	Contradictions and collaboration: partnering in-between systems of production, values and interests	Gottlieb, S. C. and Haugbelle, K.	013
	Learning for Win-Win Collaboration	Tsai, J. and Chi, C.	015

Understanding the need for a systematic approach to model partnering, Cheng and Li presented a practical model of partnering, called procedural mapping model (PMM), adopting a systematic approach (Cheng, 2003). It is intended to use the concept of modeling and integrate different aspects of the system to form an integrated model. This model has three key elements including interactive process description, success factors' monitoring and goals' assessment matrices. Same as Bresnen and Marshall, Cheng and Li also believe that collaboration is an approved practice to improve performance excellence in construction projects.

This study is based on Cheng and Li's empirical studies and originated from Kartam and Ibbs (Kartam, 1997). PMM's features a main degree of flexibility, due to its setting up of procedures for espousing strategic partnering. The PMM has three sequential stages that flow from left to right. The first stage is partnering formation that refers to any implicit or explicit agreement between all parties in order to achieve the mutually agreed goals. Partnering application is the second stage and refers to applying informal relationship to gain the goals; while the last stage includes partnering completion or rerunning the partnering relationship for the next new project. Figure 2.1 summarizes these three stages in Cheng and Li's conceptual model of PMM.

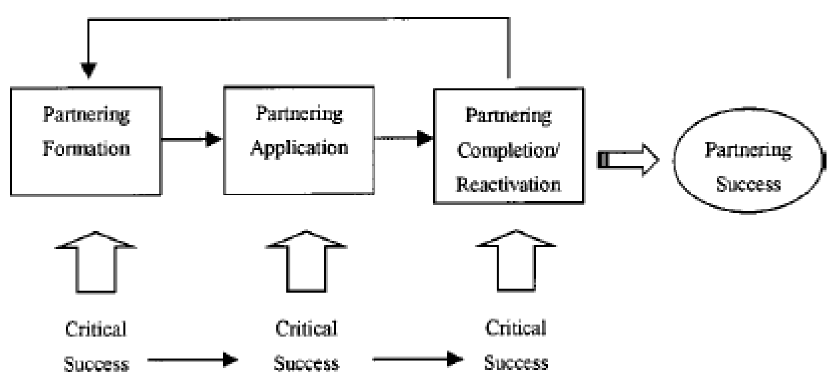

Figure 2-1 Conceptual model of partnering (Cheng and Li, 2003)

In addition to the three stages explained, there must be criteria to evaluate the performance of partnering. Due to unique nature of each construction project, it is difficult to introduce an inclusive case of successful project performance. That means the evaluation factors for each project differs from each other considering the specific conditions and objectives of each project. General success factors include improved relationships, stakeholders' satisfaction and optimize time, cost and quality of work done. Driven from PMM, it is concluded that long-term commitment, continuous improvement, open communication, and effective coordination are four functional success factors in partnership. Partners who are well prepared to form long-term relationships and completely aware of the improvements made by the partnership are more likely to form a successful partnering.

Chan et al. also tried to explore the success factors for partnering through a postal questionnaire in Hong Kong and find out the necessary requirements for a successful partnering (Chan, 2004). This research is based on their earlier research and introduces commitment, trust, respect, communication, and equality as fundamental principles of partnering. In addition to the definition given by CII, Chan et al. put forward the definition presented by Benneth and Jayes as “a set of strategic actions that deliver vast improvements in construction performance (Bennett, 1998). It is driven by a clear understanding of mutual objectives and co-operative decision-making by a number of firms who are all focused on user feedback to continuously improve their joint performance.”

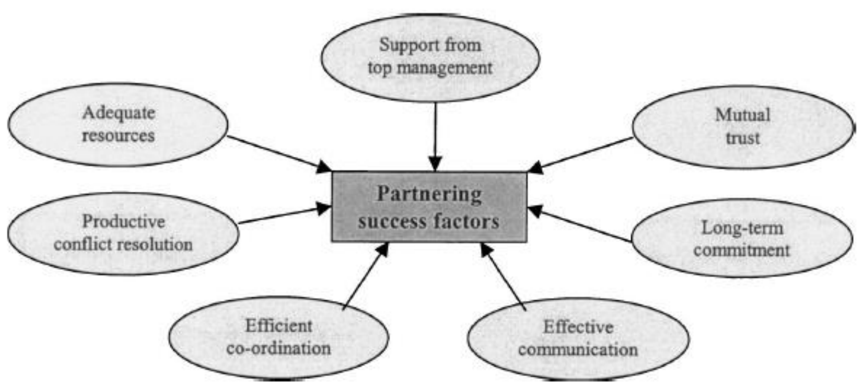

Figure 2-2 Summary of significant factors affecting partnering success (Chan et al., 2004)

Due to results of their study, partnering performance has improved experiencing partnership in Hong Kong. To measure the projects’ performance, subcontractors might be interested in time performance which due to Chan et al. 73.3% of projects were on-schedule or ahead of schedule through partnering. 82.9% of partnering projects were on-budget or under budget and 86.7% of them had less or an equal number of claims and disputes that an average project. These results strongly confirm the benefit of partnership in improving project performance in Hong Kong. Table 2.7 illustrates these results in an arranged way.

Several studies have done on essential ingredients for a successful partnering. The first factor is having adequate resources. Generally, it is not common for different subcontractors to share their resources since some resources are scarce or competitive. CII (1991) and other studies state that it is important to share resources and get the maximum use of shared resources. Subcontractors working together can strengthen their competitiveness and lower their costs by sharing their mutual resources. Commitment and support from top management is another factor. For partnering to work, subcontractors must gain mutual trust, believing that others are reliable in their exchange relationship. Next necessary factor is long-term commitment through which partners balance their short-term objectives with mutual long-term objectives. Timely communication is also significant and helps to facilitate the ideas exchange and overcoming the difficulties. Efficient coordination and productive conflict resolution are two last factors affecting the success of the partnership. Coordinated task planning and joint problem solving are productive solutions to secure a mutually agreed decision making. Success factors can be found in figure 2.2.

Performance indicator	Percentage of partnering success
Time performance	73.3% of the partnering projects were on-schedule or ahead of schedule
Cost performance	82.9% of the partnering projects were on-budget or under budget
Disputes occurrence	86.7% of the partnering projects had less or an equal number of disputes than an average project
Claims occurrence	86.8% of the partnering projects had less or an equal number of claims than an average project
Satisfaction with quality	90.9% of the partnering participants were moderately to highly satisfied with the quality
Satisfaction with working relationship	78.2% of the partnering participants strongly agreed that they were happy with the working relationship

Figure 2-3 Results of Partnering Performance of Construction Projects in Hong Kong (Chan et al., 2004)

Chan et al.'s study begins with this literature review to develop a framework for their questionnaire and interviews. Considering mentioned factors, they prepare a list of items for empirical testing and invite 22 key target project participants from Hong Kong for an interview. 41 Critical factors are determined and participants are requested to rate those partnering success factors. According to questionnaires, establishing and communicating the conflict resolution strategy is the first essential factor followed by the commitment to win-win attitude. The third factor is monitoring the partnering process including well-defined roles and responsibilities. This monitoring could be ensured by a partnering champion or team leader. To wrap this study up, they conclude that cooperative relationships are more beneficial than competitive behaviors and rewards of partnering are significant.

A year later at 2005, Kumaraswamy et al. analyze the views of Singapore-based contractors investigating cooperative teams in construction projects (Kumaraswamy M. M., 2005). Teams in comparison to individuals are more manageable and more productive. To examine the possible solutions to build a team, a questionnaire survey is conducted compromising various sections and completed by 60 respondents. The three most important factors were reputation in the industry, disclosing project information to potential partners at early stages of a project, and previous performance records on "soft factors" such as joint decision making, joint problem solving, and compromises on unclear issues. Better reputation is closely associated with greater trust; the better a firm's reputation the more likely it is to be targeted as an alliance partner.

This research also proves that it is not important to have an independent full-time facilitator going through trust building, teamworking and cooperative learning. Using ANOVA analysis, the perceptions of different groups are tested. Also, it is proved that construction firms, irrespective of their size, do not show any difference regarding the importance of success factors. To move from traditional contracting to cooperative teamworking, several convictions are required among which trust is the most important factor.

Anvuur and Kumaraswamy, are among those few researchers who tried to model partnering (Anvuur, 2007), the term for the cooperation motif in the construction industry (Phua, 2004), to lead project managers to highly cooperative processes. They first start with the reason for having subcontractors in a project. Subcontracting, as a response to uncertainty in complex projects, can guarantee the success of a project by implementing cooperation and defining common goals in an interdependent environment. In their research, Anvuur and Kumaraswamy define critical success factors as key factors absolutely necessary to reach goals. These factors are sometimes misunderstood and instead of being success factors of partnering, are outcomes of partnering. Therefore before trying to analyze these factors, the concept must be defined clearly.

The first important concept is trust. While numerous researchers believe that trust is a critical factor for partnering, Anvuur and Kumaraswamy believe that trust is a secondary outcome of partnering. It can pre-exist between partners or, it can be spontaneous, appearing as a result of "faith in humanity". Research shows that while trust creates cooperation, the other way around is possible too; cooperation can lead to trust. Same as Katzenbach and Smith, Abudayyeh, Albanese, Lazar, Wood and McDermott, the authors mention that trust is more a consequence of, that a means for, the achievement of cooperation. (Katzenbach, 1993), (Abudayyeh, 1994), (Albanese, 1994), (Lazar, 2000), (Wood, 2001),

Contractual incentives are among success factors. The objective of contractual incentives is to motivate different parties involved in a partnership to identify project objectives. In a partnership, the optimization of project's objectives is the first priority of parties with an emphasis on risk/reward arrangements. Early involvement of partners is the other success factor. Figure 2.3 summarizes the work done on this research regarding success factors.

Six years later, at 2013, Gottlieb and Haugbelle published their study in contradictions and collaboration in *construction management and economics* journal (Gottlieb, 2013). Through a combination of questionnaire surveys, interactive workshops, semi-structured qualitative research interviews and onsite observations, partnering is studied on a case study. In this case study, which is an office building project, the type and size of the project are fairly typical for

Danish projects. After a review of literature, they describe their research methodology. This study is using activity theory as the basis for studying the social origins of practical activities and systems within which people collaborate.

Through the first activity, the establishment of a partnering frame for government is examined. The main focus of this study is to understand how project participants perceive the collaboration in their partnering practice. Respondents are the key parties from five main companies involved in the project. The results show that parties are acting in a traditional manner more than a partnering practice. The respondents mention lack of structured planning, unclear communications, and unclear hierarchy as main reasons of failure in partnering manner.

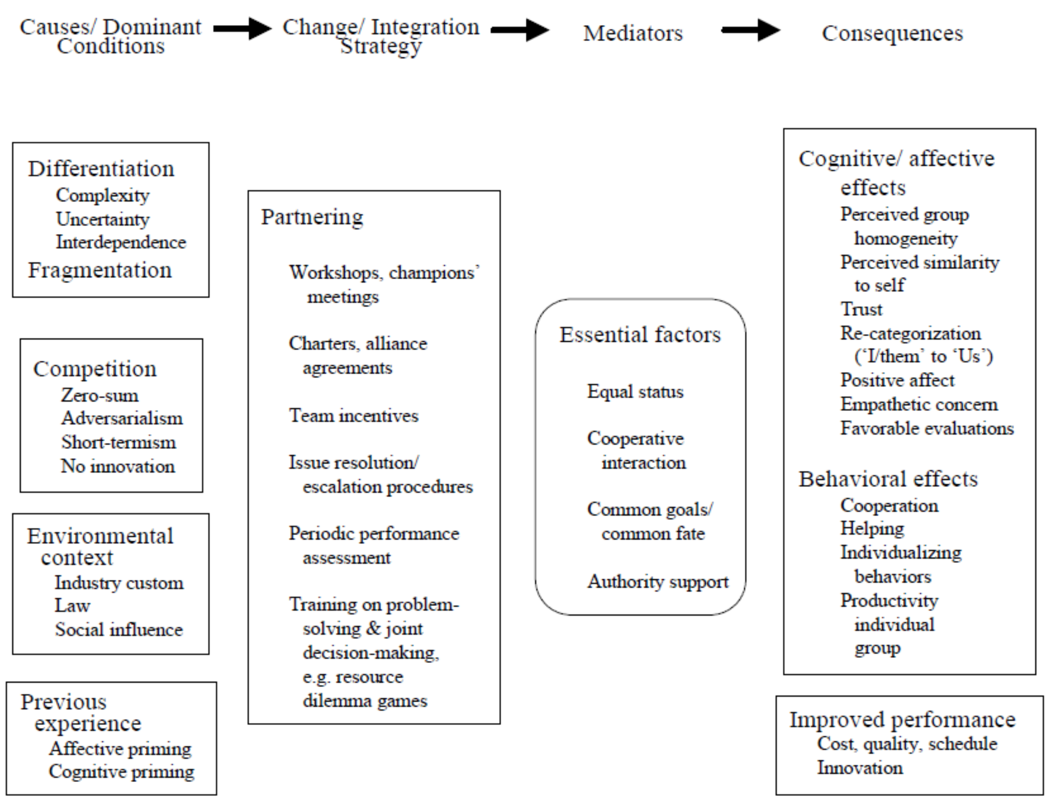

Figure 2-4 A model of partnering and its effects on project performance

The second questionnaire survey is done and the participants' opinion on the quality of collaboration on the project is extracted. Although a great improvement in the mutual respect between subcontractors and collaborative efforts is shown, an uneven resource sharing is one of the main problems due to participants' responses. This uneven distribution is the result of prioritizing main contractor's financial interests over common interests of the coalition. The contradiction between three different systems of production, interest, and value is one of the reasons for this unsuccessful partnering success. The activity system is based on the rationale of bargaining in different areas. Activities with interest system are negotiable based on either formal rules or informal procedures. Production system is the institutionalization of accomplishing tasks to deliver products or services. On the other hand, value systems exists within which the culture and identity are made. The value system is difficult to control since it is formed as a collection of the opinions of informal social groups within project. Generally, these different systems affect each other and different values of different subcontractors and this leads to contradictions and tensions between parties.

This paper, trying to find out the contradictions of collaboration, has explored that assemblage of tools and rules is directly affecting cooperation is a construction project. First finding of this study is the intertwined nature of three different systems of production, values and interests and its effect on collaboration. The second finding is that rather than being a substitute for existing practice, cooperation is a strategy growing out of existing norms. The last finding, concluded from studying collaboration, is that success of partnering is closely dependent on the strategies which are taken to handle tensions and prioritizing mutual objectives rather than individual objectives.

As a result of the synergy of ideas and resource management strategies, collaboration is described as a win-win approach. Main benefits of this approach are increased productivity, improved quality, and efficient results. Tsai and Chi studied win-win collaboration learning via a sequence of episodes between rival parties (Tsai, 2015). This learning guides individuals through how to change the motivation in a collaboration. Definition presented by Argyris and Schon defines learning as the path of error detection/correction (Argyris, 1996). They categorize learning into two single-loop and double-loop groups which defer in underlying paradigms and their change. In single-loop learning, these paradigms are not altered, while on the contrary, double-loop learning affects the paradigms and interpretive frames. In addition, learning can help individuals and shape their motivations based on cooperation and shared interests (Daniels, 2001). This shift from individual interests to common interests in an essential requisite for collaboration. Figure 2.4 summarizes the conceptual framework that guides this experimental design.

Three games are designed in order to study the effects of learning on the win-win approach. 64 undergraduate students participated in this experiment, divided into two construction and business majors. Business majors are the control group in this experiment and enter the game in the last stage. Figure 2.5 presents the details and game design. While the main goal of the first game is to make joint decisions, the second game focuses on maximizing the gain, and the third game is following the main goal of this study, which is to lead students to win-win outcomes.

Learning behavior of participants is examined by measuring the changes of interpretations and communication focuses from second to the third game. Adding control group helps to understand the differences between single-loop and double-loop learning processes. Furthermore, students are asked to summarize the lessons learned from each game and their interpretations. The spider diagram shown in figure 2.6 presents the changes from differentiation to integration from first to third game. The results prove that learning changes individuals' motivations and is able to make more trust in games. Moreover, learning affects the students' conceptual frames to favor cooperation over competition. Finally, this study shed light on how individual's behavior is improved towards win-win collaboration.

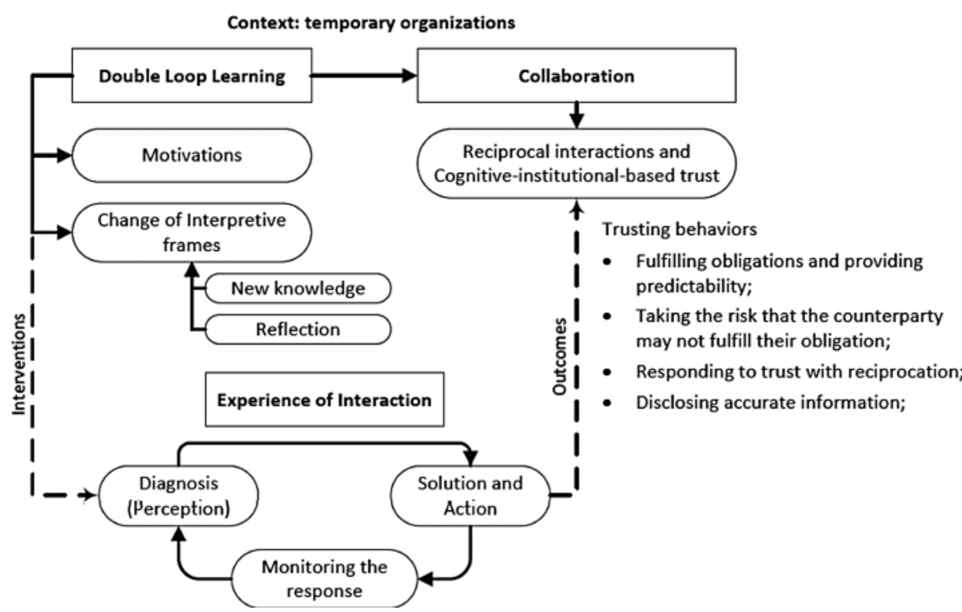

Figure 2-5 Conceptual framework of the relationship between learning and collaboration (Tsai and Chi, 2015)

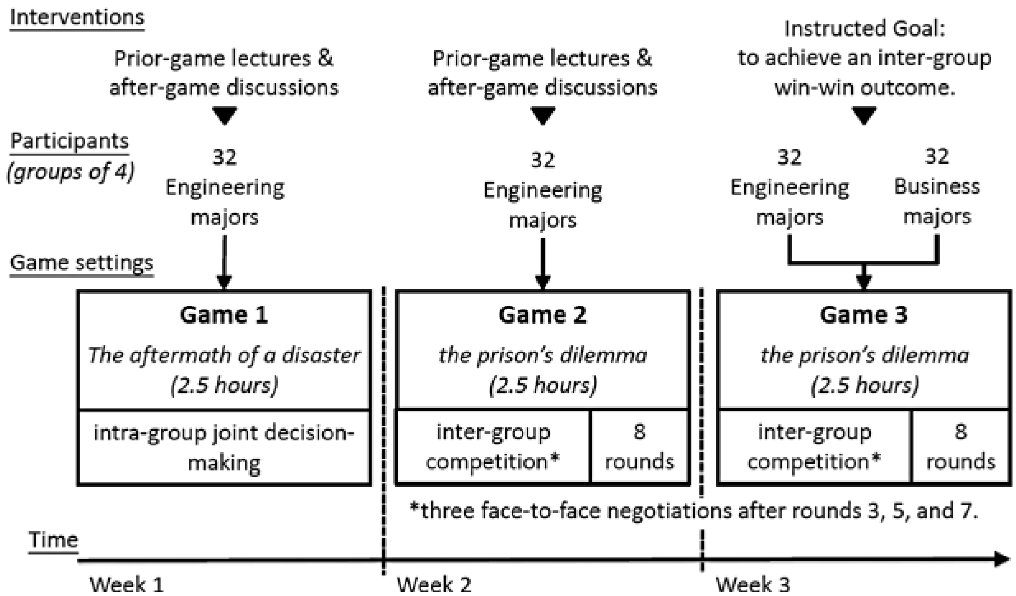

Figure 2-6 Three Game Design (Tsai and Chi, 2015)

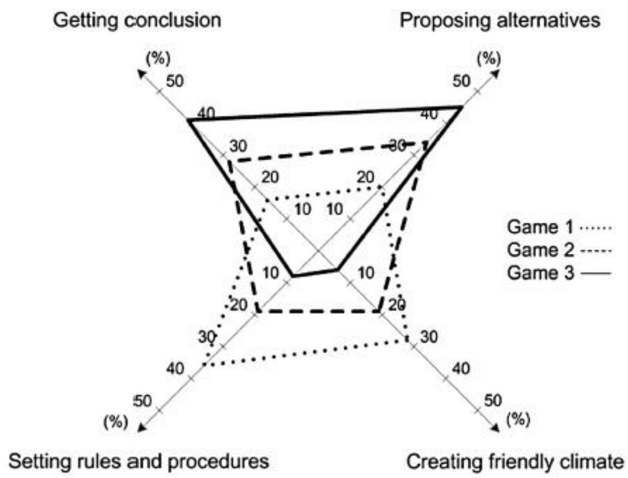

Figure 2-7 Main issues in group discussion for reaching consensus (Tsai and Chi, 2015)

Game Theory in Construction

In this section, application of game theory in civil engineering is studied. Despite game theory's power in solving problems in different fields, there is only a few studied done on the application of game theory in construction. Game theoretic models are used in studying the conflict in water resources sharing conflicts. Supposing that three elements of players, strategies, and outcomes are recognizable in a conflict, game theory could be used as a powerful tool to find efficient solutions. A brief review of researches done on the application of game theory is done here to provide the backgrounds necessary for studying the application of game theory in areas related to civil engineering. Table 2.8 demonstrates the studies which are reviewed in this section.

Public-private partnership (PPP) is one of the fields where game theory has been used. Scharle studies PPP project as a social game and publishes his work in European journal of social science research in 2002 (Scharle, 2002). Although public sector is the main provider of community interests, it lacks expertise and managerial skills in most of the areas. Thus it asks private investors to execute the projects working under a partnership contract. Scharle interprets PPP scheme as a sequential n-person game and describes it in the language of gaming. The underlying assumptions are:

1. All parties have access to same information in decision making process;
2. If the administration is accountable and the risk of strong private preferences is low, then privatization may be expensive and public-sector production is preferred.

The main message of this study is to utilize gaming perspective to understand uncertainties of PPP projects. Money is not the only utility for PPP partners. While for experienced and well-known private investors timely execution and reputation are important, government politicians are interested in being selected in elections and see PPP as a vote gaining opportunity. There are also other stakeholders with different and sometimes conflicting interests affecting the project.

Table 2-7 Summarized Papers' Detailed List

Category	Title	Authors	Year
Game Theory in Construction	Public–Private Partnership (PPP) as a Social Game	Scharle, P.	2002
	Using Bargaining-Game Theory for Negotiating Concession Period for BOT-Type Contract	Shen, L.Y. et al.	2007
	Modeling subcontractors cooperation in time; cooperative game theory approach	Asgari, M.S. and Afshar, A.	2008
	Calculating the Benefits of Transboundary River Basin Cooperation: Syr Darya Basin	Teasley, R., McKinney, D.	2011
	Game Theory Insights for the Caspian Sea Conflict	Madani, K., Gholizadeh, S.	2011
	Bringing Environmental Benefits into Caspian Sea Negotiations for Resources Allocation: Cooperative Game Theory Insights	Imen, S. et al.	2012
	Cooperation in Transboundary Water Sharing with Issue Linkage: Game-Theoretical Case Study in the Volta Basin	Bhaduri, A. and Liebe, J.	2013

Bargaining-game theory, as a branch of game theory, is used in situations in which players have an interest to cooperate despite their conflicting interests over exactly how to cooperate. Shen et al. have studied concession period in build-operate-transfer (BOT) projects employing bargaining-game theory (Shen, 2007). Concession period defines the duration in which the private party operates the facility to reimburse its investigation during building period of the infrastructure facility. If the concession period is too long, the private investor earns more benefit than the public partner (government). On the contrary, too short concession period makes it difficult for the private investor to make a profit out of the project. Consequently concession period must be a mutually agreed time span to satisfy both parties' interests.

Model designed by Shen et al. is based on an equation. This equation defines a range of concession period in which interests of both parties are protected. It states that the net present value (NPV) generated from the operation the project during concession period must be at least equal to investor's expected return from her investment. Besides, it should not exceed the net present value generated during the economic life of the project. Based on this equation, concession period is calculated, lying in a range with lower and upper limits. Each party can bargain for its maximum profit by offering a concession period lying between these limits. Bargaining negotiation is a complicated process where game theory is used to provide assistance in understanding its process.

Bargaining cost is an important characteristic of bargaining negotiation. This cost is induced in each round of bargaining as a result of delayed agreement reaching. Both parties consider the time value of money and later agreement costs more as a consequence of the value of time. In each round, one of the parties either accepts the concession period offered by another party in the previous round, or offers a new number as her preferred concession period. The flowchart shown in figure 2.1 helps to better understanding of the bargaining process. In this flowchart, G is used for government and P is for the private investor.

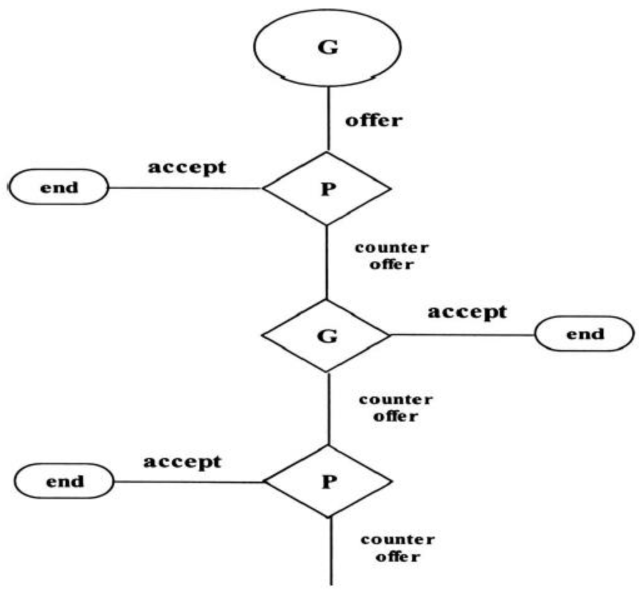

Figure 2-8 The bargaining process invited by the government (Shen et al., 2007)

A bridge case study is used to examine the application of the model. The concession period for this project is calculated based on the equation designed in this study and the time value of money. Finally, an interval is given as an agreeable concession period for the project. Model designed by Shen et al. challenges the traditional process of determining the concession period of BOT projects by adding an effective practice of negotiation instead of a firm predefined concession period by only one of the parties involved.

Asgari and Afshar are the pioneers of studying cooperation in construction projects using game theory (Asgari & approach”, 2008). They have modeled subcontractors’ cooperation in time, applying game theory. In their model, subcontractors trade time as one of the significant factors in a successful project. Time, along with cost and quality, is a crucial factor in construction. Each contractor has its own time-cost and time-efficiency functions. If the project is divided into sequential subprojects, subcontractors are able to trade time to decrease their total cost. The time-cost tradeoff is negotiated based on the cooperative game theoretic framework. The main question in this tradeoff is how to share the cooperation profit between players. In this study, the core, the Shapley value, and the nucleolus are used to answer this question. Metaheuristic methods are utilized to solve the problem. An illustrative example consisting of 3 subprojects/subcontractors is presented by Asgari and Afshar to illustrate their proposed approach. Then the benefit of cooperation is calculated using the three game-theoretic solution and results are determined.

Game theory is playing an important role in water and energy resources allocations. Several river basin management practices are done using game theoretic solutions. Water-sharing for Syr Darya basin is studied by Teasley and McKinney in a cooperative game theoretic framework (Teasley, 2011). Being part of the Soviet Union before 1991, and now flowing through four different countries after SU's breakup, Syr Darya presents a unique challenge. Teasley and McKinney have started their study, reviewing the past studies of water resources problems applying game theory (Mc.Kinney, 2007). Later on, they analyze the energy delivery to downstream countries through the existing reservoir.

Syr Darya basin model included hydropower generation and irrigated agriculture and calculates benefits of cooperation. This calculation is in monthly steps for a 10 year period. Different coalitions are assumed to calculate the benefits via a multiobjective model. The objectives are minimizing energy deficits and maximizing agricultural profits. The model includes some balance constraints on storage in reservoirs along the river.

Results indicate that the benefit of the grand coalition exceeds the sum of the benefits countries could receive in any other coalition. Different allocation methods such as the nucleolus and Nash-Harsanyi allocation are used to solve the profit sharing problem. Each country's satisfaction with its benefit allocation is used to determine the stability of each allocation model. As the conclusion, Shapley value is introduced as the most stable allocation method in this water sharing problem.

What is more, game theory has shown a great contribution to water resources management problems (Madani, 2010). In this area, Madani and Gholizadeh and Iman et al. have studied the Caspian Sea conflict (Madani K. G., 2011) (Imen, 2012) . The Caspian Sea is the largest enclosed body of water on earth bounded by five countries. The conflicts started after the collapse of Soviet Union. In these two studies, conflict resolution is done based on four cooperative game theory solutions and profit allocation for each of countries is analyzed using this powerful tool. Imen et al.'s study bridges the gap of previous studies by considering environmental utilities associated with the possible division practices. Similarly, a year later, Bhaduri and Liebe have investigated water and energy sharing in the Volta basin in the framework of cooperative games (Bhaduri, 2013). The number of studies done in water resources management using game theory is a strong proof of competency of game theory as a powerful tool in solving water resources sharing conflicts.

Chapter 3 Materials and Methods

Introduction

While most of the attention has been directed in the literature to studying cooperation between owner and contractors, in this study the cooperation between subcontractors is studied. A few literature has been done on joint resource management in construction projects. The most significant research which is done is a paper published by Asgari and Afshar, which faces many limitations. Some of these limitations are:

1. Game theory is only used in profit sharing and there is not any study done on cooperation games like prisoner's dilemma and stag hunt to model the cooperation in construction using these games.
2. There are only a few game theory solutions used in profit sharing while there are more solutions available and they might also be more suitable for analyzing cooperation in the construction.
3. Only one resource is shared in their study while in real projects there are more than one resources that can be managed jointly.
4. Their model is not used on a real project to evaluate the results for a case study having reasonable duration. Real case studies are different than simple short projects having a few number of activities.

There are some strong reasons for which construction projects' subcontractors decide to provide the maximum resources needed for the project and keep it on site during the project's duration. Some of these reasons are:

1. It is easier to plan and control the resources when the maximum resource needed during the project is provided and the project manager has no concerns about the unavailability of resources.
2. For some resources, especially the professional human resources it is too costly to hire and release the resources in short periods. Therefore project managers prefer to hire them though some might be idle in most days of the project.
3. Some resources are scarce in project location and project managers might not be able to provide resources on time, especially for critical tasks and this will cause a delay in the total duration of the project.

When the maximum number of resources are provided at a project, it is obvious that some of these resources stay idle during some hours or days of the project and this causes extra costs in projects. In other words, the project subcontractor is investing time on resources that might not be used for days, only because of the reasons mentioned above and this makes the subcontractor spend an unnecessary amount of money on resources and increases the project cost. One effective solution for this problem is to manage resources jointly. In joint resource management, subcontractors enter into coalitions, cooperating with each other, in order to share the resources by planning them jointly. This will decrease the maximum resources needed for their projects and result in lower cost for the coalition. This reduction in costs is due to lowering the number of idle resources. This reduction is stated as cooperation profit and is shared among coalition members using game theory solutions. In following, the model designed for this purpose is introduced.

Although joint resource management is an effective solution to optimize the costs of a project, there are several reasons hindering cooperation. The most notable obstacle is liabilities and responsibilities. Sharing the resources could cause conflicts and disputes between subcontractors. For instance, failure in equipment is a potential source of conflict in joint construction projects. Dealing with this problem need predefined roles and responsibilities' assignment, determining how the conflicts will be addressed and resolved.

Joint Resource Management Model

The analysis of any game begins with specifying a model to describe it. Any analytical model derives its power from simplifying assumptions that are most of the times questionable. While too simple models may ignore significant aspects of the conflict, too complicated models obscure identifying the vital issues of the problem.

The objective of this research is to optimize the costs of resources. To achieve this, a model is designed and coded in Visual Basic. The objective function is shown as:

$$\text{Min } C_T = \sum_{i=1}^{n} C_i \qquad (3\text{-}1)$$

Where:

C_T : Total Cost of Project

C_i : Cost of the i^{th} Subcontractor

And

n: Number of subcontractors.

Model Explanation

In this model, the project is divided to N subprojects and each of these subprojects are executed by subcontractors. Also, the project is divided into periods, which at the beginning of each period subcontractors provide the maximum resources needed in that period and they are not allowed to hire or release the resources during this period. When the next period starts, subcontractors are allowed to add new resources or release the ones that are needed during the new period. In this study, a monthly period is considered and subcontractors are providing the resources at beginning of each month based on the maximum needed in that month. Therefore, cost of each subproject on t_m periods (number of months the project is executed) is calculated using the equation 3-2.

$$C_i = \sum_{j=1}^{r_i} \sum_{t=1}^{t_m} R_{max_{it}j} . D_t . CR_j + \sum_{j=1}^{r_i} \sum_{t=1}^{T} R_{itj} . CM_j \quad (3\text{-}2)$$

Where for j=1 to r:

$$R_j \le R_{max_j} \quad (3\text{-}3)$$

Table 3-1 Indices

i	Subcontractor
j	Resource
t	Period

Genetic Algorithm

Genetic algorithm is one of the evolutionary algorithms used in solving optimization problems based on Darwin's natural selection theory. This algorithm is used to generate high-quality solutions to optimization and relies on bio-inspired operators like selection, crossover, and mutation. In GA a population of candidate solutions of an optimization problem, called phenotypes, is evolved to better solutions. Each phenotype consists of properties called chromosomes, which are evolved in an iterative process. In each process, the population is called a generation, for which the fitness of phenotypes is evaluated based on the objective function of the optimization problem. Better fitting phenotypes are selected stochastically and using some processes new generation is formed. This procedure is repeated to generate the next generations iteratively until a maximum number of generations is reached.

Table 3-2 Variables

C_i	Total Cost of Resources for Subcontractor i
r_i	Number of Resources for Subcontractor
T	Duration of Project
t_m	Number of periods; If each period is assumed to be 30 days, then the number of periods is calculated as: $t_m = \left\lceil \frac{T}{30} \right\rceil$
$R_{max_{itj}}$	Maximum Number of Resource j in period t for subcontractor i
D_t	The Duration of Period t in days
CR_j	Cost of Rent for Resource j
CM_j	Cost of Maintenance for Resource j
R_{itj}	Number of Resource j in period t for subcontractor i

In this model, each chromosome consists of $2 \times a$ genes, where a is the number of activities. Each pair the start date and a chosen option of each activity. This option may be the duration, float, number of resources and predecessors of the activity. While the sequence of genes is consistent with the priority of activities, the GA structure is presented in figure and table. The code is also available in the appendix.

The numbers in table 3-3 are adapted from Zahraie and Tavakolan (2009). The number of initial population is decided in order to provide a sufficient number of chromosomes to reach an acceptable output. While too many chromosomes make the optimization process long and frustrating, assigning a low number of chromosomes leads the GA to inefficient optimization results.

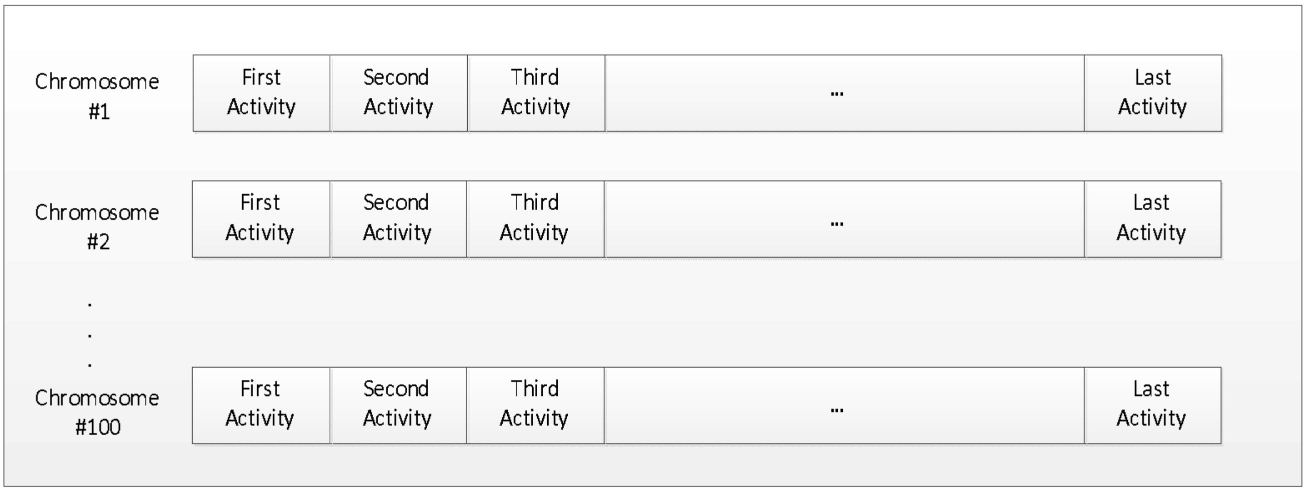

Figure 3-1 Structure of GA

Table 3-3 GA Model Information

Initial Population	100
Elitist Selection	5%
Worst Chromosomes Rejection	5%
Parent Population Selection	Stochastically
Crossover	Single point or two point (Randomly)
Mutation	All chromosomes are mutated. In each chromosome, 6 genes are mutated.

Game Theory Solutions

Game theory is covering a vast part of decision making under uncertainty and has resulted in great solutions for different types of problems. In general, a "solution" for a game is the prediction of how players might behave in that game (Myerson R. , 1991). In each game, there are two or more players who try to increase their payoff in that game. Strategic games are divided into two categories of non-cooperative and cooperative games. The main question in cooperative games is the question of how to distribute the total profit achieved as a cooperative action of all players to the different players in the game. To illustrate more, in these games, there is a payoff function which assigns a number to each coalition. Players who work together as a coalition, try to get a higher payoff for the coalition they have formed.

Another interesting characteristics of each game, is the power of each player or coalition in this game (Felsenthal & Machover, 1998).

The GA is coded in Visual Basic (VB) as the programming language used in this study. An excel sheet containing the project information is given to VB as an input. For each activity, an activity ID, duration, floats, predecessors, lag/lead, resources needed and the subcontractor responsible for performing that activity are included in excel sheet. The project manager could define the priority of resources and ask the VB to perform the optimization based on the given priority. The output of optimization process is a list of start days of activities and the optimized costs of resources. Considering the floats of activities, GA tries to shift the start day of activities to minimize the costs of resources and the best schedule is suggested as the final result of the optimization process.

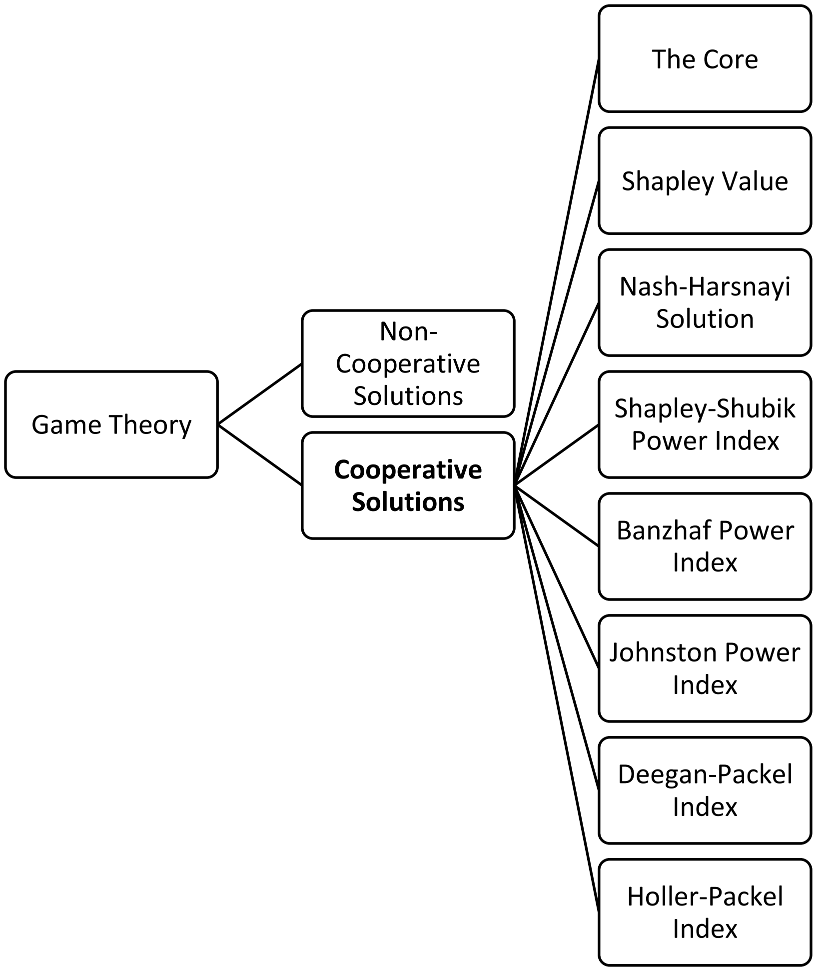

Figure 3-2 Game Theoretic Solutions

The Core

The first solution proposed for cooperative games is the Core of the game. Gillies defines the Core as a set of all undominated imputations in a game (Gillies, 1959). An imputation is in the Core if the members of any coalition S are getting, in total, at least as much as S could guarantee them (Straffin P. , 1993).

Definition: The Core of a game is the set of all undominated imputations, i.e. the set of all imputations (x_1, …, x_n) such that for all $S \subseteq N$, $\sum_{i \in S} x_i \geq v(S)$.

The main essential consideration in cooperative game theory is that coalitions will abandon the game if they are not satisfied in their legitimate demands (Kannai, 1992). This is the foundation of the Core solution. If an allocation is not in the Core, there is at least a coalition S such that its players could do better out of that allocation. In other words, none of the coalition members tend to leave the coalition, if it is in the Core. For a three player game, the Core is represented in set of inequalities 3.4 to 3.8:

$$x_1, x_2, x_3 \geq 0 \quad (3\text{-}4)$$

$$x_1 + x_2 + x_3 = 1 \quad (3\text{-}5)$$

$$x_1 + x_2 \geq v(1,2) \quad (3\text{-}6)$$

$$x_1 + x_3 \geq v(1,3) \quad (3\text{-}7)$$

$$x_2 + x_3 \geq v(2,3) \quad (3\text{-}8)$$

Shapley Value

Despite the fact that the core solution gives us great insight to all stable solutions of a game, it might be empty or quite large, making it difficult to determine a unique payoff for the players (Shubik, 1969). Addressing this problem, Shapley introduced a solution that satisfies two axioms symmetry and dummy axiom, in addition to efficiency and additivity (S Shapley, 1953). For a game with n players and characteristic function v, the imputation $\varphi = (\varphi_1, \ldots, \varphi_n)$ that:

1. Efficiency: $\sum_{i \in N} \varphi_i = v(N)$ that means the total value of the players is the value of the grand coalition.

2. Additivity: If u and v are the characteristic function, $\varphi(u+v)=\varphi(u)+\varphi(v)$. This axiom as the strongest axiom here, states that the arbitrated value of two games played at the same time should be the sum of the arbitrated values of the games if they are played at different times.
3. Symmetry: φ respects any symmetries in v. That is, if players i and j have symmetric roles in v, or $v\left(S\cup\{i\}\right)=v\left(S\cup\{j\}\right)$, then $\varphi_i=\varphi_j$.
4. Dummy Player: If for all coalitions $S\subseteq N$, $v(S)=v(S-\{i\})$ then i is a dummy player who adds no value to any coalition and $\varphi_i=0$. It means that adding a dummy player to a game, does not affect the values of φ_j for other players j in that game.

Shapley demonstrates that there is exactly one imputation $\varphi=(\varphi_1,\ldots,\varphi_n)$ that satisfies all these four axioms. For each i in N, this function satisfies the following equation:

$$\varphi_i(v)=\sum_{S\subseteq N-\{i\}}\frac{|S|!(|N|-|S|-1)!}{|N|!}(v(S\cup\{i\})-v(S)) \tag{3-9}$$

Nash-Harsnayi Solution

Another solution offered by John Nash for two-person games is given by following equation (Nash, 1953):

$$\Omega=max\left(x\left(1\right)-v\left(1\right)\right)\left(x\left(2\right)-v\left(2\right)\right) \tag{3-10}$$

Harsanyi extended the Nash solution for two-person games to the N-person games (Harrsanyi, 1959) and (Harsanyi, 1963). Equation (3.1) is his offered solution.

$$\Omega = \prod_{i=1}^{n} \left(x(i) - v(i) \right) \qquad (3\text{-}11)$$

Shapley-Shubik Power Index

As stated before, Shapley value is a powerful too in modeling the power of players in a game. Given this, Shapley and Shubik developed a measure named Shapley-Shubik power index (Shapley & Shubik, 1954). This index was first used to measure the voters' power in a voting game and is based on the definition of the pivotal player in a sequential game. These two concepts are defined as following:

Sequential Game: A group of games, in which the order in which players join the coalition is important. Based on this definition, $n!$ sequences exist in a game with n players.

Pivotal Player: The player i is pivotal if she changes the status of a coalition from "losing" to "winning" by joining that coalition. Notice that this definition is valid in a sequential game.

Taking these two definitions into account, the Shapley-Shubik index for player i in a coalition is derived using equation 3.12 (Hu, 2006).

$$\text{[illegible]}(\text{[illegible]}) = \frac{\text{[illegible]}}{\text{[illegible]}} \qquad (3\text{-}12)$$

The Shapley-Shubik index is between 0 and 1. A power of 1 means the player determines the status of the coalition by its entrance.

Banzhaf Power Index

The Banzhaf power index is named after John Banzhaf, and was initially introduced to measure the probability of changing the outcome of the voting game, when players have different shares (Banzhaf, 1965). Before introducing this index, the critical player and winning coalition must be defined (Lehrer, 1988):

Critical Player: Player i is critical if she changes the status of the winning coalition to losing, by leaving that coalition. Notice that this definition is not necessarily applicable in sequential games.

Winning Coalition: The coalition that has the minimum votes to win the voting.

The Banzhaf power index is derived using the following equation (Penrose, 1964):

$$\text{[illegible]}(\text{[illegible]}) = \frac{\text{[illegible]}}{\text{[illegible]}} \quad \text{(3-13)}$$

The Banzhaf power index is also normal and 1 means the player has full power.

Johnston Power Index

Johnston introduced a power index using the concept of critical player (Johnston, 1978). The difference between his index and the previous indexes is that Johnston believes that a player who is critical in a coalition having fewer members, is more important than a critical player in a coalition consisted of more players. To define his index, the number of coalition j’s member in which player i is critical is shown by m_j and the Johnston power index for player i is defined as following, where k is the total number of winning coalitions:

$$jPI(i) = \sum_{j=1}^{k} \frac{1}{m_j} \quad (3\text{-}14)$$

To normalize this index, the equation 3.15 could be used:

$$JPI(i) = \frac{jPI(i)}{\sum_{j=1}^{n} jPI(j)} \quad (3\text{-}15)$$

Deegan-Packel Index

The Deegan-Packel power index, gives a measure of power based on minimal coalitions (Deegan, 1978). Minimal coalition is a coalition for which the status of coalition is changed to losing if any of its players leave. Packel believes that only minimal winning coalitions are important in calculating the power indexes of game players (Lorenzo-Freire, 2007). The Deegan-Packel power index for player i is calculated using the following equation where m_j is the number of minimal coalition j's members, in which player i is critical:

$$dPI(i) = \sum_{j=1}^{k} \frac{1}{m_j} \quad (3\text{-}16)$$

The normalized form of this index is given by:

$$DPI(i) = \frac{dPI(i)}{\sum_{j=1}^{n} dPI(j)} \quad (3\text{-}17)$$

Holler-Packel Index

A different power index, based on minimal winning coalitions, is introduced by Holler (Holler, 1982). The vital difference between the Holler-Packel and the Deegan-Packel index is that in the former, being a member of the minimal winning coalition is enough while this member must be a critical member in the latter one. Considering this, the Holler-Packel index is given by equation 3.18, and equation 3.19 is the normalized index for player i.

$$hPI(i) = \sum_{j=1}^{k} \frac{1}{m_j} \quad (3\text{-}18)$$

$$HPI(i) = \frac{hPI(i)}{\sum_{j=1}^{n} hPI(j)} \quad (3\text{-}19)$$

Propensity to Disturb and Stability

A player's satisfaction with profit sharing determines the likelihood of its compliance with the arrangement (Gately, 1974). To put it another way, if a player is dissatisfied with the benefit allocations, it may leave the coalition. This is a measure of the power of a player and stability of an allocation and is calculated as the ratio of "the loss to the remaining players if that player leaves the cooperation" compared with "that player's own loss because of leaving that cooperation." Gately (1974) formulates this definition and calls it the propensity to disrupt given by equation (3.20) where v({j}) is the noncooperative benefit for player j. If d_j is positive and relatively large, player j is likely to leave the coalition unless its allocation is increased.

$$d_j = \frac{\sum_{i \neq j} \varphi_i - v(\{N - j\})}{\varphi_j - v(\{j\})} \qquad j \in N \quad (3\text{-}20)$$

Moreover, Loehman et al. suggest another measure of stability for an allocation, named Loehman power index, formulated as equation (3.21) (Loehman, 1979).

$$L_j = \frac{\varphi_j - v(\{j\})}{\sum_{i \in N} [\varphi_i - v(\{i\})]} \qquad (3\text{-}21)$$

Loehman power index for player j is a measure of "the gains of a player" relative to "gains of the coalition including that player (Dinar, 1997)". It is clear that if this index for different players is approximately equal, then the coalition is stable and players are less likely to leave it.

Examples

For the better understanding of the designed model, consider a small project in which three subcontractors are executing the project work in the construction site. Among all resources, two machine types R1 and R2 are in common. Figure 3.3 indicates the project network. The daily resources costs and the project information are shown in table 3.6 and 3.7. For each resource, two different costs are assigned; first is the rental cost of the machine and the second is the maintenance and repair cost for that machine.

The first step to analyze the cooperation in this problem is to calculate the cost of doing each subproject when there is no cooperation and subcontractors work individually. Therefore the project information is given as input of designed program and results are extracted. Next, the costs of all possible coalitions are calculated using the same process. These steps are done for singleton coalitions ({1}, {2}, {3}), two-member coalitions ({1,2}, {1,3}, {2,3}), and grand coalition ({1,2,3}). The second column in table 3.8 presents the results extracted running the GA algorithm in Visual Basic. Next step is calculating the cooperation profit using the differences in costs when two or three subcontractors work together in comparison to doing the work individually. The numbers are illustrated in the third column of table 3.8 Savings of each coalition is presented as its profit and next step is to allocate this profit to players of the coalition based on different game theoretic solutions introduced in previous section. Table 3.9 includes these profit allocation for each subcontractor using different solutions.

Table 3-4 Resources Costs

Cost Type	R1	R2
Rent (dollar per day)	1000	300
Repair and Maintenance (dollar per day)	250	100

Table 3-5 Activities' Information

Activity	Duration (days)	Predecessors	Resources	Critical	ES	LS	EF	LF
Subproject 1								
A	10	-	R1[5],R2[2]	Y	1	1	10	10
B	5	-	R1[2],R2[4]	N	1	26	5	30
C	15	A	R1[5]	Y	11	11	25	25
D	10	A,B	R1[1],R2[3]	N	11	31	20	40
E	10	C	R1[5]	Y	26	26	35	35
F	15	E	R2[5]	Y	36	36	50	50
G	10	D,E	R1[3],R2[3]	N	36	41	45	50
Subproject 2								
H	5	-	R1[6]	N	1	6	5	10
I	10	-	R2[5]	Y	1	1	10	10
J	15	H,I	R1[5]	Y	11	11	25	25
K	5	J	R1[1],R2[3]	N	26	41	30	45
L	10	J	R2[5]	Y	26	26	35	35
M	5	K,L	R1[7]	N	36	46	40	50
N	15	L	R1[5],R2[5]	Y	36	36	50	50

Table 3-5 Activities' Information (Continued)

Subproject 3

Activity	Duration (days)	Predecessors	Resources	Critical	ES	LS	EF	LF
P	10	-	R1[5]	Y	1	1	10	10
Q	15	P	R2[5]	Y	11	11	25	25
R	5	P	R1[3]	N	11	21	15	25
S	10	Q,R	R1[5],R2[4]	Y	26	26	35	35
T	10	R	R1[2]	N	16	41	25	50
U	10	S	R2[3]	N	36	41	45	50
V	15	S	R1[1],R2[6]	Y	36	36	50	50

Table 3-6 Cost and Profit of Coalition

Coalition	Total Cost ($)	Cooperation Profit ($)	Profit to Total Cost (%)
{1}	574000	0	0
{2}	1129000	0	0
{3}	565750	0	0
{1,2}	1471000	232000	15.8
{1,3}	997750	142000	11.9
{2,3}	1411750	283000	20
{1,2,3}	1693750	575000	33.9

Table 3-7 Profit Allocation to Subcontractors

C	Shapley	Nash-Harsnayi	Shapley-Shubik	Banzhaf	Johnston	Deegan-Packel	Holler-Packel
1	159667	191667	95833	115000	123214	159722	164286
2	230167	191667	383333	345000	328571	255556	246429
3	185167	191667	95833	115000	123214	159722	164286

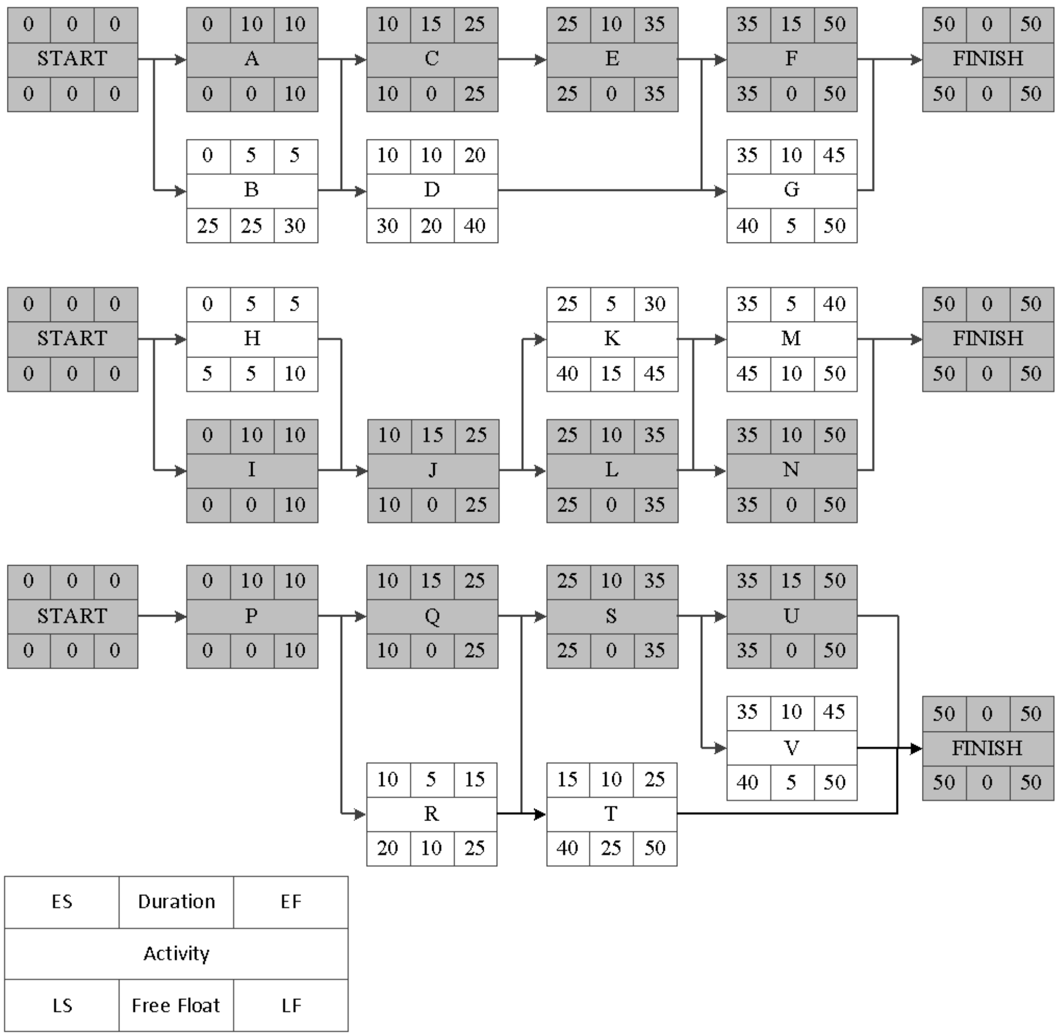

Figure 3-3 Project Network

Conclusion

In this chapter, the joint resource management model was introduced. The objective of the model is to minimize the cost of resources that is the summation of rental costs and maintenance costs for each equipment type resource. While rental cost is considered for both working and idle equipment, the maintenance cost is only assigned to working machinery and it is assumed that idle equipment do not require any maintenance. Each subcontractor is allowed to employ or release unwanted resources at the beginning of each month (each month is assumed to be 30 days long). The optimization problem is coded in visual basic, using the genetic algorithm. In this algorithm first generation of the potential solution for the optimization problem is evolved toward better solutions. The fitness for each generation is based on the objective function of the model, which is to minimize the costs of resources. Crossover and mutation are two operators that produce new generations which are closer to the ultimate answer. After running the GA code, the cost of each collaboration ({1}, {2}, {3}, {1,2}, {1,3}, {2,3} and {1,2,3}) is determined. The difference between original costs, when there is no collaboration, and the collaborative costs is defined as the profit of the collaboration. The next step is to divide this profit among the members of that collaboration. For this purpose, game theory has been suggested, offering several game solutions for the profit allocation problem. In this chapter, 7 different solutions are introduced. In the last part of this chapter, an example is given to better understand the model and the game solutions. This example will be used in the fifth chapter for further analysis of the game solutions and the concept of propensity to disrupt, and stability.

Chapter 4 Cooperation Game

Introduction

In game theory, the prisoner's dilemma and the stag hunt game help to describe the cooperation between players. Jean Jacques Rousseau describes the stag hunt game as following:

> Two hunters go out on a hunt. They have two options to hunt, to hunt a stag or a hare. It is important to note that none of hunters are aware of the other's decision. An individual can get a hare by himself but to hunt a stag, the cooperation of both hunters is needed in order to succeed.

The game of stag hunt has been known by many names in the literature of game theory, such as "trust dilemma," "assurance game," and "cooperation game." This game has taken to be an important analogy for social cooperation in different areas. In this chapter, cooperation between subcontractors is explained using the stag hunt game. For this purpose, a simplified payoff matrix, shown in table 4.1 is used to analyze the game. There are three strategies to be taken by subcontractors; first strategy is mutual cooperation where both subcontractors cooperate and get the highest overall payoff, second is unilateral cooperation in which one subcontractor schedules his activities considering the mutual profits where the other subcontractor does not cooperate and prioritize his individual profit over the overall profit and the third strategy is mutual non-cooperation where none of the players cooperate in join resource management.

Table 4-1 Payoff Matrix for Cooperation Game

	Cooperation	Non Cooperation
Cooperation	(3, 3)	(0, 2)
Non-Cooperation	(2, 0)	(1, 1)

The puzzling thing about this cooperation game is that it shouldn't be a dilemma at all. Both players should certainly cooperate – that is, gaining the best payoff. The question is why players hesitate to cooperate? In the first look, what spoils cooperation is the possibility that the other subcontractor might not cooperate. Although the best possible for both of subcontractors is to cooperate, it would be terrible for the cooperator if he is the only player who cooperates. The mutual cooperation results in the highest payoff that equals to 6 unit, which is higher than other outcome (2 units); thus this outcome looks as the most appealing outcome. Also, this result is Pareto efficient and none of the players can get more by changing his strategy. Despite these, the cooperation game has two pure Nash equilibria. If one of subcontractor cooperates and the other subcontractor knows that, he would choose to cooperate too. On the contrary, if a subcontractor is provided with the information that his peer will not cooperate, he is not interested in cooperation. The former strategy is payoff dominant since payoffs are higher than what each subcontractor gains in the latter one. The latter strategy is risk dominant since in case of uncertainty about the other subcontractor's action it provides a higher expected payoff.

The question is, what strategy is chosen by subcontractors in a real project? And also are there any solutions to lead them towards cooperation? If both subcontractors are logical and understand the situation, they will both cooperate and win 3 units. When they are less logical and they might not cooperate and each get 1 unit. How should a subcontractor act in a cooperation game? The answer to these question is more related to psychology than game theoretic! If either of subcontractors is asked why they did not cooperate, they most probable answer is "how should I make sure that the other subcontractor is going to cooperate?" Another answer to this question lays behind the mental reward system of a player who gains more than his peer and feels as a "winner" in the game. The significant question making stag-hunt a dilemma is that the non-cooperation strategy is tempting in some situations. In his book, Anatol Rapoport analyzes all the possible strategies and based on the assumption that all players have an identical mental analysis structure, concludes that the logical decision is to cooperate (Rapoport, 1960). Yet this assumption is questionable in the sense that how players may believe in it and trust that their peer has the same attitude too. Suppose that the players find a way to influence their peers and lead them toward cooperation. The simplest means for this purpose is to consider subcontractors in contact with each other, and by letting them know how they think, they can reach a mutual understanding of choosing cooperation as their ultimate strategy. The challenging question here is whether it is practical in a real-life situation to encourage other subcontractors to cooperate and also how close this situation is to the perfect situation based on trust and honesty.

Another argument for cooperation is to assume that the subcontractors are going to work on other projects in the future. This assumption might easily encourage them to cooperate. While it is difficult to encourage subcontractors to cooperate in a one-time only project, it might look easier in a long-run multiple projects. While all game theorists agree that there is not any "solution" for one-time cooperation game, assuming the long-run condition for this game might help to solve it. Next section addresses the long-run games throughout a phenomenon called "the shadow of the future", trying to find a solution for cooperation game.

The Shadow of the Future

The shadow of the future is a concept in game theory expressing the idea that the players' behavior is quite different in repeated games. One of the essential questions, which this concept is trying to answer is the cooperation dilemma, by expecting a punishment for the player that misbehaves by not cooperating. In many real-life situations, people have multiple interactions with each other, and if they ruin their reputation by misbehaving, they may lose their future chances. The same happens when two subcontractors are working together, their cooperation builds trust and this leads to future cooperation. Robert Axelrod is a game theorist who uses the shadow of the future as a tool to justify the cooperation in repeated cooperation game (Aaxelrod, 1997). There are two assumptions possible:

1. Infinite repeated rounds of the cooperation game;
2. Finite repeated rounds of cooperation game.

Although the number of repetition might not look important, it affects the game in cooperation game. If subcontractors are not aware of the number of projects they might work together in future (first assumption), they prefer to choose cooperation in each game and trust their peers because it leads them to the best outcome ever. In infinite repetition condition, by misbehaving, subcontractors will lose the chances of future cooperation. The second assumption completely changes the results. Assuming that subcontractors are going to work on a common project for limited rounds in the future, they expected to behave completely different than an unlimited repetition of cooperation game. For instance, assume that the subcontractors are willing to work on exactly ten common projects. The last game (the tenth game) is a single game where the shadow of future is not effective anymore. In other words, there is no difference between the tenth game and a one-time-only cooperation and subcontractors have the same problems as they had in a single cooperation game. Considering this, the game is reduced to a 9 round game. Having the same induction, it is reduced to an 8 round game and so on. At the end, a limited number of repetitions lead the subcontractors to the same situation and dilemma, as they face in a one-round game. The traumatic conclusion is that a repeated cooperation game, which is repeated for limited (or finite) rounds is same as a one-time-only game and falls victim to a logical domino-type argument.

The next question to answer is that whether the shadow of the future is able to guarantee a cooperation between subcontractors even in case of unlimited rounds of a repeated game. The surprising answer is that although the game theory, as a mathematical tool, expects a definite cooperation, in real-life situations there are subcontractors who are not cooperating though they are expecting unlimited repeated games. Psychology is assisting the mathematicians to explain this behavior, based on a human’s mind. Subcontractors, as human beings, have a different understanding of “present” value of a reward in comparison to its “future” value. That is to say, the instantaneous benefits are preferred over gains over a long period of time. The last but not the least conclusion is that the analyses based on the shadow of the future are valuable only when the “present” and “future” are equally valued in a subcontractor’s mental reward system. Having this in mind, the next section is investigating the possible set of strategies taken by subcontractors in unlimited repeated games.

Suggested Strategies for Subcontractors in Cooperation Game

If prisoner’s dilemma is only played once, as Rapoport suggests, a stag-hunt game player has two strategies:

1. To cooperate regardless of the other player’s strategy.
2. Not to cooperate regardless of the other player’s strategy.

Real-life games are played more than once. Having this in mind, a set of strategies are offered in this section for a repeated stag-hunt game. Based on Axelrod’s study, “Tit for Tat” is one of the winning strategies players had taken in the experiment done by him. He explains this strategy in two steps:

1. Start the game by choosing cooperation in first round.
2. Thereafter, watch the other player’s strategies and react to it by choosing the same strategy your opponent has chosen in the previous round.

This strategy has three characteristics that make it advantageous:

1. It starts with cooperation and is based on having a positive attitude in the game.
2. The player forgives her opponent if he changes his decision from not cooperating to cooperation.

3. It is straightforward and easy to follow.

Axelrod's research illustrated that Tit for Tat is the winner strategy in prisoner's dilemma. Based on the similarities between prisoner's dilemma and stag-hunt this strategy might have been the winning strategy for stag-hunt too. However, a set of programmed tournaments are needed to prove the result of Tit for Tat for the latter game as well.

Example of Cooperation Game

Introduction

To better understand the cooperation game, a simple example is provided in this section. A project consisting of two subprojects, which are taken by two subcontractors is assumed. Each subproject is composed of three activities that need a common resource. The project information is shown in table 4.2. The network flowchart in figure 4.1 helps us to calculate the duration of each subproject. In the first Subproject, activities B and C are critical activities and the total duration of subproject is five days. The second subproject has the same duration, and activities D and F are critical activities. Tables 4.3 and 4.4 illustrate the Gantt charts for these subcontractors. Critical activities are shown in grey where uncritical activities are in white. In the first subproject, activity A is not critical and its start can be delayed for 4 days. In the second subproject, activity E is not critical and its start can be delayed for 2 days.

Table 4-2 Information of Cooperation Game

Subcontractor	Activity	Duration	Predecessor	Resource
1	A	1	-	R1[1]
	B	4	-	R1[3]
	C	1	B	R1[4]
2	D	2	-	R1[3]
	E	1	D	R1[1]

	F	3	E	R1[1]

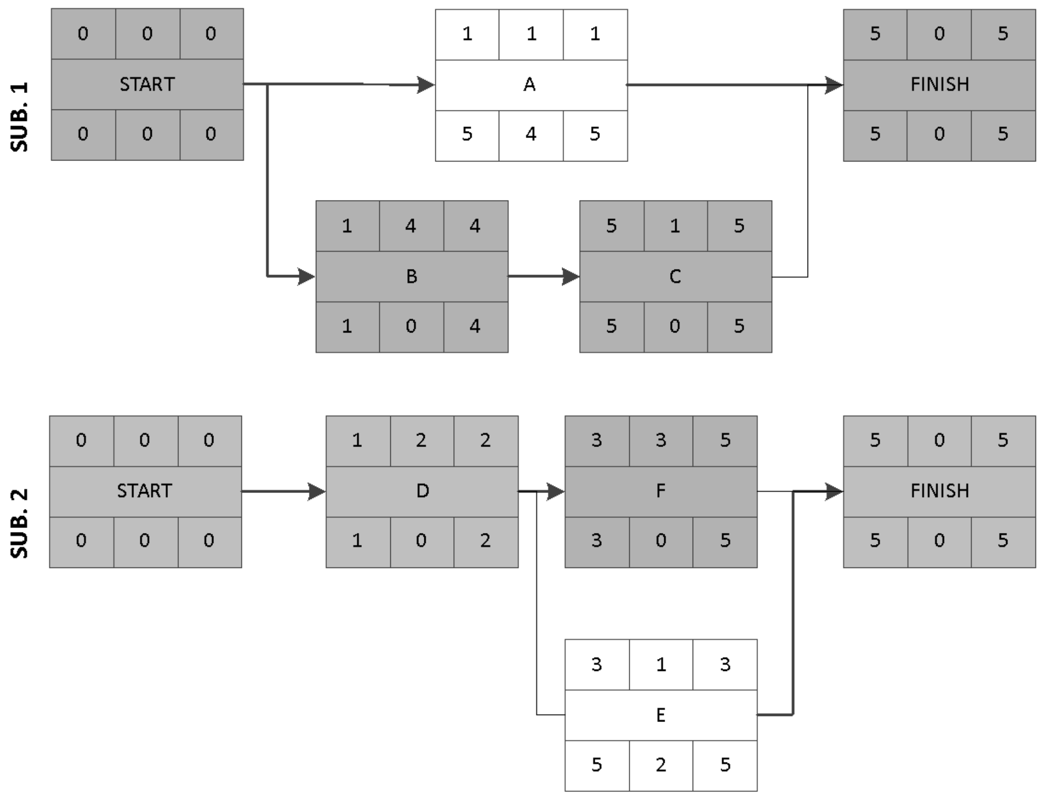

Figure 4-1 Network Flowchart for Cooperation Game

Table 4-3 Gantt chart for First Subproject

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A	1				
B	3	3	3	3	
C					4
Total Resources	4	3	3	3	4

Table 4-4 Gantt chart for Second Subproject

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
D	3	3			
E			1		

F			1	1	1
Total Resources	3	3	2	1	1

Analysis

In this section, different options for each subcontractor are analyzed and the game tree for this example is drawn based on this analysis. First, assume that each subcontractor decides to work separately and there is not any joint resource management. The second assumption is that the subcontractors are not allowed to hire or fire the resources during the project. Thus they must provide the maximum resources needed, at the beginning of the project. The first subcontractor has to execute activities B and C with no float. Start of activity A is more flexible and it can be delayed up to 4 days. By executing this activity through first to fourth day, the maximum resources needed for subproject A are 4 units. Postponing this activity to fifth day, increases the maximum resources needed to 5 units. Gantt charts in tables 4.5 to 4.9 illustrate the five different possible cases for the first subcontractor. Accordingly, first subcontractor prefers to execute activity A on day 1 to 4 to minimize its costs. The same logic is applicable for the second subproject. Since activity E must be executed after activity D finishes, it cannot start earlier than the third day. Considering the two day float for activity E, it can be executed on fourth or fifth day too. However these three different options do not make any difference in the maximum resources needed for the second subproject and it remains as 3 units. Hence, the least resources needed is 7 (4+3) units in case of separate resource management. Tables 4.10 to 4.12 give the Gantt charts for three different cases possible for the second subcontractor.

Table 4-5 Gantt chart for First Subproject-Case 1

Activity	D ay 1	D ay 2	D ay 3	D ay 4	D ay 5
A	1				
B	3	3	3	3	
C					4
Total Resources	4	3	3	3	4
Maximum Resources	4				

Table 4-6 Gantt chart for First Subproject-Case 2

Activity	D ay 1	D ay 2	D ay 3	D ay 4	D ay 5
A		1			
B	3	3	3	3	
C					4
Total Resources	4	3	3	3	4
Maximum Resources	4				

Table 4-7 Gantt chart for First Subproject-Case 3

Activity	D ay 1	D ay 2	D ay 3	D ay 4	D ay 5
A			1		
B	3	3	3	3	
C					4
Total Resources	4	3	3	3	4

Maximum Resources	4

Table 4-8 Gantt chart for First Subproject-Case 4

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A				1	
B	3	3	3	3	
C					4
Total Resources	4	3	3	3	4
Maximum Resources	4				

Table 4-9 Gantt chart for First Subproject-Case 5

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A					1
B	3	3	3	3	
C					4
Total Resources	4	3	3	3	4
Maximum Resources	5				

Table 4-10 Gantt chart for Second Subproject-Case 1

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
D	3	3			
E			1		
F			1	1	1
Total Resources	3	3	2	1	1
Maximum Resources	3				

Table 4-11 Gantt chart for Second Subproject-Case 2

Activity	D ay 1	D ay 2	D ay 3	D ay 4	D ay 5
D	3	3			
E				1	
F			1	1	1
Total Resources	3	3	2	1	1
Maximum Resources	3				

Table 4-12 Gantt chart for Second Subproject-Case 3

Activity	D ay 1	D ay 2	D ay 3	D ay 4	D ay 5
D	3	3			
E					1
F			1	1	1
Total Resources	3	3	2	1	1
Maximum Resources	3				

Second, assume that subcontractors decide to cooperate based on mutual trust by means of joint resource management. In simple words, they try to minimize the maximum resources needed for the coalition of {1, 2}. Figure 4.14 illustrate one of the possible options for subcontractors to minimize their resources and hire 6 units of resources daily to execute the project activities in total. This means a 1 unit saving in resources. Different permutations of executing activities A and E are studied and the results are shown in Tables 4.13 to 4.27. Figure 4.2 is the game tree for this cooperation example. In this game tree, Y states executing the uncritical activities (A and E) and N means not executing those activities. The five stages of the tree are because of the 5 day duration of the project and at each stage (day), subcontractors are able to execute the critical activities or not. 15 (5*3) states are possible, of which 8 states optimize the costs through cooperation. For instance, assume that the daily cost of resources is 10 units. Thus a one unit reduction in daily resources results in 50 units (1*5days*10unit/day) saving in total cost of the project. To simplify the example, Nash solution is used for allocating this profit, which assigns a 25 units to each subcontractor. The outcome of cooperation is shown as (25, 25) and not cooperating is simply shown as (0, 0).

Table 4-13 Gantt chart for Coalition of {1, 2}-Case1

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A	1				
B	3	3	3	3	
C					4
D	3	3			
E			1		
F			1	1	1
Total Resources	7	6	5	4	5
Maximum Resources	7				

Table 4-14 Gantt chart for Coalition of {1, 2}-Case2

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A		1			
B	3	3	3	3	
C					4
D	3	3			
E			1		

F			1	1	1
Total Resources	6	7	5	4	5
Maximum Resources	7				

Table 4-15 Gantt chart for Coalition of {1, 2}-Case3

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A			1		
B	3	3	3	3	
C					4
D	3	3			
E			1		
F			1	1	1
Total Resources	6	6	6	4	5
Maximum Resources	6				

Table 4-16 Gantt chart for Coalition of {1, 2}-Case4

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A				1	
B	3	3	3	3	
C					4
D	3	3			
E			1		
F			1	1	1
Total Resources	6	6	5	5	5
Maximum Resources	6				

Table 4-17 Gantt chart for Coalition of {1, 2}-Case5

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A					1
B	3	3	3	3	
C					4
D	3	3			
E			1		
F			1	1	1
Total Resources	6	6	5	4	6
Maximum Resources	6				

Table 4-18 Gantt chart for Coalition of {1, 2}-Case6

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A	1				
B	3	3	3	3	
C					4
D	3	3			
E				1	
F			1	1	1
Total Resources	7	6	4	5	5
Maximum Resources	7				

Table 4-19 Gantt chart for Coalition of {1, 2}-Case7

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A		1			
B	3	3	3	3	
C					4
D	3	3			

E				1	
F			1	1	1
Total Resources	6	7	4	5	5
Maximum Resources	7				

Table 4-20 Gantt chart for Coalition of {1, 2}-Case8

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A			1		
B	3	3	3	3	
C					4
D	3	3			
E				1	
F			1	1	1
Total Resources	6	6	5	5	5
Maximum Resources	6				

Table 4-21 Gantt chart for Coalition of {1, 2}-Case8

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A				1	
B	3	3	3	3	
C					4
D	3	3			
E				1	
F			1	1	1
Total Resources	6	6	4	6	5
Maximum Resources	6				

Table 4-22 Gantt chart for Coalition of {1, 2}-Case9

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A					1
B	3	3	3	3	
C					4
D	3	3			
E				1	
F			1	1	1
Total Resources	6	6	4	5	6
Maximum Resources	6				

Table 4-23 Gantt chart for Coalition of {1, 2}-Case11

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A	1				
B	3	3	3	3	
C					4
D	3	3			
E					1
F			1	1	1
Total Resources	7	6	4	4	6
Maximum Resources	7				

Table 4-24 Gantt chart for Coalition of {1, 2}-Case12

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A		1			
B	3	3	3	3	
C					4
D	3	3			
E					1

F			1	1	1
Total Resources	6	7	4	4	6
Maximum Resources	7				

Table 4-25 Gantt chart for Coalition of {1, 2}-Case13

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A			1		
B	3	3	3	3	
C					4
D	3	3			
E					1
F			1	1	1
Total Resources	6	6	5	4	6
Maximum Resources	6				

Table 4-26 Gantt chart for Coalition of {1, 2}-Case14

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A				1	
B	3	3	3	3	
C					4
D	3	3			
E					1
F			1	1	1
Total Resources	6	6	4	5	6
Maximum Resources	6				

Table 4-27 Gantt chart for Coalition of {1, 2}-Case15

Activity	Day 1	Day 2	Day 3	Day 4	Day 5
A					1
B	3	3	3	3	
C					4
D	3	3			
E					1
F			1	1	1
Total Resources	6	6	4	4	7
Maximum Resources	7				

Finally, in this simplified example, in 53% of conditions, mutual trust and cooperation are feasible, which results in 14% cost saving. In remaining 47% of conditions, subcontractors are not interested in cooperation since they have no monetary incentives to cooperate.

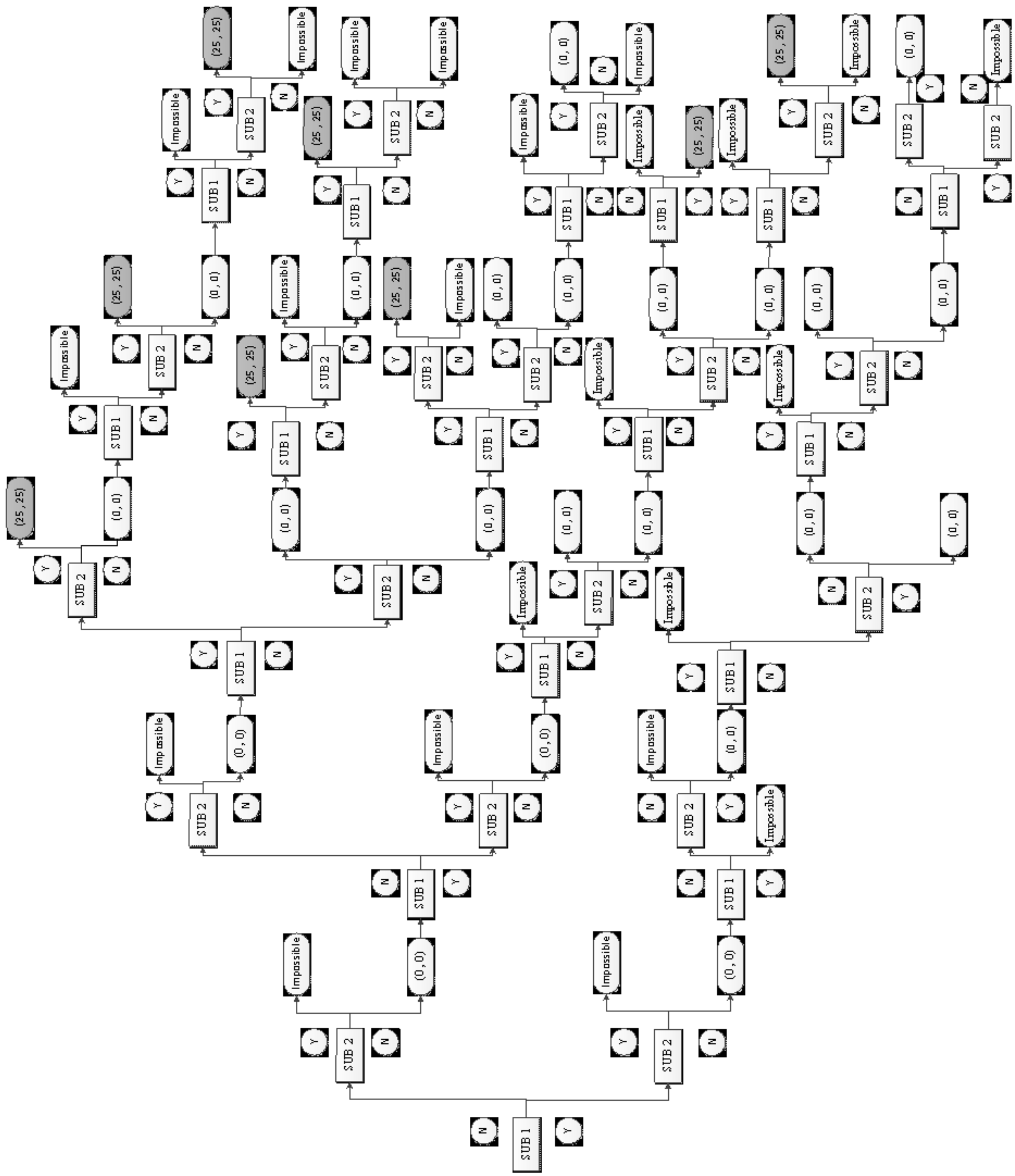

Figure 4-2 Game Tree for Cooperation Example

Conclusion

In this chapter, stag hunt game is introduced as a basis for studying the cooperation between subcontractors. The prisoner's dilemma, as well as the stag hunt game, are two well-known games for studying the coordination, trust, or cooperation between game players. In this chapter, two subcontractors are assumed as game players, playing the stag hunt game. Each player has two options to choose, cooperation or non-cooperation. While non-cooperation is a conservative option, cooperation results in a better outcome if chosen by both subcontractors. In other words, if subcontractors believe (or trust) that their peer would choose cooperation, by choosing cooperation they will receive a much higher utility in comparison to the non-cooperative act.

One of the motivations to build trust between subcontractors is the possibility of working together in the future projects. This concept is named the shadow of the future and studied in game theory to anticipate the today's behavior of a player, expecting to play with her peers in the future. In this chapter, it is explained that the shadow of the future only could affect the decisions of a player when the exact number of games played in the future is not determined. In other words, there is no difference between a one-time played game and a set of games which will be played for a finite (known) rounds.

The last section of this chapter studies a designed cooperation game and illustrates the outcomes of the game in a game tree. Sharing the common resources is the cooperative action in this game while scheduling them individually is considered the non-cooperative behavior.

Chapter 5 Case Study

Introduction

In chapter 3, several game theory solutions are reviewed and propensity to disturb, and Stability are defined. Since there is more than one solution to allocate the benefit to subcontractors, there is a need to define criteria based on which solution is expected to be selected. This chapter aims to introduce criteria to rank the solutions and to find out which solution is more recommended in cooperative construction projects, where subcontractors are willing to share the resources. For this purpose, a case study and ten other illustrative projects are defined and the data is given as input of the model. The model's output is the costs of different coalitions of the project. The difference between cooperative coalitions' cost and the individual costs for each subcontractor is the utility that is gained from that coalition. Game theory enters in this step and this utility is shared between coalition members. Running the model for 11 projects and 33 subcontractors, the utility allocation results are illustrated in several tables and using the criteria for ranking the game solution, different solutions are ranked and introduced as the most useful solutions in cooperative joint resource management problems.

Deralok Dam Project

Introduction

The Deralok Dam is a gravity dam currently being constructed on the Great Zab River just upstream of the town of Deralok in Dohuk Governorate, Northern Iraq. For its primary purpose, the dam will support a 37.6 MW run-of-the-river hydroelectric power station. Construction on the dam began in November

2015. The $129 million (USD) contract to build the dam and power station was awarded to Boland Payeh-Farab, an Iranian Consortium. It is being financed by a Japanese financing agency, called Japan International Cooperation Agency (JICA, 2015). The project is expected to be complete in mid-2019 (bolandpayeh, 2015). Table 5.1 summarizes the project attributes and figure 5.1 shows the project site located in Iraq.

Table 5-1 Project Attributes

Client	Ministry of Electricity of Kurdistan
Consulting Company	ELC ELECTRO
General Contractor	Boland Payeh-Farab
Financing Company	Japan International Cooperation Agency
Location	Kurdistan, Iraq

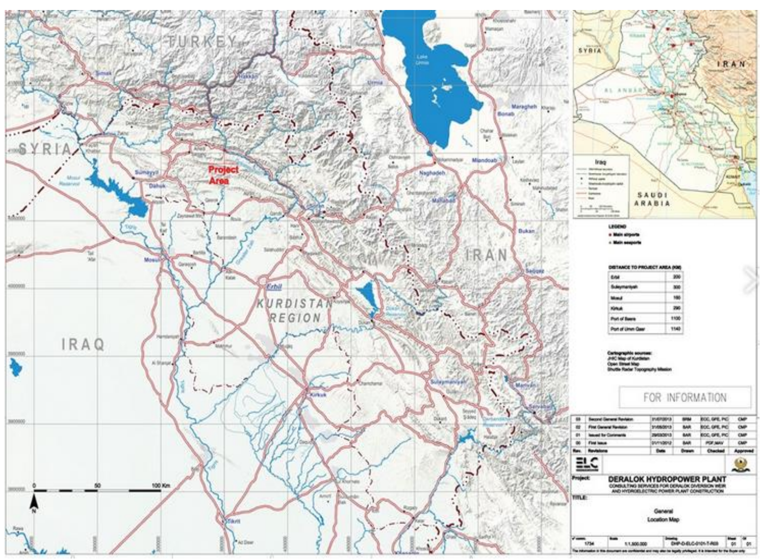

Figure 5-1 Deralok Dam Location

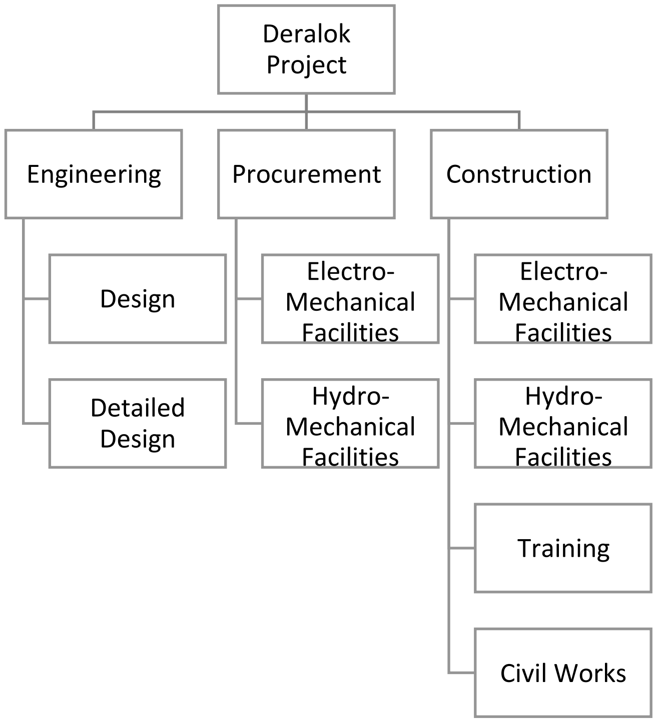

Figure 5-2 Deralok Work Breakdown Structure

This project consists of more than 1300 activities, under three engineering, procurement and construction groups. The construction work is awarded to three major subcontractors which are working with groups of suppliers and trade contractors to conduct the work. The three subprojects, undertaken by these main subcontractors, includes hydro-mechanical subproject (Sub1), electro-mechanical subproject (Sub2) and civil works subproject (Sub3). 15 activities of subproject 1, 12 activities of subproject 2, and 9 activities of subproject 3 are selected from this project, as the main activities that need common resources to be completed by the subcontractors.

Table 5.2 shows the activities of the hydro-mechanical subproject, which consists of 15 main activities. Stop logs' manufacturing and erection, Gates and trash racks' manufacturing and shop tests, Foundation excavation and concrete pouring, building cofferdams at downstream and upstream and their removal, as well as pavement and lighting systems, are some of the activities first subcontractor is responsible for completing during the first subproject. First subproject's duration is 688 days, based on the information provided in table 5.3. In this table, activities sequencing is given, defining the dependencies between subproject's activities. In addition, the resources needed to conduct each activity is given to help to calculate the costs of activities. Different types of dependencies are possible in sequencing a project's activities while in this case study, all types of other dependencies are converted to finish-to-start that is known as the simplest dependency type in scheduling a project.

Table 5-2 Subproject 1 Information

Subproject 1		
Activity ID	Activity	Activity Duration (days)
A1	Intake stop logs and ancillary equipment (Manufacturing and shop tests)	80
A2	Erection (including second phase concrete)	65
A3	Gates, trash racks and other equipment (Manufacturing and shop tests)	72
A4	Foundation excavation - right bank	60
A5	Pouring mass concrete - lower part of the weir/right bank	84
A6	Grout curtain + sewing plus drains + water tests/right shoulder	55
A7	Foundation excavation - left bank	40
A8	Pouring mass concrete - lower part of the intake and flushing channel/left bank	63
A9	Grout curtain + sewing plus drains + water tests/left shoulder	147
A10	Pouring concrete - elevation and bridge or top slabs for intake and flushing channel	84
A11	Building downstream and upstream cofferdam, first rush	35
A12	Pouring mass concrete for lower part of the weir	40
A13	Removal of the cofferdams and phase III activation	30
A14	Railing, monitoring system, pavement, lighting and finishing	21
A15	Completion of flushing intake and finishing	50

Table 5-3 Dependency and Resources Information-Subproject 1

ID	Predecessor 1	Type	Lag	Predecessor 2	Type	Lag	Predecessor 3	Type	Lag	Resources
A1										R1[2]
A2	A1	FS	0							R1,R2[3],R5
A3	A1	FS	15							R1
A4	A1	FS	21							R1,R2[3],R3[3],R5
A5	A4	FS	0							R1[2]
A6	A5	FS	5							R1[2],R2
A7	A4	FS	0							R1[2],R2[3],R3[3],R5[2]
A8	A5	FS	0	A7	FS					R1[2]
A9	A6	FS	0	A8	FS					R1[2],R2[3]
A10	A9	FS	0							R1
A11	A10	FS	3							R1[2],R2[3]
A12	A11	FS	0							R1[3]
A13	A11	FS	0							R1[3],R4[2]
A14	A12	FS	0	A13	FS					R1,R2
A15	A2	FS	0	A3	FS		A14	FS	0	R1,R2[2],R3,R4,R5[3]

The second subcontractor is experienced in the electro-mechanical field and is undertaking the subproject 2, including 12 main activities. As shown in table 5.4, the main focus is placed on manufacturing and shop testing the electro-mechanical equipment, erecting it, manufacturing two draft tubes and transporting them to the site and erecting them before assembling the tubes. Using the critical path method, same as the method used for subproject 1, and considering the dependencies summarized in table 5.5, the total duration for the second subproject is calculated as 774 days.

Table 5-4 Subproject 2 Information

Subproject 2		
Activity ID	Activity	Activity Duration (days)
B1	Electromechanical equipment (Manufacturing & shop tests)	65
B2	Erection including second phase concrete	80
B3	Powerhouse intake gates, stop logs & trash racks (Manufacturing & shop tests)	56
B4	Erection including second phase concrete	100
B5	Draft tube no.1 (Manufacturing & shop tests)	45
B6	Transportation tube no.1 to site	87
B7	Erection tube no.1	35
B8	Draft tube no.2 (Manufacturing & shop tests)	103
B9	Erection tube no.2	46
B10	Transportation to site	110
B11	Preassembly	37
B12	Erection (Stator)	20

Table 5-5 Dependency and Resources Information - Subproject 2

ID	Predecessor 1	Type	Lag	Predecessor 2	Type	Lag	Resources
B1							R1
B2	B1	FS	10				R1[2]
B3	B2	FS	5				R1
B4	B3	FS	0				R1
B5	B4	FS	7				R1
B6	B5	FS	3				R1
B7	B6	FS	1				R1
B8	B6	FS	0				R1[2]
B9	B7	FS		B8	FS		R1[2]
B10	B9	FS	0				R1[2]
B11	B10	FS	0				R1[3],R2,R3,R4
B12	B11	FS	0				R1[2],R2[2]

Subproject 3 is composed of 9 activities, including excavation and concrete work. Using the activity durations and dependencies presented in tables 5.6 and 5.7, the duration of this subproject is calculated as 465 days.

A project consisting of these three subprojects is studied in this chapter as the first case study. The total duration of the project is equal to the duration of the critical path of the project which is 774 days. Activities on the critical path are B1, B2, B3, B4, B5, B6, B8, B9, B10, B11 and B12. The precedence diagram is shown in figure 5.3, in which the critical activities are shown in grey boxes and noncritical activities in white boxes. This diagram includes total and free floats as well.

After introducing the project and its attributes, the costs of resources are assigned. As explained in the model introduction part in chapter 3, two types of costs are assigned to each resource type. Five common resources in this project are Trucks, loaders, excavators, bulldozers, and graders. Based on the literature review on equipment costs, cost of maintenance for each type of equipment is around 20-40% of rental costs for that equipment. Table 5.8 contains the cost of rent and maintenance for the resources used in this project. It must be mentioned that these data are directly extracted from procurement documents and any difference in ranges could be due to several reasons such as low resources cost in that country, low labor cost which affects the maintenance costs of the equipment and many other factors.

Table 5-6 Subproject 3 Information

Subproject 3		
Activity ID	Activity	Activity Duration (days)
C1	Excavation & supporting	76
C2	Completion work	23
C3	Double duct excavation	87
C4	Double duct concrete	65
C5	Spillway excavation & concrete	30
C6	Concreting	70
C7	Excavation & support of slopes including care of water	45
C8	Roof and completion of civil works	98
C9	Cofferdam dismantlement	23

Table 5-7 Dependency and Resources Information-Subproject 3

ID	Predecessor 1	Type	Lag	Predecessor 2	Type	Lag	Resources
C1							R1[2],R2[2],R3,R4,R5[2]
C2	C1	FS	0				R1[2],R2
C3	C1	FS	0				R1[3],R3[3],R4[2]
C4	C2	FS	0	C3	FS		R1
C5	C3	FS	0				R1[2],R2[3],R3[3]
C6	C5	SS	45				R1[2]
C7	C4	FS		C6	FS	21	R1[2],R3[3],R4[4]
C8	C7	FS					R1
C9	C8	FS					R1[2],R2

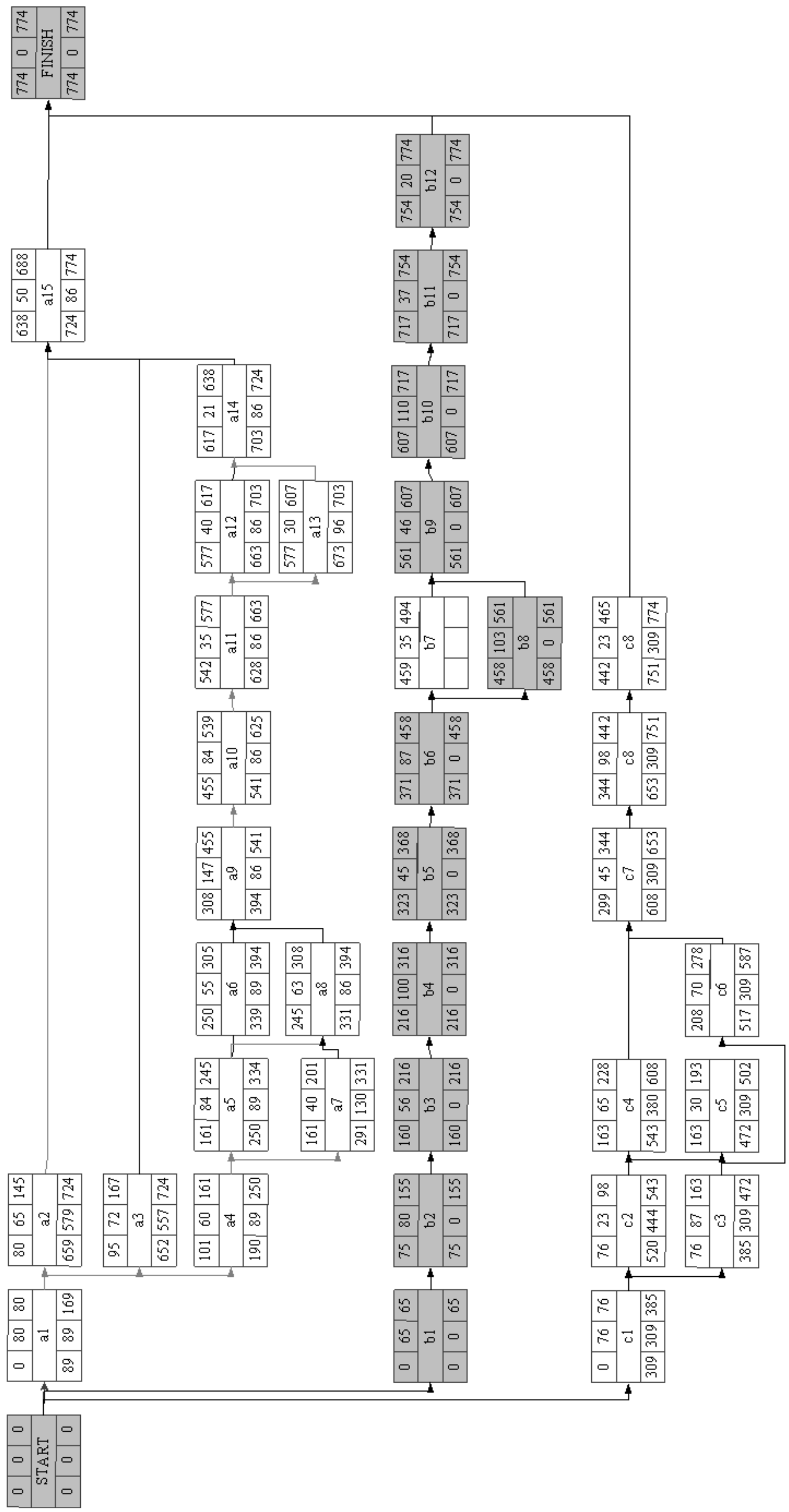

Figure 5-3 PDM for Deralok Project

Table 5-8 Resource Information

Resource ID	Type	Cost of Rent ($/day)	Cost of Maintenance ($/day)
R1	Truck	100	30
R2	Loader	150	50
R3	Excavator	250	70
R4	Bulldozer	200	80
R5	Grader	150	40

Analysis

All project data are entered to the program, organized in excel sheets, including the activity ID, duration, predecessors and successors, lag and lead, floats, types and amount of resources. In a separate sheet, the resources' costs are entered as well as the data related to the genetic algorithm. The program asks for the members of the coalition. In first three tries, an individual subcontractors' costs are optimized by considering a fixed duration for the whole project. The results are shown in table 5.9. As shown in that table, costs of resources for subprojects 1 and 3 are about two times of subproject 2. Even though subproject 2 is the longest subproject among the three subprojects, it needs fewer resources in comparison to other subprojects. This is also the reason for having less total costs in comparison to others.

For the next step, two member coalitions are defined, which are {1, 2}, {1, 3} and {2, 3}. The model is managing joint resources to optimize the costs without affecting the project duration. Based on the results shown in table 5.9, these coalitions are able to save costs up to 16.3%, 12.1% and 11.8% of the original costs of coalitions.

In the last step, the program is asked to minimize the costs for the grant coalition, consisting of all three subcontractors and outcome is a considerable amount of 26.7% saving in project costs.

This number proves that the grand coalition leads subcontractor to have the greatest collaboration since the percentage of saving through this coalition is the biggest among all coalitions.

Table 5-9 Coalitions' Costs

Coalition	Costs of Resources ($)	Utility ($)	(%) Utility percentage
{1}	959,500	0	0
{2}	494,860	0	0
{3}	952,780	0	0
{1, 2}	1,250,860	203,500	16.3
{1, 3}	1,705,880	206,400	12.1
{2, 3}	1,294,540	153,100	11.8
{1, 2, 3}	1,900,240	509,600	26.7

After optimizing the costs for the case study, there is an important question to answer. How game solutions allocate the utility to each of the subcontractors? Using the equations introduced in chapter 3, the game profit is divided between subcontractors as shown in table 5.10. The Shapley solution assigns the largest profit to subcontractor 1, followed by subcontractors 3 and 2. The Nash-Harsnayi solution does not differentiate between any of the players and allocates an equal amount to each of the subcontractors. All the other solutions are working with two concepts of pivotal and critical player which are explained in chapter 3. According to none of these solutions, subcontractor 2 is neither the pivotal nor the critical and it receives nothing as the cooperation profit. The next arising question is that how this subcontractor should be motivated to cooperate with subcontractors 1 and 3 since those two subcontractors are not able to save more than 206,400$ if subcontractor 2 leaves. In other words, the grand cooperation has nothing to offer to subcontractor 2 if it is decided to allocate the cooperation utility based on solutions other than the Shapley or the Nash-Harsanyi.

Table 5-10 Utility Allocation to Each subcontractor

Project	C	Shapley	Nash-Harsanyi	Shapley-Shubik	Banzhaf	Johnston	Deegan-Packel	Holler-Packel
Deralok		186250	168967	253450	253450	253450	253450	253450
		159600	168967	0	0	0	0	0
		161050	168967	253450	253450	253450	253450	253450

Using the equation for propensity to disrupt, table 5.11 is built. As expected, subcontractors 1 and 2 have the same propensity to disrupt throughout any solutions except the Shapley and the Nash-Harsanyi. The Nash solution does not differentiate between players and all three subcontractors have same propensity to disrupt. While the Shapley solution assigns a higher utility to the first subcontractor, the propensity to disrupt is completely the opposite of it. By omitting subcontractor 2, the grant coalition is affected the most and that is why this subcontractor has a higher propensity to disrupt among three subcontractors.

Table 5-11 Propensity to Disturb Using Different Game Solutions

Project	C	Shapley	Nash-Harsanyi	Shapley-Shubik	Banzhaf	Johnston	Deegan-Packel	Holler-Packel
Deralok		1.7	2	1	1	1	1	1
		2.2	2	N.D.	N.D.	N.D.	N.D.	N.D.
		2.1	2	1	1	1	1	1

Discussion

As seen above, in this example, the grand coalition, consisting of all three subcontractors, offers the greatest saving in costs of resources which is equal to 26.7% of original costs of resources when each subcontractor works individually and no cooperation exists. This saving is called profit and divided among three subcontractors. Seven game solutions introduced in chapter 3 are applied for this purpose. Shapley solution is the first solution to apply. This solution is based on difference in project costs, with/without a subcontractor's participation. In other words, $v(S \cup \{i\}) - v(S)$ that is the difference in the utility of the coalition S when subcontractor i joins the coalition and when she is not participating in the coalition. Using this solution, subcontractor 2 has the greatest effect on the coalition cost, followed by subcontractor 2 and 3. This causes receiving more profit by subcontractor 2 in comparison to subcontractors 3 and 1. The next solution is the Nash-Harsanyi solution, which is trying to maximize the product of profits, $\prod_{i=1}^{3}\left(v(i)\right)$, ending up in allocating an equal amount to each subcontractor. Taking a look at subcontractor 2's costs of resources and comparing it with other coalitions, shows that this subcontractor is neither critical nor pivotal in this example. This means that subcontractor 2 gets nothing as profit due to its dummy role. In other words, the profit gained in the grand coalition is divided equally between subcontractors 1 and 3, using any of the other 5 solutions. The conservative suggestion of this study is to use either of Shapley or Nash-Harsanyi solutions to achieve the saving in costs. Allocating no profit to subcontractor 2 makes the grand coalition extremely unstable. The other suggestion to subcontractors 1 and 3 is to negotiate with subcontractor 2 and offer his/her an acceptable amount, to gain his/her consent to form the grand coalition.

Illustrative Examples

Introduction

An example was used in chapter 3, to explain the designed model. In this chapter, 9 more examples are designed, which are similar to that example. The main purpose was to define different dependencies between activities, and assigning different resources while having the same scale as the original example. Each project's information is given in a table, containing the subcontractors, the activities each subproject consists of, activities' duration, the predecessors or successors of each activity and the number of common resources they need. An important column in this table is the float for each activity which is calculated through critical path analysis. Project's information tables are available in the appendix.

Analysis

The projects' information is given to the program as the model input. Considering the objective function of the model, the costs of different coalitions are extracted as the output. This procedure is conducted for all of the 10 projects. Applying game solutions, the utility is divided between subcontractors. The propensity to disrupt is the most critical factor considered in this study and calculated for each subcontractors. Table 5.12 summarizes the propensity to disrupt for each subcontractor, applying different game solutions.

As shown in table 5.12, each solution results in a different propensity to disrupt for each subcontractor. For instance, consider project 1. By applying the Shapley solution, the propensity to disrupt for subcontractors 1 to 3, is 2.6, 1.5 and 2.11 consecutively. Using the Nash solution, subcontractors 1 to 3, have an equal propensity to disrupt, while the Shapley-Shubik solution is assigning amount of 5 to both subcontractors 1 and 3, and 0.5 to subcontractor 2. Figure 5.2 illustrates the different solution's allocation to different subcontractors in project 1.

Table 5-12 Propensity to Disturb Using Different Game Solutions

Project	C	Shapley	Nash-Harsanyi	Shapley-Shubik	Banzhaf	Johnston	Deegan-Packel	Holler-Packel
1		2.6	2	5	4	3.67	2.6	2.5
		1.5	2	0.5	0.67	0.75	1.25	1.33
		2.11	2	5	4	3.67	2.6	2.5
2		1.67	2	2	2	2	2	2
		1.67	2	2	2	2	2	2
		3	2	2	2	2	2	2
3		2.93	2	5	4	3.67	2	2.5
		1.16	2	0.5	0.67	0.75	2	1.33
		2.54	2	5	4	3.67	2	2.5
4		5	2	2.5	2	2	2	2
		1.4	2	6	2	2	2	2
		1.4	2	0.75	2	2	2	2
5		1.06	2	1	1	1	1	1
		3.02	2	1	1	1	1	1
		2.77	2	-	-	-	-	-
6		1.83	2	5	4	3.67	2.6	2.5
		1.65	2	0.5	0.67	0.75	1.25	1.33

		2.72	2	5	4	3.67	2.6	2.5
7		1.2	2	2	2	2	2	2
		1.78	2	2	2	2	2	2
		4.37	2	2	2	2	2	2
8		2.93	2	-	-	-	-	-
		1.16	2	1	1	1	1	1
		2.54	2	1	1	1	1	1
9		2.33	2	2	2	2	2	2
		1.86	2	2	2	2	2	2
		1.86	2	2	2	2	2	2
10		1.19	2	0.5	0.67	0.75	1.25	1.33
		3.58	2	5	4	3.67	2.6	2.5
		2.07	2	5	4	3.67	2.6	2.5

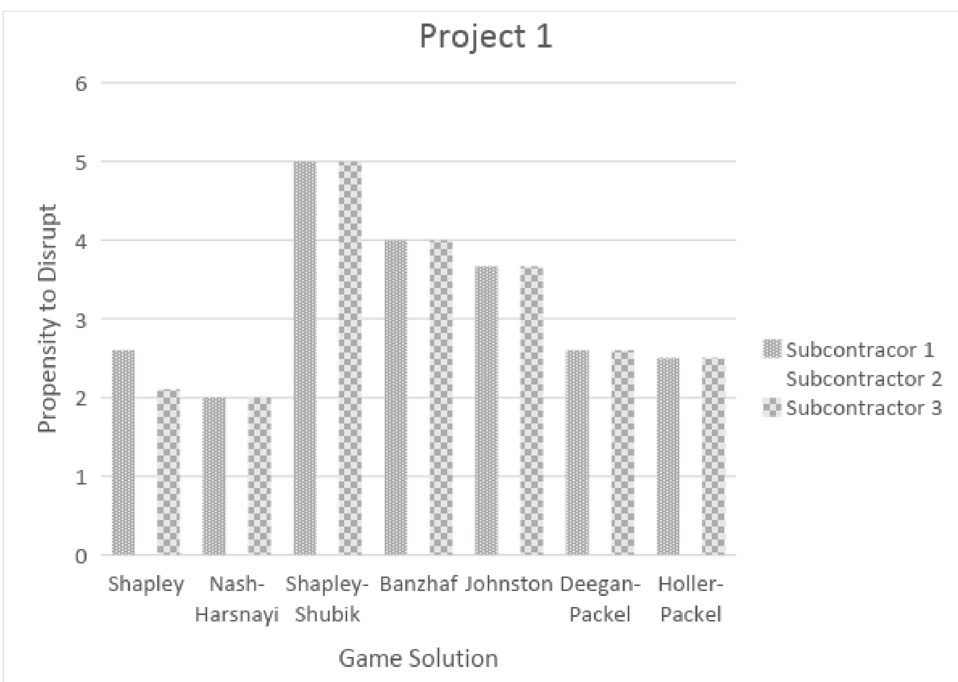

Figure 5-4 Propensity to Disrupt for each Solution and each Subcontractor in Project 1

To measure the effectiveness of each solution in allocating utility to each subcontractor, different criteria are defined and used in following:

1. Using the highest propensity to disrupt

One strategy could be based on the maximum of d_i allocated to each subcontract through applying a specific strategy. In other words, this criterion's main focus is on introducing the ranking of solutions based on the maximum propensity to disrupt each contractor has using that solution. Subcontractors having high propensity to disrupt have the power to leave the coalition, and this power makes the coalition unstable. For the 10 illustrative examples of this chapter, this criterion is applied to rank game solutions and the results are shown in table 5.13 and figure 5.3.

Table 5-13 Ranking of Game Solutions Based on Maximum of Propensity to Disrupt

Solution	Shapley	Nash-Harsanyi	Shapley-Shubik	Banzhaf	Johnston	Deegan-Packel	Holler-Packel
Max (di)	5	2	6	4	3.67	2.6	2.5
Rank	7	1	6	5	4	3	2

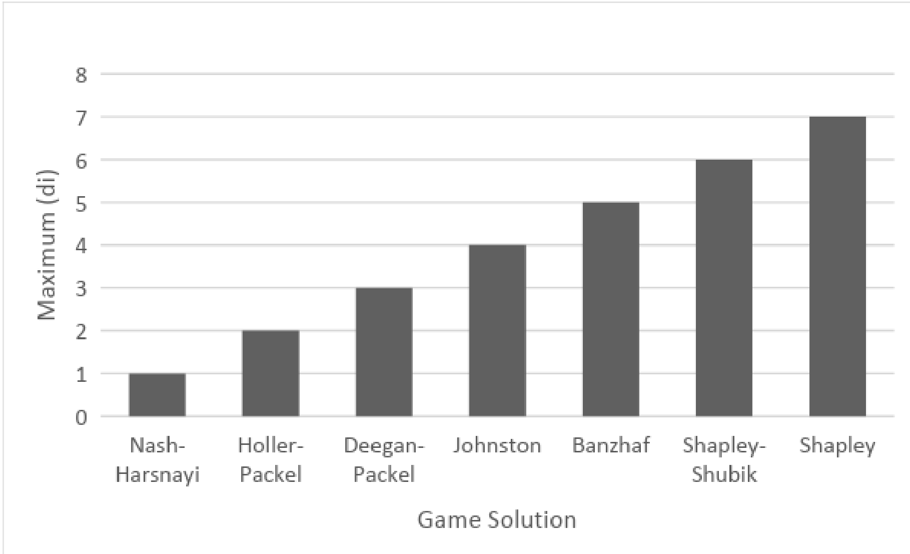

Figure 5-5 Ranking of Game Solutions Based on Maximum of Propensity to Disrupt

2. Using the maximum and minimum amounts of propensity to disrupt

Another criterion to make a decision based on it is the difference between the highest and the lowest amounts of propensity to disrupt using equation 5.1. In comparison to the first criterion, this one provides a better insight to decide on which game solution to choose. A solution having a greater D(A) is less stable and the players are more inclined to leave the coalition.

$$D(A) = Max\,(d_i) - Min(d_i) \quad (5.1)$$

Ranking of solutions does not change using either of criteria except for the Shapley and Shapley-Shubik solutions. The other solutions including Nash-Harsnayi and Holler-Packel solutions have the same ranking due to either the maximum or the difference between maximum and minimum amounts. Solutions' ranking is presented in table 5.14 and figure 5.6.

Table 5-14 Ranking of Game Solutions Based on the Max. and Min. of di

S olution	hapley	Nash- Harsanyi	Shaple y-Shubik	B anzhaf	J ohnston	Deega n-Packel	Holl er-Packel
M ax (di)		2	6	4	3 .67	2.6	2.5
M in (di)	.06	2	0.5	0 .67	0 .75	1	1
D (A)	.94	0	5.5	3 .33	2 .92	1.6	1.5
R ank		1	7	5	4	3	2

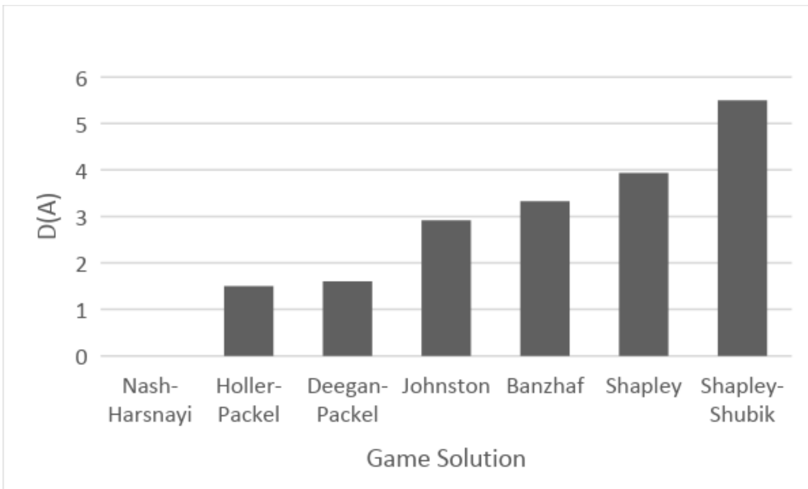

Figure 5-6 Ranking of Game Solutions Based on the Max. and Min. of di

3. Using standard deviation and mean

The last strategy is to introduce a dimensionless parameter to rank the stability of the solution. Through this strategy, the stability of an allocation is measured using equation (5.2), where the standard deviation of propensity to disrupt is divided by the average propensity to disrupt, resulting in a dimensionless parameter.

$$S_A = \frac{\sigma(d_i)}{\overline{d_i}} \quad (5.2)$$

The game solutions are ranked using this dimensionless parameter, and the results are presented in table 5.15. The first three solutions, the Nash-Harsanyi, the Holler-Packel and the Deegan-Packel are still the most stable solutions among the game solutions used for utility allocation. The ranking for game solutions based on the third criterion is demonstrated in figure 5.7. In addition, table 5.16 and figure 5.8 show the ranking for different solutions based on each of the three criteria.

Table 5-15 Ranking of Game Solutions Based on the Difference between S(A)

Solution	Shapley	Nash-Harsanyi	Shapley-Shubik	Banzhaf	Johnston	Deegan-Packel	Holler-Packel
S(A)	0.421	0	0.694	0.544	0.495	0.273	0.272
Ranking	4	1	7	6	5	3	2

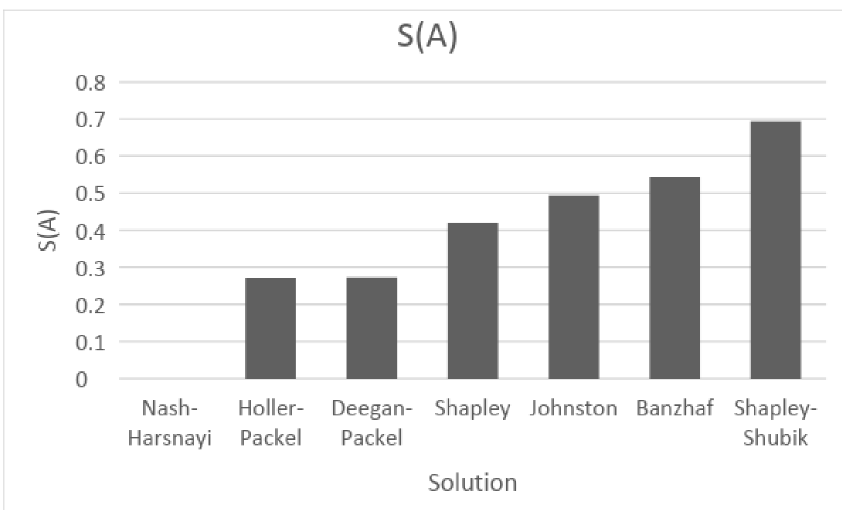

Figure 5-7 Ranking of Game Solutions Based on the Difference between S(A)

Table 5-16 Ranking of Game Solutions Using Different Criteria

Solution	Nash-Harsanyi	Holler-Packel	Deegan-Packel	Johnston	Banzhaf	Shapley	Shapley-Shubik
S(A)	1	2	3	5	6	4	7

D (A)	1	2	3	4	5	6	7
M ax	1	2	3	4	5	7	6

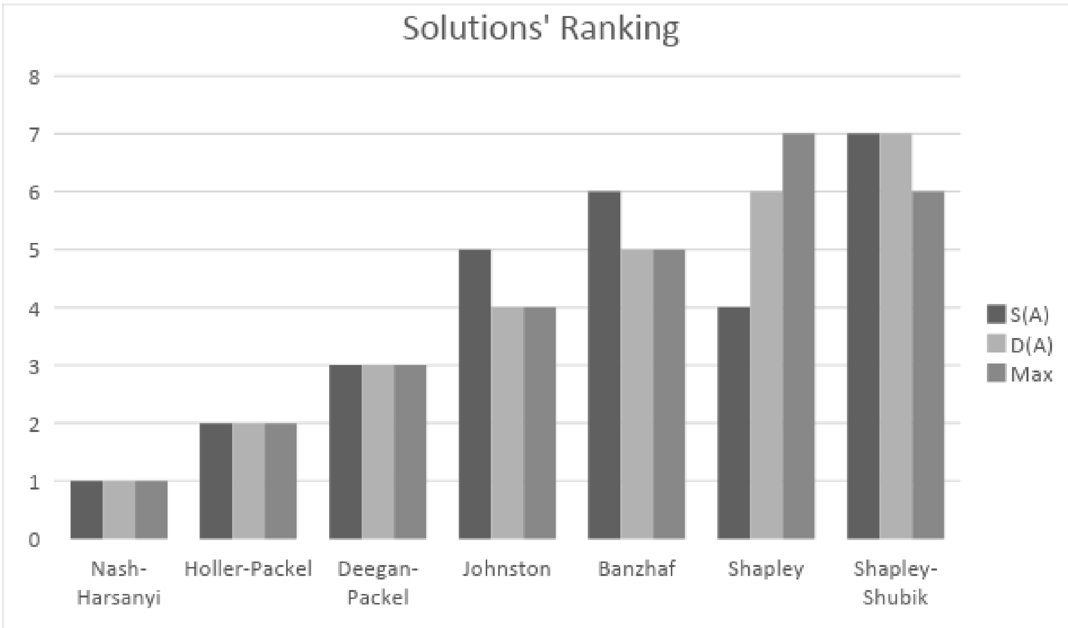

Figure 5-8 Ranking of Game Solutions Using Different Criteria

Conclusion

This chapter has studied a set of examples, including a case study and 10 illustrative examples to understand the ranking of different solutions and introduce the most stable solution. Stability is one of the factors that guarantees that cooperative decisions will be made to the end of the project and none of the subcontractors is willing to leave the collaboration. In the first project, one of the subcontractors are executing all the critical activities and has no recognizable contribution to the grand coalition. This makes the solutions not to allocate any profit to that subcontractor. In the second set of examples, 10 projects are designed and the model is applied to those projects. By ranking the game solution used for profit sharing, the

Nash solution is determined as the most stable solution. The next solutions are the Holler-Packel, Deegan-Packel, Johnston, Banzhaf, Shapley, and the Shapley-Shubik. If the only significant factor for decision making is the stability of the game solution, this ranking provides an insight into the game players' decision with regards to which solution to choose.

Chapter 6 Conclusion

Joint resource management helps the subcontractors working on heavy projects including highway or railway projects, dam projects, and utility distribution projects to manage their common equipment as a pool and optimize the costs of resources.

In today's highly competitive construction industry, resource management is one of the necessary activities in project management. Optimizing the costs of resources will help the project manager to gain a competitive advantage for the company's project. This study has introduced joint resource management as one of the solutions to optimize costs of resources in a cooperative manner. Even though cooperation is one of the topics studied in construction projects in the last 15 years, joint resource management is a new area that is barely studied. This study defines joint resource management as follows:

Joint resource management is based on cooperation between different subcontractors involved in a construction project, managing the common resources together as a pool of resources to achieve the most efficient resource employment. The main objective of this cooperation is to optimize costs of resources by decreasing their idle time and lowering total costs of resources. Subcontractors are individuals or firms who contract to perform a part of a contract's work. The main reasons for subcontracting the work to subcontractors are their expertise and experience in the specified field of the contract, sharing the risks of projects and lowering the costs and time of the project. By entering into cooperation, subcontractors agree on working together to achieve the business objectives of the cooperation which is considered as a whole, instead of several individuals. The literature review states that by cooperation, subcontractors are able to lower project costs by 30%.

The main objective of this research is to optimize the costs of resources in a cooperative environment by means of game theory. One definition for game theory defines it as a mathematical model for studying the cooperation and also conflicts between rational players. This strong tool is being used in a vast area of science, from biology to economics and psychology to engineering. For the purpose of using game theory to study a problem, three essential components of a game must be first identified. These components are:

1. At least two individual who are concerned in the problem. They are called players of the game in this framework.
2. Set of actions each player is able to follow. These actions or decisions are called strategies of players.
3. The result of each strategy and a value associated with each result which is called the payoff of the game.

Rationality is the foundation for game theory. Rational players always try to take actions in order to maximize their own payoff. This is mentioned in this study that there is a difference between what we expect from the behavior of players in comparison with how they behave in reality. This difference is caused by the underlying assumption of game theory which assumes that all of the players are rational however real-life examples has proved that human beings are not perfectly rational. The psychology of the brain of real players is different from a rational player and this causes a gap between how they should act and how they really act in any conflict.

There is also a difference between robots and humans as game players. Although it is easy to measure the utility for an emotionless player, satisfaction or happiness resulted from an outcome for a human is difficult to measure. There are too many factors affecting how to interpret satisfaction for players whose mental system of values and attitudes are different, and this difference makes the utility a complex concept in the game theory.

In this study, the payoff of the game is the savings in the costs of resources which is achievable through different strategies grouped under the concept of join resource management. In joint resource management, subcontractors try to schedule their assigned activities to minimize the number of idle resources which results in decreasing the costs of resources. Idle resources are the outcome of providing the maximum number of resources needed during a specified period of project execution. In this study, a period of 30 days is assumed for the employing or releasing the equipment type of resources needed for the project. Due to high costs of transportation for equipment and in situations resources are scarce, and for the purpose of managing them easily, project managers do not employ or release resources daily. This monthly employment of resources, cause having idle resources on project site. Join resource management focuses on minimizing this idle resources by controlling the maximum resources employed in each period.

A mathematical model is designed in this research by means of optimizing the costs of resources. These costs are grouped into rental costs and maintenance costs. It is assumed that the maintenance cost is only for the resources in use and idle resources do not require any maintenance. To solve the optimization problem, genetic algorithm is used and the solution is coded using the visual basic as the programing language. In GA, a population of candidate solutions which are the start dates of activities, is evolved to find the best solution. For each subcontractor, each chromosome is associated with a single activity, and list of all activities, their duration, floats, and resources needed. The first population is composed of activities considering the earliest start for each activity. The cost of each subproject is calculated and saved as the fitness for the first population. Considering the rates of elitism, and crossover and mutation a new generation is produced. In the new generation, activities might use their float and start later than their earliest start. The fitness of new generation is again calculated and this process is repeated iteratively to reach an idle generation that owns the best fitness which is the lowest cost of resources in this study.

For the purpose of joint resource management, GA works in a different way. Instead of working on individual subproject, each population consists of activities of the collaborating subcontractors. For instance, for optimizing the costs of the collaboration of {1,2}, activities of both subprojects 1 and 2 are given as the chromosomes of the GA. The fitness is defined based on the overall cost of the collaboration instead of the cost of individual subprojects. The final output of running the code for different collaborations is the optimized cost of resources for each collaboration.

The next important step is to divide the savings in cost of resources (called utility or profit) between each collaboration’s members. An important question to answer in this step is how this profit is allocated to each subcontractor. Game solutions are used in this step to address different answers to this question. In this study, seven game solutions are introduced. These solutions, based on cooperative games, try to provide insight in allocating the profit between players, each on different considerations. For example, while the Nash-Harsanyi solution is dividing the profit equally between players, the Banzhaf solution is based on the definition of the critical player. To illustrate more, case studies will be reviewed.

The first case study in chapter 5 is a dam project located in Iraq. This dam, named Deralok, is awarded to an Iranian contractor to be constructed. The main contractor is performing the work under three subprojects named hydro-mechanical (subproject 1), electro-mechanical (subproject 2) and civil works (subproject 3). A few number of these subprojects' activities are selected and studied applying the designed model in this study. 36 main activities are selected, given their sequencing, duration, and resources needed. Five common resource types between these subprojects are trucks, loaders, excavators, bulldozers, and graders. Costs of rent and maintenance for each resource type is given in the project documents. The projects' information is given to GA as the input to build the first generation of chromosomes. After running the GA, for seven different coalitions {1}, {2}, {3}, {1,2}, {1,3}, {2,3}, {1,2,3} the costs of resources for each coalition is gained as the output of the program. The grand coalition consisted of all three subcontractors, offers the greatest saving in costs of resources, equal to 26.7%. The next step is to divide these saving between subcontractors. Shapley solution is the first solution to apply. This solution is based on the difference in project costs, with/without a subcontractor's participation. In other words, $v(S \cup \{i\}) - v(S)$ is the difference in the utility of the coalition S when subcontractor i is in/out of the coalition. Using this solution, subcontractor 2 has the greatest effect on the coalition cost, followed by subcontractor 2 and 3. This causes allocating more profit to subcontractor 2 in comparison to subcontractors 3 and 1. Next solution to apply is the Nash-Harsanyi, which is allocating an equal amount to each subcontractor. The purpose of this solution is to maximize the product of profits, $\prod_{i=1}^{3}(v\ (i\ ))$.

Taking a look at subcontractor 2's costs of resources and comparing it with other coalitions, shows that this subcontractor is neither critical nor pivotal in this example. This means that subcontractor 2 gets nothing in profit allocation between subcontractors due to its dummy role. Therefore the profit is divided equally between subcontractors 1 and 3, using any of the other 5 solutions. The conservative solution suggested in this study is to use either of Shapley or Nash-Harsanyi solutions to achieve the saving in costs. Allocating no profit to subcontractor 2 makes the grand coalition extremely unstable and decreases the chance of forming the coalition.

The second section of the fifth chapter is studying 10 illustrative examples. The first example, is the same example used in the third chapter to explain the model, and the other 9 projects are projects in the same frame, for which the sequence of activities, their durations, and the critical paths are changed, still staying in a similar range of duration and resources in comparison to first example. The same process, as done for the Deralok case study, is applied and the outcome of running the program is achieved. After profit allocation between subcontractors, calculation of propensity to disrupt for each subcontractor is done and the final result is shown in a table, including all 10 projects, 30 subcontractors and the propensity to disrupt assigned to each subcontractor applying a different game solution. The next step is to interpret the results in order to identify the most stable solutions. Three different criteria are defined for this purpose. The first criterion is based on the maximum propensity to disrupt found between 30 subcontractors using each game solution. The results illustrate that the Nash-Harsanyi solution has the least maximum amount of propensity to disrupt which means subcontractors are most satisfied applying this solution. The holler-Packel solution, Deegan-Packel, Johnston, Banzhaf, Shapley-Shubik, and Shapley are the next stable solutions regarding this criterion. Since it is possible that there might be a great difference between the minimum and the maximum amount of propensity to disrupt, the second criterion is based on the difference between those two amounts. Again regarding this criterion, the order of stability of solutions is the same as for the first criterion, except for the last two solutions, the Shapley and the Shapley-Shubik. The last criterion is to introduce a dimensionless parameter, the ratio of standard deviation to mean of propensity to disrupt. Using this parameter, game solutions are ranked and the results are almost same as the other two criterion. The most stable solution is the Nash-Harsanyi, followed by Holler-Packel, Deegan Packel, Shapley (which is the last according to the first solution), Johnston, Banzhaf, and Shapley-Shubik solution. These three rankings introduce the Nash-Harsanyi solution as the most stable solution in this set of examples and the Shapley solution as the least stable game solution.

To conclude based on these two sections, the Deralok dam, and the set of illustrative examples, there is no unique ranking for different solutions. Each project is a unique game, and different subcontractors play different roles of the dummy, critical or pivotal, which results in different propensity to disrupt for them. Using the dimensionless parameter introduced in the fifth chapter is a better means to find out the order of stability for different solutions. While the Nash-Harsanyi solution is the most stable solution, it could not be suggested as the best solution in allocating the game profit between players of all games. For each cooperation game, the procedure suggested in this study must be applied and the ranking of different solutions extracted.

Game theory is also used to analyze the cooperation between contractors using the stag hunt game. This game, called the cooperation game, is one of the widely used games to study the cooperation and between game players. In this study, two subcontractors are assumed as game players, playing the stag hunt game, having two options to choose from. The first option is cooperating with the other subcontractor in order to achieve the highest utility possible in the joint resource management, and the second option is non-cooperation, or in other words scheduling the subproject individually. While the first option results in a better outcome, it is risky and requires trust between subcontractors.

One of the motivations to build this trust is the possibility of mutual projects in the future. This concept, called the shadow of the future has been studied in game theory to anticipate the behavior of players who are willing to play games in the future. This study elaborates this concept and its effect on the cooperation problem. It also offers strategies for subcontractors based on the infinite rounds of the games played with their peers.

Future Research

This study provides useful insight to understand the cooperation between subcontractors in the construction industry. A model is presented to analyze this topic considering the simplifications needed. To extend this research, future studies should focus on a couple of areas to make the constructed model closer to real situations.

1. Define stochastic duration for each activity instead of deterministic duration. Another suggestion is to derive three estimations for each activity, named pessimistic, optimistic and most likely durations for each activity and apply Program Evaluation and Review Technique (PERT).

2. Splitting the activities based on project manager's opinion. By splitting a task, it can be stopped and the assigned resources could be released. This helps the subcontractors to reduce the maximum resources they need temporarily and might be helpful to reduce the total costs of resources.

3. Case studies in which more subcontractors are assigned to execute the work. As the number of players in a game increase, the game becomes more complicated.

4. One of the important questions to answer is that "Who provides resources to be shared?" In future research, the possible resource provision suggestion should be addressed. One possible suggestion is that common resources could be provided by the general contractor and under its supervision, the joint resource management could be applied. However, this solution might not be applicable for all projects where one of the main reasons for subcontracting the project by general contractors is to use the subcontractors' resources.

5. A sensitivity analysis could be conducted to examine the extent to which model outcomes are affected by changes in rental and maintenance costs and their ratio. The hypothesis to be studied could be stated as "The joint resource management is more feasible if rental/maintenance costs increase".

Appendix

Visual Basic Code

```
// Win32Project1.cpp : Defines the entry point for the console application.

//


#include "stdafx.h"

#include <iostream>

#include <math.h>

#include <string.h>

#include <conio.h>

#include <time.h>

#include <stdio.h>

#include <stdlib.h>

#include <fstream>

using namespace std;


#define NOA 19

#define MNOO 6

#define MNOP 4

#define MNOS 4
```

```
#define ROM 111

#define ING 1111

#define MNOG 11

#define MNOC 201

#define IC 0.5

#define TMAX 250

#define CMAX 300

#define NOR 20

#define NOE 20

#define TaxnOverheadRate 0.17

#define AdvPayment 9.7

#define MobiiCost 3.5

#define MBondCost 0.9

#define Markup 0.2

#define AdvRetain 3

#define Retaining 0.1


//NOA=Number of Activities+1 MNOO=Maximum Number of Options+1

//MNOP=Maximum Number of Predecessors+1 MNOS=Maximum Number of Successors+1

// ROM=Rate OF Mutation   ING= Initial Number Of Generation

// MNOG=Maximum Number of Generations+1

// MNOC=Maximum Number of Chromosomes+1
```

```
// IC=Indirect Cost

// TMAX=Max Duration    CMAX=Max Cost

//NOR= Number of Reproductions

//NOE= Number of Elitism

//Chromosomes : this class contains the answers and is the main class of the program

class Option

{

public:

        double c; //c=cost

        int d; //d=duration

};

class Activity

{

public:

        Option opt[MNOO];

        int actc, ES, EF, LS, LF, NOP, NOS, pre[MNOP], suc[MNOS], CON, noo;//ES=Early Start ...

LF ... , actc=Activity Code

        //NOP=Number of Predeccessors NOS=Number of Successors

        //CON=Current Option Number

};

Activity PD[NOA]; //PD=project data

class chromosome
```

```
{
public:
	int gen[NOA - 1], td; //td=Total Duration, tc=Total Cost, noo=Number of Options
	double tc, profit;
	double cost[TMAX], cash[TMAX];
	double fitness;
};
chromosome ch[MNOC];
/////////////////End Classs////////////////////////


//////////////////Start Functions/////////////////
void ShowChormosome(int start, int finish)
{
	for (int i = start; i < finish; i++)
	{
		cout << "T:" << ch[i].td << " C:" << ch[i].tc << " fitness:" << ch[i].fitness;
		cout << "  ch: ";
		for (int j = 1; j < NOA; j++)
			cout << ch[i].gen[j];
		cout << endl;
	}
}
```

```
bool IsSame(chromosome x, int chNum)
{
	bool Is = true;
	if (chNum > 1)
	{
		for (int i = 1; i < chNum; i++)
		{
			Is = true;
			if (x.td == ch[i].td && x.tc == ch[i].tc)
			{
				for (int j = 1; j < NOA; j++)
					if (x.gen[j] != ch[i].gen[j])
						Is = Is & false;
				if (Is == true)
				{
					/*cout << i << " = " << chNum << endl;
					ShowChormosome(i, i + 1);
					ShowChormosome(chNum, chNum + 1);*/
					_getch();
					return Is;
				}
			}
```

```
                    else
                        Is = false;
                }
            }
            else Is = false;
            return Is;
}
int GetMax(int a[MNOP], int limit)
{
            int Max = 0;
            for (int i = 1; i <= limit; i++)
                if (a[i] > Max)
                    Max = a[i];
            return Max;
}
int CalES(int pre[MNOP], int preNum)
{
            int EF[MNOP];
            for (int i = 1; i <= preNum; i++)
                EF[i] = PD[pre[i]].EF;
            return GetMax(EF, preNum);
}
```

```
chromosome CPM(chromosome x)
{
	int i;
	PD[1].ES = 0;
	PD[1].EF = PD[1].ES + PD[1].opt[x.gen[1]].d;
	for (i = 2; i < NOA; i++)
	{
		PD[i].ES = CalES(PD[i].pre, PD[i].NOP);
		PD[i].EF = PD[i].ES + PD[i].opt[x.gen[i]].d;
	}
	//PD[NOA - 1].LF =  PD[NOA - 1].EF+PD[NOA-1].opt[x.gen[i]].d;
	//PD[NOA - 1].LS = PD[NOA - 1].EF + PD[NOA - 1].opt[x.gen[i]].d;
	x.td = PD[NOA - 1].EF;
	return x;
	//to be continued...
}
int RandOption(int AN)
{
	return (rand() % PD[AN].noo) + 1;
}
double CalTCost(chromosome x)
{
```

```
	double tc = 0;
	for (int i = 1; i < NOA; i++)
		tc = tc + (PD[i].opt[x.gen[i]].c);
	tc += (IC*x.td);
	//cout << tc << " td-->"<<x.td<< endl;
	return tc;
}
int CalTDuration(chromosome x)
{
	return CPM(x).td;
}
void sortFitness(int NNDA, int limit)
{
	int i = NNDA, j = 0;
	chromosome hold;
	for (i = NNDA + 1; i < limit - 1; i++)
		for (j = i + 1; j < limit; j++)
			if (ch[i].fitness >= ch[j].fitness)
			{
				hold = ch[i];
				ch[i] = ch[j];
				ch[j] = hold;
```

```
				}
}
int sort(int limit)//sorts and returns number of non-dominated answers
{
	int i = 0, j = 0;
	chromosome hold;
	for (i = 1; i < limit - 1; i++)
		for (j = i + 1; j < limit; j++)
			if (ch[i].td >= ch[j].td)
			{
				if (!(ch[i].td == ch[j].td && (ch[i].tc <= ch[j].tc)))
				{
					hold = ch[i];
					ch[i] = ch[j];
					ch[j] = hold;
				}
			}
	int NNDA = 1;//NNDA=number of Non-Dominate Answer;
	double d = ch[1].td;
	for (i = 2; i < limit; i++)
		if (ch[i].td > d)
		{
```

```
                    NNDA++;
                    hold = ch[i];
                    ch[i] = ch[NNDA];
                    ch[NNDA] = hold;
                    d = ch[NNDA].td;
                }
        sortFitness(0, NNDA + 1);
        return NNDA;
}
void UpdateProfit(int x)//x:chromosome number
{
        int i, j, l = AdvRetain;
        double remaining = 0;
        for (i = 0; i <= TMAX; i++)
        {
                if (i <= ch[x].td + 1)
                        ch[x].cost[i] = IC;
                else ch[x].cost[i] = 0;
                ch[x].cash[i] = 0;
        }
        for (i = 1; i < NOA; i++)
        {
```

```
                for (j = PD[i].ES + 1; j <= PD[i].EF + 1; j++)
                        ch[x].cost[j] = ch[x].cost[j] + (PD[i].opt[ch[x].gen[i]].c /
PD[i].opt[ch[x].gen[i]].d);
        }
        ch[x].cost[0] = MobiiCost + MBondCost;
        ch[x].cash[0] = AdvPayment - (MobiiCost + MBondCost);
        remaining += ch[x].cost[0] * (1 + Markup) * Retaining;
        ch[x].cash[5] = ch[x].cost[0] * (1 + Markup)*(1 - Retaining) - (AdvPayment / AdvRetain);
        l--;
        for (i = 0; i <= ((ch[x].td + 1) / 5) + 1; i++)
        {
                for (j = (5 * i) + 1; j <= 5 * (i + 1); j++)
                        ch[x].cash[(5 * i) + 3] += ch[x].cost[j];
                ch[x].cash[(5 * i) + 3] *= -1 * (1 + TaxnOverheadRate);
                ch[x].cash[(i + 2) * 5] = ch[x].cash[(5 * i) + 3] * (-1 - Markup)*(1 - Retaining);
                remaining += ch[x].cash[(5 * i) + 3] * (-1 - Markup) * Retaining;
                if (l > 0)
                {
                        ch[x].cash[(i + 2) * 5] = ch[x].cash[(i + 2) * 5] - (AdvPayment / AdvRetain);
                        l--;
                }
                if (i + 1 > ((ch[x].td + 1) / 5) + 1)
```

```
            {
                ch[x].cash[(i + 2) * 5] += remaining;
                j = (i + 2) * 5;
            }
        }
        ch[x].profit = ch[x].cash[j];
        //_getch();

}
/////////////////End Functions////////////////


////////////////////////////////Class GeneticAlgorithm///////////////////////////////
class GeneticAlgorithm
{
public:
        void Create_Chromosomes(int, int);
        int Crossover(int);
        int Selection(int);
        void Reproduction(int, double);
        int Mutate(int);

};
```

```
void GeneticAlgorithm::Create_Chromosomes(int MaxNum, int StartFrom)
{
	int i, j;
	for (i = StartFrom; i < MaxNum; i++)
	{
		for (j = 1; j < NOA; j++)
			ch[i].gen[j] = RandOption(j);
		ch[i].td = CalTDuration(ch[i]);
		ch[i].tc = CalTCost(ch[i]);
		UpdateProfit(i);
		ch[i].fitness = (ch[i].td / TMAX) + (ch[i].tc / CMAX);
		if (IsSame(ch[i], i) == true)
			i--;
	}
	/*for (j = 1; j < NOA; j++)
	ch[1].gen[j] = 3;
	ch[1].td = CalTDuration(ch[1]);
	ch[1].tc = CalTCost(ch[1]);
	ch[1].fitness = (ch[1].td / TMAX) + (ch[1].tc / CMAX);*/
}

int GeneticAlgorithm::Crossover(int nond)
```

```
{
	int i, point, j, newAns;
	int ansCopy;
	int limit = (nond - NOE) / 2;
	for (i = 1; i <= limit; i++)
	{
		newAns = nond + (2 * i) - 1;
		//cout << newAns << endl;
		ch[newAns] = ch[NOE + (2 * i) - 1];
		ch[newAns + 1] = ch[NOE + (2 * i)];
		//srand(time(NULL));
		point = (rand() % (NOA - 2)) + 1;
		for (j = 1; j <= point; j++)
		{
			ansCopy = ch[newAns].gen[j];
			ch[newAns].gen[j] = ch[newAns + 1].gen[j];
			ch[newAns + 1].gen[j] = ansCopy;
		}
		/*for (j = 1; j < NOA; j++)
		if (ch[newAns].gen[j]>PD[j].noo)
		ch[newAns].gen[j] = RandOption(j);*/
		ch[newAns].td = CalTDuration(ch[newAns]);
```

```
}

ch[newAns].tc = CalTCost(ch[newAns]);

UpdateProfit(newAns);

//ch[newAns].fitness = (ch[newAns].td / TMAX) + (ch[newAns].tc / CMAX);

/*(for (j = 1; j < NOA; j++)

if (ch[newAns+1].gen[j]>PD[j].noo)

ch[newAns + 1].gen[j] = RandOption(j);*/

ch[newAns + 1].td = CalTDuration(ch[newAns + 1]);

ch[newAns + 1].tc = CalTCost(ch[newAns + 1]);

UpdateProfit(newAns + 1);

//ch[newAns+1].fitness = (ch[newAns+1].td / TMAX) + (ch[newAns+1].tc /
CMAX);

/*ShowChormosome(NOE + (2 * i) - 1, NOE + (2 * i) + 1);

_getch();

ShowChormosome(newAns, newAns + 2);*/

//_getch();

/*if (IsSame(ch[newAns], newAns) == true || IsSame(ch[newAns + 1], newAns +
1) == true)

{

//cout << rand() % 10 << endl;

i -= 2;

}*/

}
```

```
        return newAns + 1;
}


void GeneticAlgorithm::Reproduction(int N, double fit)
{
        int i, j;
        for (i = MNOC - N - 1; i < MNOC; i++)
        {
                for (j = 1; j < NOA; j++)
                        ch[i].gen[j] = RandOption(j);
                ch[i].td = CalTDuration(ch[i]);
                ch[i].tc = CalTCost(ch[i]);
                UpdateProfit(i);
                ch[i].fitness = (ch[i].td / TMAX) + (ch[i].tc / CMAX);
                if (IsSame(ch[i], i) == true)
                        i--;
                else if (ch[i].fitness >= fit)
                        i--;
        }
}
int GeneticAlgorithm::Selection(int nond)
{
```

```
	int i;
	if (nond > MNOC)
		return nond;
	else
	{
		Reproduction(MNOC - nond, ch[nond].fitness);
		return MNOC - 1;
	}
}
int GeneticAlgorithm::Mutate(int nond)
{
	int i, k, j;
	for (i = NOE + 1; i <= nond; i++)
	{
		k = (rand() % (NOA - 1)) + 1;
		j = ch[i].gen[k];
		while (j == ch[i].gen[k])
			j = RandOption(k);
	}
	return nond;
}
```

```
///////////////////////////////End Class GeneticAlgorithm/////////////////////////////


GeneticAlgorithm GA;



int _tmain(int argc, _TCHAR* argv[])
{
	clock_t start = clock();
	srand(time(NULL));
	fstream fp("input_file.txt", ios::in);
	if (!fp)
	{
		cerr << "file can not open!" << endl;
		_getch();
		exit(1);
	}
	int i, j, k; //Only use for countering

	//Start Reading Data from File
	for (i = 1; i < NOA; i++)
```

```
{
	fp >> PD[i].actc >> PD[i].NOP;
	for (j = 1; j <= PD[i].NOP; j++)
		fp >> PD[i].pre[j];
	fp >> PD[i].NOS;
	for (j = 1; j <= PD[i].NOS; j++)
		fp >> PD[i].suc[j];
	fp >> PD[i].noo;
	for (j = 1; j <= PD[i].noo; j++)
		fp >> PD[i].opt[j].d >> PD[i].opt[j].c;
}
//End Reading Data from file


//Start Creating Initial Generation
fstream output_file("Output.txt", ios::out);
if (!output_file)
{
	cerr << "File can not open." << endl;
	exit(1);
}
GA.Create_Chromosomes(MNOC, 1);
int nond = sort(MNOC);
```

```
if (nond < MNOC - NOR - 1)
	GA.Reproduction(MNOC - nond - 1, ch[nond].fitness);
else
	GA.Reproduction(NOR, ch[MNOC - NOR - 2].fitness);
//ShowChormosome(1, MNOC);
nond = sort(MNOC);
//Start Creating next Generations
output_file << "Initial Generation" << endl;
output_file << "Duration:" << endl;
for (k = 1; k <= nond; k++)
{
	output_file << ch[k].td << endl;
}
output_file << "Total Cost:" << endl;
for (k = 1; k <= nond; k++)
{
	output_file << ch[k].tc << endl;
}
for (i = 1; i < MNOG; i++)
{
	cout << i << endl;
	nond = sort(GA.Crossover(nond) + 1);
```

```
		nond = sort(GA.Mutate(nond) + 1);
		nond = GA.Selection(nond);
		nond = sort(nond + 1);
		/*cout << "generation Number " << i << endl;
		ShowChormosome(1, nond + 1);
		_getch();*/
		cout << i << endl;


	}
	output_file << "Generation " << i << endl;
	output_file << "Duration:" << endl;
	for (k = 1; k <= nond; k++)
	{
		output_file << ch[k].td << endl;
	}
	output_file << "Total Cost:" << endl;
	for (k = 1; k <= nond; k++)
	{
		output_file << ch[k].tc << endl;
	}
	output_file << "Total Profit:" << endl;
	for (k = 1; k <= nond; k++)
```

```
	{
		output_file << ch[k].profit << endl;
	}
	output_file << "\nTime elapsed: " << ((double)clock() - start) / CLOCKS_PER_SEC << endl;
	//ShowChormosome(1, MNOC);
	//End Creating Initial Generation
	cout << "\nTime elapsed: " << ((double)clock() - start) / CLOCKS_PER_SEC << endl;
	_getch();
	//printf("\nTime elapsed: %f\n", ((double)clock() - start) / CLOCKS_PER_SEC);


	return 0;
}
```

Illustrative examples

Table 8-1 Project 2

Project 2						
A ctivity	D uration	Re sources	Prede cessors	Suc cessors	To tal float	Fr ee Float
Subproject 1						
A 2	1 0 days	R1[5]		5,6	13	1
A 3	5 days	R1[2]		6	6	8
A 4	1 5 days	R1[5]	3	7	20	1
A 5	1 0 days	R1	3,4	9	13	22
A 6	1 0 days	R1[5]	5	8,9	13	1
A 7	1 5 days	R1[5]	7		20	0
A 8	1 0 days	R1[3]	6,7		13	0
Subproject 2						
A 10	5 days	R1[6]		13	6	8
A 11	1 0 days	R1[5]		13	13	1
A 12	1 5 days	R1[5]	11,12	14, 15	20	1
A 13	5 days	R1	13	16	6	8
A 14	1 0 days	R1[5]	13	16, 17	13	1
A 15	5 days	R1[7]	14,15		6	0
A 16	1 5 days	R1[5]	15		20	0
Subproject 3						
A 18	1 0 days	R1[5]		20, 21	13	1
A	1	R1[	19	22	20	1

19	5 days	5]				
A 20	5 days	R1[3]	19	22, 23	6	1
A 21	10 days	R1[5]	20,21	24, 25	13	1
A 22	10 days	R1[2]	21	25	13	15
A 23	15 days	R1[5]	22		20	0
A 24	10 days	R1	22,23		13	0

Table 8-2 Project 3

Project 3						
Activity	Duration	Resources	Predecessors	Successors	Total float	Free Float
Subproject 1						
A 2	10 days	R1[5]		5,6	13	1
A 3	5 days	R1[8]		6	6	8
A 4	15 days	R1[5]	3	7	20	1
A 5	10 days	R1[6]	3,4	9	13	22
A 6	10 days	R1[5]	5	8,9	13	1
A 7	15 days	R1[5]	7		20	0
A	10 days	R1[7]	6,7		13	0

8							
Subproject 2							
A10	5 days	R1[6]		13	6	8
A11	10 days	R1[5]		13	13	1
A12	15 days	R1[5]	11,12	14, 15	20	1
A13	5 days	R1	13	16	6	8
A14	10 days	R1[5]	13	16, 17	13	1
A15	5 days	R1[7]	14,15		6	0
A16	15 days	R1[5]	15		20	0
Subproject 3							
A18	10 days	R1[5]		20, 21	13	1
A19	15 days	R1[5]	19	22	20	1
A20	5 days	R1[3]	19	22, 23	6	1
A21	10 days	R1[5]	20,21	24, 25	13	1
A22	10 days	R1[2]	21	25	13	15
A23	15 days	R1[5]	22		20	0
A24	10 days	R1	22,23		13	0

Table 8-3 Project 4

Project 4						
Activity	Duration	Resources	Predecessors	Successors	Total float	Free Float
Subproject 1						
A2	10 days	R1[5]		5,6	13	1
A3	5 days	R1[2]		6	6	8
A4	15 days	R1[5]	3	7	20	1
A5	10 days	R1	3,4	9	13	22
A6	10 days	R1[5]	5	8,9	13	1
A7	15 days	R1[5]	7		20	0
A8	10 days	R1[3]	6,7		13	0
Subproject 2						
A10	5 days	R1		13	6	8
A11	10 days	R1[5]		13	13	1
A12	15 days	R1[5]	11,12	14,15	20	1
A13	5 days	R1	13	16	6	8
A14	10 days	R1[5]	13	16,17	13	1
A15	5 days	R1[3]	14,15		6	0
A16	15 days	R1[5]	15		20	0
Subproject 3						
A18	10 days	R1[5]		20,21	13	1
A19	15 days	R1[5]	19	22	20	1

A 20	5 days	R1[3]	19	22,2 3	6	1
A 21	1 0 days	R1[5]	20,2 1	24,2 5	13	1
A 22	1 0 days	R1[2]	21	25	13	15
A 23	1 5 days	R1[5]	22		20	0
A 24	1 0 days	R1	22,2 3		13	0

Table 8-4 Project 5

Project 5						
A ctivity	D uration	Re sources	Prede cessors	Suc cessors	To tal float	Fr ee Float
Subproject 1						
A 2	1 0 days	R1[5]		5,6	13	1
A 3	5 days	R1[2]		6	6	8
A 4	1 5 days	R1[5]	3	7	20	1
A 5	1 0 days	R1	3,4	9	13	2 2
A 6	1 0 days	R1[5]	5	8,9	13	1
A 7	1 5 days	R1[5]	7		20	0
A	1	R1[	6,7		13	0

8	0 days	3]				
Subproject 2						
A 10	5 days	R1[6]		13	6	8
A 11	1 0 days	R1[5]		13	13	1
A 12	1 5 days	R1[5]	11,12	14, 15	20	1
A 13	5 days	R1	13	16	6	8
A 14	1 0 days	R1[5]	13	16, 17	13	1
A 15	5 days	R1[7]	14,15		6	0
A 16	1 5 days	R1[5]	15		20	0
Subproject 3						
A 18	1 0 days	R1[5]		20, 21	13	1
A 19	1 5 days	R1[5]	19	22	20	1
A 20	5 days	R1[8]	19	22, 23	6	1
A 21	1 0 days	R1[5]	20,21	24, 25	13	1
A 22	1 0 days	R1[6]	21	25	13	1 5
A 23	1 5 days	R1[5]	22		20	0
A 24	1 0 days	R1[7]	22,23		13	0

Table 8-5 Project 6

Project 6						
Activity	Duration	Resources	Predecessors	Successors	Total float	Free Float
Subproject 1						
A2	10 days	R1[5]		5,6	13	1
A3	5 days	R1[5]		6	6	8
A4	15 days	R1[5]	3	7	20	1
A5	10 days	R1[5]	3,4	9	13	22
A6	10 days	R1[5]	5	8,9	13	1
A7	15 days	R1[5]	7		20	0
A8	10 days	R1[5]	6,7		13	0
Subproject 2						
A10	5 days	R1[6]		13	6	8
A11	10 days	R1[5]		13	13	1
A12	15 days	R1[5]	11,12	14,15	20	1
A13	5 days	R1	13	16	6	8
A14	10 days	R1[5]	13	16,17	13	1
A15	5 days	R1[7]	14,15		6	0
A16	15 days	R1[5]	15		20	0
Subproject 3						
A18	10 days	R1[5]		20,21	13	1
A19	15 days	R1[5]	19	22	20	1

A20	5 days	R1[3]	19	22,23	6	1
A21	10 days	R1[5]	20,21	24,25	13	1
A22	10 days	R1[2]	21	25	13	15
A23	15 days	R1[5]	22		20	0
A24	10 days	R1	22,23		13	0

Table 8-6 Project 7

Project 7						
Activity	Duration	Resources	Predecessors	Successors	Total float	Free Float
Subproject 1						
A2	10 days	R1[5]		5,6	13	1
A3	5 days	R1[2]		6	6	8
A4	15 days	R1[5]	3	7	20	1
A5	10 days	R1	3,4	9	13	22
A6	10 days	R1[5]	5	8,9	13	1
A7	15 days	R1[5]	7		20	0
A	1	R1[	6,7		13	0

8	0 days	3]					
Subproject 2							
A10	5 days	R1[5]		13	6	8
A11	10 days	R1[5]		13	13	1
A12	15 days	R1[5]	11,12	14,15	20	1
A13	5 days	R1[5]	13	16	6	8
A14	10 days	R1[5]	13	16,17	13	1
A15	5 days	R1[5]	14,15		6	0
A16	15 days	R1[5]	15		20	0
Subproject 3							
A18	10 days	R1[5]		20,21	13	1
A19	15 days	R1[5]	19	22	20	1
A20	5 days	R1[3]	19	22,23	6	1
A21	10 days	R1[5]	20,21	24,25	13	1
A22	10 days	R1[2]	21	25	13	15
A23	15 days	R1[5]	22		20	0
A24	10 days	R1	22,23		13	0

Table 8-7 Project 8

Project 8						
Activity	Duration	Resources	Predecessors	Successors	Total float	Free Float
Subproject 1						
A2	10 days	R1[5]		5,6	13	1
A3	5 days	R1[2]		6	6	8
A4	15 days	R1[5]	3	7	20	1
A5	10 days	R1	3,4	9	13	22
A6	10 days	R1[5]	5	8,9	13	1
A7	15 days	R1[5]	7		20	0
A8	10 days	R1[3]	6,7		13	0
Subproject 2						
A10	5 days	R1[6]		13	6	8
A11	10 days	R1[5]		13	13	1
A12	15 days	R1[5]	11,12	14,15	20	1
A13	5 days	R1	13	16	6	8
A14	10 days	R1[5]	13	16,17	13	1
A15	5 days	R1[7]	14,15		6	0
A16	15 days	R1[5]	15		20	0
Subproject 3						
A18	10 days	R1[5]		20,21	13	1
A19	15 days	R1[5]	19	22	20	1

A 20	5 days	R1[5]	19	22,2 3	6	1
A 21	1 0 days	R1[5]	20,21	24,2 5	13	1
A 22	1 0 days	R1[5]	21	25	13	1 5
A 23	1 5 days	R1[5]	22		20	0
A 24	1 0 days	R1[5]	22,23		13	0

Table 8-8 Project 9

Project 9						
A ctivity	D uration	Re sources	Prede cessors	Suc cessors	Tot al float	Fr ee Float
Subproject 1						
A 2	1 0 days	R1[5]		5,6	13	1
A 3	5 days	R1[2]		6	6	8
A 4	1 5 days	R1[5]	3	7	20	1
A 5	1 0 days	R1	3,4	9	13	22
A 6	1 0 days	R1[5]	5	8,9	13	1
A 7	1 5 days	R1[5]	7		20	0
A	1	R1[	6,7		13	0

8	0 days	3]				
Subproject 2						
A10	5 days	R1[6]		13	6	8
A11	10 days	R1[5]		13	13	1
A12	15 days	R1[5]	11,12	14,15	20	1
A13	5 days	R1	13	16	6	8
A14	10 days	R1[5]	13	16,17	13	1
A15	5 days	R1[7]	14,15		6	0
A16	15 days	R1[5]	15		20	0
Subproject 3						
A18	10 days	R1[5]		20,21	13	1
A19	15 days	R1[5]	19	22	20	1
A20	5 days	R1[3]	19	22,23	6	1
A21	10 days	R1[5]	20,21	24,25	13	1
A22	10 days	R1[2]	21	25	13	15
A23	15 days	R1[5]	22		20	0
A24	10 days	R1	22,23		13	0

Table 8-9 Project 10

Project 10						
Activity	Duration	Resources	Predecessors	Successors	Total float	Free Float
Subproject 1						
A2	10 days	R1[5]		5,6	13	1
A3	5 days	R1[2]		6	6	8
A4	15 days	R1[5]	3	7	20	1
A5	10 days	R1	3,4	9	13	22
A6	10 days	R1[5]	5	8,9	13	1
A7	15 days	R1[5]	7		20	0
A8	10 days	R1[3]	6,7		13	0
Subproject 2						
A10	5 days	R1[6]		13	6	8
A11	10 days	R1[5]		13	13	1
A12	15 days	R1[5]	11,12	14,15	20	1
A13	5 days	R1	13	16	6	8
A14	10 days	R1[5]	13	16,17	13	1
A15	5 days	R1[7]	14,15		6	0
A16	15 days	R1[5]	15		20	0
Subproject 3						
A18	10 days	R1[5]		20,21	13	1
A19	15 days	R1[5]	19	22	20	1

A20	5 days	R1[3]	19	22,23	6	1
A21	10 days	R1[5]	20,21	24,25	13	1
A22	10 days	R1[2]	21	25	13	15
A23	15 days	R1[5]	22		20	0
A24	10 days	R1	22,23		13	0

References

Aaxelrod, R. (1997). The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration. Princeton: Princeton University Press.

Abudayyeh, O. (1994). Partnering: a team building approach to quality construction management. *J. Manage. Eng.*, 10(6), p26.

Albanese, R. (1994). Team-building process: key to better project results. *J. Manage. Eng.*, 10(6), 36-44.

Anvuur, A. M. (2007). Conceptual model of partnering and alliancing. *J. Constr. Eng. Manage.*, 133(3), 225–234.

Argyris, C. a. (1996). *Organizational learning—II.* MA: Addison-Wesley, Reading.

Asgari, M. S., & approach", c. g. (2008). Modeling subcontractors' cooperation in time; approach", cooperative game theory. *First International Conference on Construction in Developing Countries (ICCIDC-I)*, (pp. 312 – 319). Karachi, Pakistan.

Axelrod, R., & Hamilton, W. (1981). The evolution of cooperation. *Science*, 211: 1390–1396.

Banzhaf, J. F. (1965). Weighted Voting Doesn't Work: A Mathematical Analysis. *Rutgers Law Review*, 19 (2): 317–343.

Bennett, J. a. (1998). *The seven pillars of partnering: A guide to second generation partnering.* London: Thomas Telford.

Bhaduri, A. a. (2013). Cooperation in Transboundary Water Sharing with Issue Linkage: Game-Theoretical Case Study in the Volta Basin . *J. Water Resour. Plann. Manage.*, 10.1061, 235-245.

bolandpayeh. (2015). Retrieved from http://www.bolandpayeh.com

Bresnen, M. a. (2000). Building partnerships: case studies of client/contractor collaboration in the UK construction industry. *Construction Management and Economics*, 18:7 - 819-832.

Bresnen, M. a. (2000). Partnering in construction: a critical review of issues, problems and dilemmas. *Construction Management and Economics*, 18:2, 229-237.

Brresnen.M. and Marshall, N. (2000). Partnering in construction: a critical review of issues, problems and dilemmas. *Construction Management and Economics*, 229-237.

Chan, A. P. (2004). Exploring Critical Success Factors for Partnering in Construction Projects. *J. Construction Engineering and Management*, 130(2), 188-198.

Cheng, E. W. (2003). Development of a Practical Model of Partnering for Construction Projects . *J. Manage. Eng.*, 130(6), 790-798.

Choudhry, R. H. (2012). Subcontracting practices in the construction industry of Pakistan. *J. Constr. Eng. Manage.*, 1353–1359.

Daniels, S. E. (2001). *Working through environmental conflict: The collaborative learning approach.* CT: Praeger, Westport.

Deegan, J. a. (1978). A new index of power for simple n–person games. *International Journal of Game Theory* , 113–123.

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

Felsenthal, D. S., & Machover, M. (1998). The Measurement of Voting Power Theory and Practice, Problems and Paradoxes. Cheltenham, England: Edward Elgar.

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, NJ: Princeton University Press.

Gottlieb, S. C. (2013). Contradictions and collaboration: partnering in-between systems of production, values and interests. *Construction Management and Economics*, 31(2), 119-134.

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, NJ,: Princeton University Press,.

Harsanyi, J. C. (1963). A simplified bargaining model for the n-person game . *Int. Econ. Rev.*, 4(2), 194–220.

Holler, M. (1982). Forming coalitions and measuring voting power. *Political Studies 30*, 262–271.

Holti, R. a. (1996). *Partnering as Inter-related Technical and Organizational Change.* avistock, London.

Hu, X. (2006). An Asymmetric Shapley–Shubik Power Index. *International Journal of Game Theory*, 34 (2), 229–240.

Imen, S. M. (2012). Bringing Environmental Benefits into Caspian Sea Negotiations for Resources Allocation: Cooperative Game Theory Insights. *World Environmental and Water Resources Congress 2012*, (pp. 2264-2271).

JICA. (2015). Retrieved from https://www.jica.go.jp

Johnston, R. (1978). On the measurement of power: Some reactions to Laver. *Environment and Planning*, A 10, 907–914.

Kannai, Y. (1992). "The core and balancedness" In Aumann, Robert J.; Hart, Sergiu. Handbook of Game Theory with Economic Applications. I. Amsterdam. *Elsevier*, 355–395.

Kartam, S. B. (1997). Introducing a new concept and approach to modeling construction . *J. Manage. Eng.*, 123(1), 89–97.

Katzenbach, J. a. (1993). The discipline of teams. Harvard : Harvard Bus.

Kumaraswamy, M. M. (2000). Improved subcontractor selection employing partnering principles. *J. Manage. Eng.*, 47.

Kumaraswamy, M. M. (2005). Reconstructing relationally Integrated Teams. *J. Constr.Eng. Manage.*, 131(10), 1076-1086.

Lazar, F. (2000). Project partnering: improving the likelihood of win/win outcomes. *J. Manage. Eng.*, 16(2), 71-83.

Lehrer, E. (1988). An Axiomatization of the Banzhaf Value. *International Journal of Game Theory*, 17 (2): 89–99.

Lewis, D. (1976). *Counterfactuals.* Oxford: Basil Blackwell.

Loehman, E. O. (1979). Cost allocation for a regional wastewater treatment system. *Water Resour. Res.*, 15(2), 193–202.

Lorenzo-Freire, S. A.-M.-M.-J. (2007). Characterization of the Deegan-Packel and Johnston power indices. *European Journal of Operational Research* , 177, 431–444.

Madani, K. (2010). Game Theory and Water Resources. *Journal of Hydrology*, 381, 225-238.

Madani, K. G. (2011). Game Theory Insights for the Caspian Sea Conflict . *Proceeding of the 2011 World Environmental and Water Resources Congress* (pp. 2815-2819). Palm Springs, California: ASCE.

Maynard-Smith, J. a. (1973). The Logic of Animal Conflict. *Nature*, 15–18.

Mc.Kinney, D. a. (2007). Cooperative Game Theory for Transboundary River Basins: The Syr Darya Basin. *World Environmental and Water Resources Congress 2007*, (pp. 1-10).

Mesterton-Gibbons, M. (2000). An introduction to game-theoretic modelling. Rhode Island: The American Mathematical Society.

Myerson, R. (1991). Game Theory: Analysis of Conflict. Cambridge: Harvard University Press.

Myerson, R. (1991). Game Theory: Analysis of Conflict. Cambridge, Mass: Harvard University Press.

Nash, J. (1953). Two-person cooperative games. *Econometrica: J. Econometric Soc.*, 21(1), 128–140.

Penrose, L. (1964). The Elementary Statistics of Majority Voting. *Journal of the Royal Statistical Society. Blackwell Publishing.* , 109 (1): 53–57.

Phua, F. a. (2004). How important is cooperation to construction project success? A grounded empirical quantification. *Eng. Const. Arch. Manage.*, 11(1), 45-54.

Rapoport, A. (1960). In *Fights, Games, and Debates.* Ann Arbor: University of Michigan Press.

S Shapley, L. (1953). In *A value for n-Person games* (pp. 307–317). Princeton: Princeton University Press.

Samuelson, L. (1997). *Evolutionary Games and Equilibrium Selection.* Cambridge: The MIT Press.

Scharle, P. (2002). Public-Private Partnership (PPP) as a Social Game, Innovation. *The European Journal of Social Science Research*, 15(3), 227-252.

Schelling, T. (1960). *The Strategy of Conflict .* Cambridge: Harvard University Press.

Shapley, L. S., & Shubik, M. (1954). A Method for Evaluating the Distribution of Power in a Committee System . *American Political Science Review*, 48 (3): 787–792.

Shen, L. B. (2007). Using Bargaining-Game Theory for Negotiating Concession Period for BOT-Type Contract. *J. Constr. Eng. Manage.*, 133(5), 385-392.

Shubik, M. S. (1969). Market Games. *Journal of Economic Theory*, (1), 9–25.

Straffin, P. (1993). Game Theory and Strategy, The Mathematical Association of America . Washington: The Mathematical Association of America.

Straffin, P. (1993). Game Theory and Strategy, Washington. The Mathematical Association of America.

Tam, V. W. (2011). Impacts of multi-layer chain subcontracting on project management performance. *Int. J. Project Manage.*, 29(1), 108–116.

Teasley, R. M. (2011). Calculating the Benefits of Transboundary River Basin Cooperation: Syr Darya Basin. *J. Water Resour. Plann. Manage.*, 481-490.

Tsai, J. a. (2015). Learning for Win-Win Collaboration. *J. Constr. Eng. Manage.*, 1-10.

Wood, G. a. (2001). Building on trust: a co-operative approach to construction procurement. *J. Constr. Procure.*, 7(2), 4-14.

Yik, F. W. (2008). Multilayer subcontracting of specialist works in buildings in Hong Kong. *Int. J. Project Manage.*, 26(4), 399–407.

Curriculum Vitae

Education

- Syracuse University, Syracuse, NY (August 2016 – May 2018)

Master of Science in Construction Management

- University of Tehran, Tehran, Iran (Oct 2015 – August 2016)

Mini-Master of Business Administration (MBA)

- Sharif University of Technology, Tehran, Iran (Sep 2010 - June 2014)

Bachelor of Science in Civil Engineering

Publications

- A Game Theoretic Model for Trust-Based Relationship of Subcontractors Partnership in Construction: Win-Win Game" (CRC2016)
- "Optimum Concession Period in BOT-Type Contract" (CSCE 2016)
- "Concession Period in Public-Private Partnership" (National Construction Conference, Iran, 2016)

Technical Skills

- Programming Languages: C++, Pascal, Visual Basic, R
- Engineering Software: Primavera, Microsoft Project, Crystal Ball, Navisworks, Revit, ETABS, Civil 3D, AutoCAD, MATLAB, SPSS

Language Proficiency

- Native: Azeri
- Fluent: English, Persian, and Turkish
- Beginner: Arabic, French

Honors and Awards

- Syracuse University Graduate Fellowship (2016)
- Ranked in the top 1% in the national entrance examination for Iranian students, Civil and environmental engineering, Iran (2014 and 2009)
- Being among the 30 eligible students selected for chemistry Olympiad, Iran (2008)