PERFORMANCE MEASUREMENT AND IMPROVEMENT IN CONSTRUCTION INDUSTRY: "AN APPLICATION OF TURKEY CASE"

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Approval of the Graduate School of Natural and Applied Sciences, Atılım University.

____

(Title and Name)

Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

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(Title and Name)

Head of Department

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_______________________	_______________________
(Title and Name)	(Title and Name)
Co-Supervisor	Supervisor

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ABSTRACT

PERFORMANCE MEASUREMENT AND IMPROVEMENT IN CONSTRUCTION INDUSTRY:

“AN APPLICATION OF TURKEY CASE”

Tuncer, Veysel Emre

M.S., Industrial Engineering Department

Supervisor: Assoc. Prof. Dr. Turan Erman Erkan

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This thesis reviews the performance evaluation and improvement in construction industry. A balanced scorecard framework is proposed for performance measurement in Turkish Construction Industry. In addition, two mixed integer mathematical programming models are developed for performance improvement.

Keywords: Balanced Scorecard, performance measurement, mixed integer mathematical modelling, hybrid flow shop problem.

ÖZ

İNŞAAT SEKTÖRÜNDE PERFORMANS ÖLÇÜMÜ VE GELİŞTİRİLMESİ:

"TÜRK İNŞAAT SEKTÖRÜ İÇİN BİR UYGULAMA"

Tuncer, Veysel Emre

Yüksek Lisans, Endüstri Mühendisliği Bölümü

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Bu çalışma, inşaat sektöründe performans ölçümünü ve geliştirilmesini ele almaktadır. İlk olarak Türk İnşaat Sektöründe performans ölçümü kapsamında bir kurumsal karne yöntemi önerilmiştir. Buna ek olarak, performans artışının sağlanması için iki adet karışık tam sayılı programlama modeli geliştirilmiştir.

Anahtar Kelimeler: Kurumsal karne, performans ölçümü, matematiksel modelleme, esnek akış tipi problemi.

To My Family

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I express sincere appreciation to my supervisor Assoc. Prof. Dr. Turan Erman Erkan for his guidance and insight throughout the research. I would also like to thank respected members of the examining committee for their valuable comments and suggestions. To my wife and family, I offer sincere thanks for their continuous support and patience during this period.

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LIST OF ABBREVIATIONS

PMS	Performance measurement system
BSC	Balanced Scorecard
HFS	Hybrid Flow Shop

1. INTRODUCTION

In the 21st century with the effect of globalization and the extremely competitive environment created in the world markets, business performance turned into a highly significant and critical topic for the success of the companies in different sectors. As a result, improvement, measurement and evaluation of performance turned into a highly popular research area and accordingly within the last two decades the issue attracted considerable attention by the researchers. For example, Neely describes this as a revolution and between the years 1994 and 1996, about 3600 articles were published together with several books (Neely, 1999).

Performance improvement and evaluation is not a topic that is specific to certain industries, in contrast it is critical in almost every branch of industry including construction sector. As construction industry is a large industry that has connections with several industries, the productivity in construction has a significant effect on national productivity and economy (Allmon, 2000). A typical construction project requires involvement of up to six or more different professional disciplines (Anumba, 2000). In this respect, the problem becomes more complex in construction compared to other manufacturing industries.

The main purpose of this study is to review the major performance improvement and evaluation applications and studies in the literature, evaluate these applications, and adapt for Turkish Construction Industry. Our objective is to fill the gap between the practice, theory, and application. In the study, we mainly concentrate on the issue from the internal management perspective instead of clients or stakeholders' perspective. In the first part of the study, we consider the performance measurement issue and provide the literature related with the topic and we propose a balanced scorecard application for the performance measurement in Turkish Construction Industry. Then, in the second part, we first concentrate on the performance improvement issue from a financial performance viewpoint, specifically mathematical programming applications. Next, we explain the problem and give a literature review related with the defined problem.

Finally, the mathematical formulations of the problem are presented and the results are illustrated by means of a set of test instances.

2. PERFORMANCE MEASUREMENT

In this part, our main objective is to develop a framework for measuring the performance of a construction firm that has international investments and projects. We used Balanced Scorecard (BSC) approach in our framework. We identify and measure performance measures based on our 2-step design. We made a detailed literature review and identified 27 measures that are categorized under five management dimensions. Then a questionnaire survey is conducted in order to select and weight the important measures in Turkish Construction Industry.

Performance measurement is a significant issue in terms of strategic level decision making from the senior management perspective. In construction industry, several studies have proved the significance of performance measurement and as a result, performance measurement level up to a new stage. (Egan, 1998). These studies have resulted in common use of performance benchmarking for monitoring the performance of the companies and construction sector as a whole.

The performance benchmarking programs initiated by the companies resulted in development of quantitative measurement culture and these tools become more popular within the industry. Especially the companies that operate in global markets these tools become much more important because of turbulent business environment, tight competition in international markets. Hence, the companies need to evaluate their position within the sector for strategic decision-making.

Despite the increase in studies, there is no consensus on evaluating the performance of construction companies yet especially for Turkish construction industry. In this study our objective is to develop a framework that helps these companies in evaluating their performance in a more robust and practical manner. In this chapter, first, we provide a literature review on performance measurement, and then we present our framework and methodology for measuring performance.

2.1. Literature Review

With the evolution of global markets, the traditional methods that are used in PM could not satisfy the needs of competitive markets (Kaplan & Norton, 1992). The researchers started to study on this issue and they explain their discontent with the traditional PMs (Bourne et al., 2000). As a result, the main weakness of the traditional PMs is identified to be the lack of nonfinancial measures such as quality, productivity, and leadership (Neely, 2005). Because of this weakness, it is not possible to link the strategic goals of the companies with the performance measures. In addition to that the companies focus on external reporting instead of their internal decision making process. As a result, traditional PMs are evaluated to be inadequate and thus the researchers started to study on improving PM (Neely et al., 1995). In order to close the gap between financial and nonfinancial PMs, some frameworks designed such as performance pyramid (Cross & Lynch, 1989). Then with the introduction of Balanced Scorecard (BSC), the researchers gave considerable attention to this tool (Kaplan & Norton, 1992).

These advancements in PM literature also continued in the construction industry (Bassioni et al., 2004). Most of the large-scale construction companies implemented Performance measurement system (PMS) and some of the other organizations started to use BSC and some other excellence models (Robinson et al., 2005). Some industry wide reports were published that indicates the critical areas that need performance improvement and these studies illustrated the function of PM for improving performance of the construction industry (Egan, 1998). Despite these studies, PM was used mainly in a project-focused manner and PM cannot received too much attention from the construction companies (Love & Holt, 2000).

With the increasing focus on performance measurement among researchers, performance related issues in constriction industry have also received attention among practitioners and researchers. Especially the published reports on construction industry had revealed that there are several areas for improvement and hence the need for performance measurement is emphasized (Latham, 1994; Egan, 1998).

2.2. Balanced Scorecard

BSC is developed by Kaplan and Norton (1992) and considered as one of the most influential ideas developed in the past 75 years. It is estimated that BSC is employed by 40 percent of fortune 1000 companies in 2001 (Marr & Schiuma, 2003). BSC is designed to measure firm performance considering the balance between financial and nonfinancial factors comprehensively. The approach considers four perspectives as shown in Figure 1.

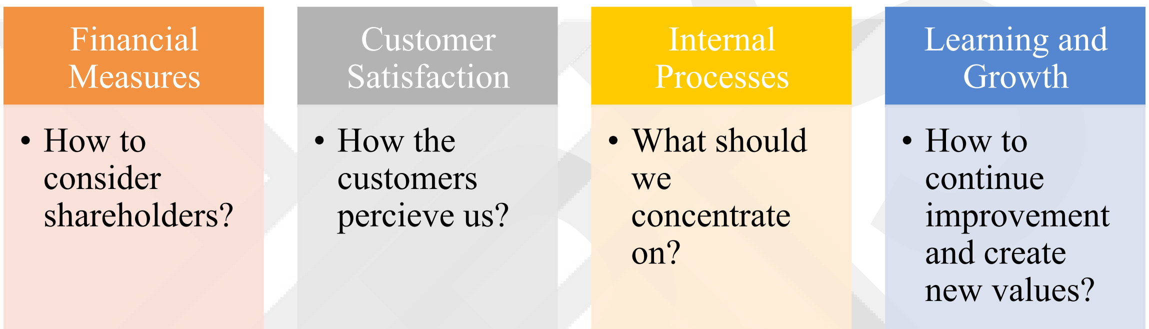

Figure 1. Perspectives of BSC (Kaplan & Norton, 1992)

The strategy and vision of the company is always at the center of BSC perspectives and it is assumed that these perspectives are connected by a cause and effect relation. For example if the company develop more efficient techniques and processes in learning and growth perspective, then the costs are decreased and efficiency is increased in internal processes perspective. As a result, more value is supplied to the customers and satisfaction increases. This in turn increases the profitability of the company in terms of financial measures perspective. To sum up all of the perspectives are linked to each other and a change in one perspective effects other perspectives as well. The initial work proposed by Kaplan and Norton is further developed in terms of applicability and theoretical foundations because of the serious criticism directed and increased popularity on the worldwide (Kaplan & Norton,1993; Kaplan & Norton, 1996; Kaplan, 2008).

BSC is applied widely to measure organizational performance; however, its impact on financial performance is not clear. In some of the studies, statistical analysis indicates that the impact of BSC on organizational financial performance depends on whether BSC is linked with strategies of the company (Banker et al., 2004). This study indicates that BSC can be successful if only it serves to the strategic goals of the company. On the other hand, Neely (2008) could not find any positive relationship between BSC and financial performance.

Similar with other industries, the popularity of BSC also spread among construction companies. For example in UK, about 25 percent of the construction companies used BSC in performance measurement (Robinson et al., 2005). In construction industry, BSC is mainly used for: (i) designing performance measurement frameworks, (ii) developing empirical performance measurement systems, (iii) making case studies for strategic performance evaluation, (iv) estimating company performance quantitatively and identifying performance inconsistencies. Absence of some critical dimensions such as supplier evaluation and project management are criticized in construction industry BSC applications (Bassioni et al., 2005). To sum up the main strength of BSC is presented in Figure 2 (Jin et al., 2013).

Figure 2. Strength of BSC Approach

2.3. Research Methodology

The methodology used in this research is given in Figure 3. We have a two-step methodology. In the first step, we develop BSC framework with a set of performance measures for each management perspective category. To determine performance measures we made a detailed literature review. In the second step, we identify the weights of each performance measures based on the results of the questionnaire survey.

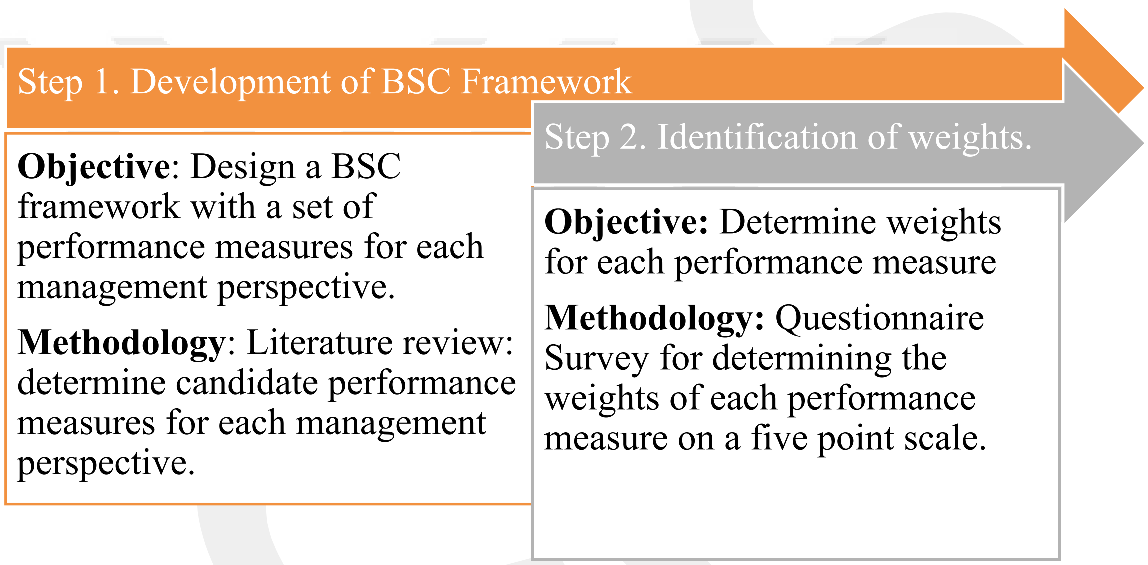

Figure 3. The Research Methodology

In the first step, we conduct a detailed literature review to identify mostly used performance measures in five major management perspectives, namely financial, market, customer, internal business measures, and learning and growth measures. In this stage, our objective is to compile candidate performance measures in each management perspective, then evaluate these measures, and determine the most significant measures to be used in our proposed framework. The management perspectives, corresponding performance measures and the source of information are provided in Table 1.

Table 1. Performance Measures obtained from Literature Review

Performance Measures	Source of Information
Part 1. Financial Measures	
Asset turnover rate	Financial textbooks (Parker, 2007)
Return on equity	
Revenue	
Revenue growth rate	Construction management researches (Bassioni et al., 2005; Robinson et al., 2005; Kagioglou, 2001)
Operating profit	
Profit growth rate	
Operating profit growth rate	
Sales per-capita	
Part 2. Market Measures	
Number of markets dominated	Construction management researches (Love & Holt, 2000; Han, 2010)
Revenue growth rate in existing markets	
Income proportion from international activities	
Number of countries that the company operates	
Income growth rate from international activities	
Part 3. Customer Measures	
Customer value realization	Construction management researches (Horta, 2010; Kagioglou, 2001)
Customer satisfaction	
Regular customer proportion	
Customer cooperation	
Part 4. Internal Business Measures	
Number of core areas	Construction management researches (Han, 2010; Bassioni H. A., 2005)
Profit rates	
Construction works profit proportion	
Number of international businesses	
Coordination and integration of businesses	
Supply chain management	
Growth of businesses	
Part 5. Learning and Growth Measures	
R&D efficiency	Construction management researches (Bassioni H. A., 2005; Kagioglou, 2001; Horta, 2010)
IT applicability	
IT competitiveness	
Employee satisfaction	
Training investments	
Efficiency of organization and management	
Information sharing	

Before evaluating performance measures, first the management perspectives and their significance is explained as follows:

2.3.1. Financial Measures

Determining the financial goals is the first and most significant step in constructing the BSC model as it provides internal and external benchmarking. In addition to traditional financial measures such as asset turnover rate, return on equity, and revenue, some other measures such as revenue growth rate, profit growth rate, and operating profit growth rate provides useful information about the sustained growth and profits from the internal and international markets. These growth rates have direct effect on performance of the company.

2.3.2. Market Measures

If a company is expanding its shares in international construction markets, it shows the capabilities of the company in winning and executing construction projects in international markets. We can see the international performance of the company from the income proportion from international activities and income growth rate from international activities measures. If a company acts in the international markets then the company minimizes the risks in internal markets because of market fluctuations and recessions. Hence, the companies can increase their financial performance by making investments on international markets.

2.3.3. Customer Measures

Customer satisfaction improvement projects results in establishment of close relationships with customers and high quality products in construction industry. To improve customer satisfaction, the company has identify customer requirements. Then these requirements are converted into technical requirements and standards, which increase the quality of products and services. As a result, both customer satisfaction and company performance increases extensively. Moreover, as customer satisfaction increases, then the profitability of the company also increases, as more customers demand the products of the company. As a result improving customer satisfaction has direct effects on other management perspectives as well.

2.3.4. Internal Business Measures

As a company achieves to integrate internal business processes, then the company can convert intangible resources to tangible results. Integrating business processes results in (a) continuous business innovations, (b) enhanced operational productivity, (c) improved cost management strategies, (d) improved quality and safety. Therefore internal business integration has direct effects on company performance in different management perspectives.

2.3.5. Learning and Growth Measures

The main weakness of the most construction company is the low organizational learning capacity. This is because the jobs are conducted by means of temporary project teams and the generated knowledge is not shared within the company. However learning capability of a company is a significant performance indicator especially for the larger companies that operate in international markets. When a company gains the ability to learn then operational efficiency increases which results in improved performance in all operations.

2.4. Evaluation of Performance Measures

In the previous section, we identified 5 management dimensions and a number of performance measures for each dimension as illustrated in Table 1. However, we observe that some of these measures are related to each other and hence they measure similar criteria. Therefore, we send the performance measures to 10 experts employed in different construction companies and want them to select the most significant performance measures in each management dimension together with the reason for selection. Then we evaluate the returns and then decrease number of performance measures from 31 to 22. The final list together with the definition of the performance criteria is given in Table 2.

Table 2. Selected Performance Measures and Their Definition

#	Performance Measure	Definition of the Criteria
	Financial Measures	
F1	Asset turnover rate	total revenue/total asset
F2	Return on equity	(net profit − preferred stock dividend) / shareholder equity × 100
F3	Revenue growth rate	annual operating revenue growth rate
F4	Operating profit	income from main operation + other operating profit − period expense
F5	Sales per Capita	total turnover/number of employees
	Market Measures	
M1	Number of markets dominated	number of countries where the company is within the first 10 companies
M2	Income proportion from international activities	income from international activities / total income
M3	Number of countries that the company operates	number of countries entered
M4	Income growth rate from international activities	annual growth rate of income from international activities
	Customer Measures	
C1	Customer value realization	overall customer satisfaction
C2	Regular customer proportion	Number of regular customers / all customers
C3	Customer cooperation	Cooperative relations with customers such as partnering
	Internal Business Measures	
I1	Number of core businesses	number of core businesses involved
I2	Construction works profit proportion	profit from construction works / all profit
I3	Number of international businesses	number of international businesses involved
I4	Coordination and integration of businesses	Coordination level between businesses
I5	Supply chain management	Integration and efficiency of supply chains
	Learning & Growth Measures	
L1	R&D efficiency	inputs/outputs in R&D activities
L2	IT applicability	Usage level of IT technologies such as ERP systems
L3	Employee satisfaction	employee satisfaction rate
L4	Efficiency of organization and management	company's incentives for teamwork, diversity, and cohesion of company culture
L5	Information sharing	Efficiency and capacity of information sharing within company

In order to evaluate the performance measures and management dimensions, we conduct an empirical investigation. In this evaluation, we identify the degree of importance of each management dimension among others together with the degree of each performance measure among other performance measures under the same management dimension. For that purpose, we prepare a questionnaire survey and ask the participants to rate the significance of each performance metric. We use a five-point Likert scale (1- very unimportant to 5-very important). Results of this type of surveys cannot be generalized. However, our purpose is to design a robust framework of performance evaluation of a company rather than analyzing the significance of single performance metrics. Hence, our approach can be regarded as reasonable. The prepared questionnaire is provided in Appendix A.

The questionnaire is sent to 250 participants by e-mail and 52 participants responded to the questionnaire. The participants are selected from well-known companies in Turkey and the general profiles of them are given in Table 3.

Table 3. Profile of Questionnaire Participants

Characteristics	**Questionnaire Participants**	
	Number	**%**
Job Position		
Senior engineer	26	50.0
Project manager	14	26.9
Corporate department head	8	15.4
Corporate director or executive	4	7.7
Total	52	100
Construction Industry		
Building Construction	16	30.8
Transportation and Infrastructure	14	26.9
Industrial Systems	10	19.2
Water and Waste Distribution and Disposal Systems	5	9.6
Power and Energy Systems	7	13.5
Total	52	100

The results from the participants collected and results are entered into a common file for analysis. All of the questionnaire results are provided in Appendix B for each management dimension. Appendix B also presents the calculation of averages and weights of each performance criteria within each dimensions and weights of each management dimension. The weights of the performance measures under each dimension are calculated as follows:

w_{ij} : *weight of performance measure j under dimension i*

μ_{ij} : *average significance score of performance measure j under dimension i*

k_i : *number of performance measures in management dimension i*

$$w_{ij} = \frac{\mu_{ij}}{\sum_{j=1}^{k_i} \mu_{ij}} \qquad (1)$$

The weights of the each management dimension are calculated as follows:

μ_i : *average significance score of management dimension i*

w_i : *weight of dimension i*

$$\mu_i = \frac{\sum_{j=1}^{k_i} \mu_{ij}}{k_i} \qquad (2)$$

$$w_i = \frac{\mu_i}{\sum_{i=1}^{5} \mu_i} \qquad (3)$$

In addition to weights, another significant issue is the reliability of the questionnaires and used evaluation scale. To asses internal consistency of multiple Likert questions in questionnaire surveys, a common measure is developed, which is called Cronbach's alpha (Cronbach, 1951). Cronbach's alpha is calculated as follows:

σ_{ij}^2 : $variance\ of\ performance\ measure\ j\ in\ dimension\ i\ over\ all\ participants$

σ_i^2 : $variance\ of\ total\ scores\ for\ each\ particiant\ for\ dimension\ i$

$$\alpha_i = \left(\frac{k}{k-1}\right)\left(1 - \frac{\sum_{j=1}^{k_i} \sigma_{ij}^2}{\sigma_i^2}\right) \qquad (4)$$

To calculate Cronbach's alpha, we used Stat<Multivariate< Item Analysis function of Minitab Statistics Software. This tool calculates Cronbach's alpha values for the management dimensions and performance measures. The Minitab outputs are given in Appendix B and the summary Cronbach's alpha values are given in Table 4. As can be seen from the table, for all management dimensions we have $\alpha \geq 0.6$ which is regarded as acceptable in terms of reliability (Hair, 1998).

The results given in Appendix B are summarized in Table 4 given below. In this table, the mean significance weights given by all of the participants are given in the 3rd column. In the next column the weights of management dimensions and performance measures under each dimension is calculated according to formulas given by (21) and (23). Here we observe that the management dimensions have close weight values. Learning and Growth dimension has the greatest weight with a value of 0.211, but customer dimension is very close with a weight of 0.209.

On the other hand, the performance measures under each dimension have different weight values. For finance dimension, operating profit has the greatest weight. For the market dimension, Number of markets dominated, income proportion from international activities, and income growth rate from international activities have very close weights and hence each has equivalent significance level. For customer dimension, Customer value realization and Customer cooperation have close weights and hence have equal significance levels.

Table 4. Weights of Performance Measures and Management Dimensions

#	Performance Measure	Mean	Weight	Cronbach's α
Financial Measures		**3.738**	**0.199**	**0.6026**
F1	Asset turnover rate	3.635	0.194	0.4867
F2	Return on equity	3.788	0.203	0.5150
F3	Revenue growth rate	3.769	0.202	0.5224
F4	Operating profit	3.904	0.209	0.5853
F5	Sales per capita	3.596	0.192	0.6148
Market Measures		**3.404**	**0.181**	**0.6746**
M1	Number of markets dominated	3.462	0.254	0.5780
M2	Income proportion from international activities	3.442	0.253	0.5583
M3	Number of countries that the company operates	3.250	0.239	0.6560
M4	Income growth rate from international activities	3.462	0.254	0.6273
Customer Measures		**3.942**	**0.209**	**0.6527**
C1	Customer value realization	4.019	0.340	0.5320
C2	Regular customer proportion	3.808	0.322	0.5521
C3	Customer cooperation	4.000	0.338	0.5955
Internal Business Measures		**3.762**	**0.200**	**0.6142**
I1	Number of core businesses	3.712	0.197	0.5044
I2	Construction works profit proportion	3.769	0.200	0.5605
I3	Number of international businesses	3.846	0.204	0.5294
I4	Coordination and integration of businesses	3.808	0.202	0.5780
I5	Supply chain management	3.673	0.195	0.6199
Learning and Growth Measures		**3.981**	**0.211**	**0.6597**
L1	R&D efficiency	3.808	0.191	0.5537
L2	IT applicability	4.019	0.202	0.5646
L3	Employee satisfaction	3.981	0.200	0.6263
L4	Efficiency of organization and management	4.192	0.211	0.6822
L5	Information sharing	3.904	0.196	0.6105

For internal business dimension, the performance measures have close weights; however, number of international businesses has the greatest significance. Finally, for the Learning and Growth dimension, efficiency of organization and management is the most significant performance measure.

In conclusion, we developed a framework for evaluating construction companies' performance under five different management dimensions. The proposed framework both determines the weights of the management dimensions within each other and the significance weights of performance measures under each management dimension. Hence, the construction companies can evaluate their performance and compare it with the other companies. Therefore, they can identify the strengths and weaknesses and then take necessary precautions for improving their performance.

3. PERFORMANCE IMPROVEMENT

Performance improvement within the construction industry is a complex task. That is because the business environment in construction industry is complex and dynamic, which decreases the probability of success. Moreover, construction industry has undergone considerable changes in the last decades, which makes the problem harder to solve. In the new environment, the customers are more demanding and the competitors are more challenging. This challenge resulted in differentiation of products, improvement of customer services, developing lasting and trusting relationships with their supply chains, and developing new marketing strategies (Preece et al., 2003).

The complexity of the problem mainly originated from the difficulty in integrating planning and control aspects of project management activities with the financial and budgeting aspects. To solve this problem, it is necessary to construct some cost models that implements the relationships between cost and activity time relationship. If the project cannot be completed on time, then the companies pay penalties to the customers.

To minimize these costs, the companies incur additional costs to accelerate some activities and compress the project time. As the resources are cheaper, then more resources can be employed to complete an activity (Rasmy et al., 2008). This compromise is usually called as time-cost trade-off problem in the literature. To solve such a problem mathematical programming is the best tool that optimizes the use of resources and minimizes the costs.

In this part of the study, we specifically concentrate on financial performance of the construction companies. For that purpose, we propose two mathematical programming formulations. The first model minimizes the makespan of the project and hence the construction company can transfer available resources to other projects as the current project completed. The reduction in project completion time results in extensive cost savings to the company and hence increases the profitability of the company. As a result minimizing makespan of the project improves the financial performance of the company. In the second model we have a fixed due date and as project cannot be completed on time then penalty costs incur. In this model, our objective is the minimization of these penalty costs together with the subcontractor assignment costs. This model also tries to improve the financial performance of the company by minimizing the total costs. In this chapter, first, we describe the problem structure and then provide the related literature.

3.1. Problem Definition

In this study, we consider a large construction firm that has the capability of managing simultaneous projects at the same time. The company carries on large construction projects on different locations. In addition, the company has several subcontractors with different capabilities and capacities that can be employed for specific activities in some of the projects. Each project has a time window and hence the company should complete the projects before the due dates in order not to pay lateness penalty costs. Hence, to minimize the costs, the company has to assign the resources in a detailed manner considering the completion times of the projects. Moreover, in each project, there are several tasks and there is a precedence relation between the tasks. Therefore, one task cannot be initiated unless all tasks that precede this task have been completed. In this problem, our objective is to contribute to the planning process by means of an optimization model that enables the optimum assignment of the resources and minimization of costs.

Consider a construction project that includes a number of single-story buildings to be completed including all tasks starting from very beginning. The buildings can be identical or not. To complete each building a number of tasks should be completed. However, there is a precedence relation between these activities and hence this relation should be considered in resource assignment. The tasks are same for all of the buildings but the resource requirements can be different depending on the size of the buildings. The tasks are given in the following table.

To complete the activities, the company has a set of subcontractors that have different teams that can conduct specific jobs. For example, a contractor may have several teams that can perform all of the tasks. On the other hand, some other contractors may concentrate on specific activities. In addition, the contractor teams are in different experience levels and hence they have different processing times for completing the corresponding tasks. Each task of each building should be assigned to one subcontractor team. It is not possible to assign several tasks simultaneously to a team. In other words, a team can perform one task at a time.

Table 5. Activity Set in a Typical Construction Project

Activity #	Activity Name
1	Footing and excavation works
2	Site preparation and foundation construction
3	Concrete work and completion of rough frame
4	Masonry Work
5	Framing works
6	Windows and doors installations
7	Electrical, heating, and plumbing works
8	Drywall, interior texture works and hard-surface flooring
9	Painting works
10	Kitchen and bathroom cabinets and counters
11	Water and sewer system connections
12	Landscaping works

In this problem, different objective functions can be used. One objective can be minimization of the makespan. The project is completed when all of the tasks are completed for the last building. This objective can be used if the resource level is limited and several projects are executed simultaneously. Hence, by minimizing the makespan, the company minimizes the penalty costs. Another objective function can be minimization of total costs, which covers penalty costs and subcontractor assignment costs. In this model, we can add a latest completion time constraint and if project completion time is greater than this completion time, then penalty costs incurs per day late. Hence, if the resources are insufficient then the company has to pay penalty costs. Otherwise, the model assigns required amount of subcontractors to each building for each task.

In the problem, 12 tasks should be completed for each building sequentially. For example, task i should be completed before starting task $i + 1$ for each building. On the other hand, different number of subcontractors can perform each task. Each subcontractor team has different processing times for each task. Hence, we may have bottlenecks for some tasks that have long processing times and limited number of subcontractor teams. Hence, the optimization model assigns the teams to the tasks considering all of these limitations. Now we will present the related literature and then explain the model.

3.2. Literature Review

Despite the fact that the problem defined above seems like a subcontractor assignment and scheduling problem, the structure of the problem is very similar to the Hybrid Flow Shop (HFS) problem in the machine scheduling literature. In this section, we will first explain the HFS problem, provide related literature, and then establish the connection with our model and HFS. In this problem, there are n jobs and these jobs should be processed in m different manufacturing stages. There are several variants of the problem but the common aspects of HFS are as follows (Ruiz et al., 2010)

i) There are at least 2 production stages and hence $m \geq 2$

ii) There are at least one machines in each of the stages and at least in one of the stages there are two machines. Hence, some of the stages are performed by more than one machine.

iii) The stages are ordered and the jobs pass through stage 1 to m.

iv) The jobs have different processing times in different stages.

In the most basic version of HFS, it is assumed that all machines and jobs are available at time zero. The machines in a stage are parallel and they are assumed identical. Any machine can be assigned to any job; hence, we do not have any restriction for task and machine assignment. In addition, the machines can perform only one job at a time and jobs do not have any precedence relation. Therefore, preemption is not allowed and if a machine starts a job, then the job should be completed before a new job assignment. Machine set up times are included in the process times, so they are not considered explicitly. Finally, we assume that all of the parameters are deterministic (Ribas et al., 2010).

The problem is a machine scheduling problem, however it has several application areas in other problem settings such as electronic industry (Wittrock, 1988), paper industry (Sherali et al., 1990), concrete production (Guinet, 1991), textile (Grabowski & Pempera, 2000) and so on. The problem is also applied to some non-manufacturing industries such as internet services (Allahverdi & Al-Anzi, 2006), container handling (Chen et al., 2007), and civil engineering (Dror & Mullaserif, 1996). As a result, we conclude that the problem is originally developed in machine scheduling literature, but then applied to several areas, as the problem structure is applicable to many different environments. Ruiz et al. (2010) provides an extensive review of the problem in different industries.

4. MATHEMATICAL MODEL 1: MINIMIZATION MAKESPAN

As explained beforehand, in our problem we have a set of buildings that should be completed by means of a production process conducted in a set of different stages as listed in Table 5. There is a precedence relation between the stages and it is not possible to start a stage before completing the previous stage. Moreover, the buildings follow the same sequence of stages but they may have different processing times as the size of the buildings may differ.

When all of the stages for all of the jobs are completed then the production process is ended and the company wants to minimize this time subject to resource constraints. On the other hand, the company can assign a set of subcontractors to different stages of the process. However, different subcontractors can perform different set of stages and as a result; we have different number of subcontractors for each production stage. In the problem, we assign the subcontractors to the jobs for each stage considering the precedence relations between the tasks while minimizing makespan of the project. The mathematical model is as follows:

4.1. Sets

B : $set\ of\ buildings, indexed\ by\ i\ and\ j$

T : $set\ of\ tasks\ in\ construction\ stages, indexed\ by\ t$

S : $set\ of\ subcontractors, indexed\ by\ k$

S^t : $set\ of\ subcontractors\ that\ can\ perform\ task\ t$

4.2. Parameters

$$S_{kt} = \begin{cases} 1, & if\ subcontractor\ k\ can\ perform\ task\ t: k \in S^t \\ 0, & otherwise \end{cases}$$

D_{kit} : $process\ duration\ of\ subcontractor\ k\ for\ building\ i\ and\ task\ t$

Note: If the buildings are identical and subcontractors perform the tasks in the same duration then $D_{kit} = D_t$. This case corresponds to identical parallel machines and identical jobs in the machine scheduling literature.

Q : $a\ sufficiently\ large\ number, a\ lower\ bound\ can\ be\ found\ as\ follows$:

$$\sum_{k}\sum_{i}\sum_{t} S_{kt} * D_{kit} \leq Q \quad (5)$$

4.3. Decision Variables:

c_{it} $= completion\ time\ of\ building\ i\ at\ construction\ stage\ t$

$$x_{kit} = \begin{cases} 1, & if\ task\ t\ of\ building\ i\ is\ scheduled\ to\ subcontractor\ k, k \in S^{t} \\ 0, & otherwise \end{cases}$$

$$y_{ijt} = \begin{cases} 1, & if\ building\ i\ precedes\ building\ j\ for\ task\ t \\ 0, & otherwise \end{cases}$$

m $= make\ span, completion\ time\ of\ the\ project$

4.4. Mathematical Model:

$Minimize\ m$

$subject\ to$

$$m \geq c_{it}, for\ \forall\ i \in B\ and\ t \in T \quad (6)$$

$$\sum_{k \in S} S_{kt} * x_{kit} = 1, for\ \forall\ i \in B\ and\ t \in T \quad (7)$$

$$c_{it} - c_{i,t-1} \geq \sum_{k \in S} S_{kt} * D_{kit} * x_{kit}, for \; \forall \; i \in B \; and \; t \in T \quad (8)$$

$$Q(2 - x_{kit} - x_{kjt} + y_{ijt}) + c_{it} - c_{jt} \geq D_{kit}, \\ for \; \forall \; t \in T, k \in S, i \in B, and \; j \in B \; such \; that \; i < j \quad (9)$$

$$Q(3 - x_{kit} - x_{kjt} - y_{ijt}) + c_{jt} - c_{it} \geq D_{kjt}, \\ for \; \forall \; t \in T, k \in S, i \in B, and \; j \in B \; such \; that \; i < j \quad (10)$$

$$x_{kit} \in \{0,1\}, for \; \forall \; k \in S, i \in B, and \; t \in T \quad (11)$$

$$y_{ijt} \in \{0,1\}, for \; \forall \; i \in B, j \in B, and \; t \in T \quad (12)$$

$$c_{it} \geq 0, for \; \forall \; i \in B \; and \; t \in T \quad (13)$$

We minimize the makespan in the objective function. Constraint (2) identifies the value of the makespan and it is equal to the completion time of the final building in the last production stage. Hence, makespan is greater than or equal to the completion time of each building for each task. In constraint (3), each building is assigned to one available subcontractor for each construction task. The assigned subcontractor should have the capability to perform corresponding task. Constraint (4) identifies the precedence relation between the construction stages for each building. The completion time of a task for a building should be larger than or equal to the completion time of the previous task for the building plus the processing time of the building for the assigned subcontractor for the current task.

Constraint set (5) and (6) prevent the overlapping of jobs in a common subcontractor at each stage. Constraint (5) ensures that if buildings i and j are assigned to the same subcontractor for a task k and i do not precede j, then $c_{it} - c_{jt} \geq D_{kit}$. In other words i is processed after j. Otherwise, since Q is a sufficiently large number then constraint is not restrictive. Constraint (6) guarantees that if buildings i and j are assigned to the same subcontractor for a task k and i precede j, then $c_{jt} - c_{it} \geq D_{kjt}$. Otherwise, since Q is a sufficiently large number then constraint is not restrictive. Finally, constraints (7), (8), and (9) define the decision variable ranges and types.

4.5. Computational Experiments

To solve the problem defined in the previous section we used General Algebraic Modeling System (GAMS). The GAMS code of the problem is given in Appendix C. In order to test the problem and see the relationship between problem size and complexity, we generate random test instances of different sizes. The test instances and their set sizes, problem types, number of equations, variables, and binary variables, solution times, and relative gaps are presented in Table 6. The HFS problem is in the NP-hard problem class and as the size of the sets increases then the problem size and solution time increases exponentially (Ruiz et al., 2010). We consider different problem sizes in terms of size of the building set, task set, and subcontractor set.

In addition to size of the problems, we also consider problem type. In the base case we assume that the buildings may have different sizes (require different processing types) and the subcontractors have different capability levels (have different processing times for the same tasks). We call this case as nonhomogeneous case and show it with "N". In the second case we assume that the buildings and the subcontractors are identical and hence $D_{kit} = D_t \; for \; \forall \; k \in S, i \in B, and \; t \in T$. We name this case as homogeneous case and show with "H" as illustrated in Table 6. The modified mathematical model for the homogeneous case is given in Appendix D.

Table 6. Summary of Problem Instances

#	Size of BxTxS (i-t-k)	Problem Type	Number of Equations	Number of Variables	Number of Binary Variables	Solution Time (minutes)	Percent Gap
1	5-5-5	H	575	200	175	0.419	0
2	5-5-5	N	575	200	175	0.079	0
3	10-5-5	H	2400	525	475	60.000	0.3
4	10-5-5	N	2400	525	475	60.000	0.5
5	5-5-10	H	1075	325	302	0.016	0
6	5-5-10	N	1075	325	302	0.020	0
7	5-12-5	H	1380	480	422	0.447	0
8	5-12-5	N	1380	480	422	6.651	0
9	10-12-10	H	11160	1860	1742	60.000	0.16
10	10-12-10	N	11160	1860	1742	60.000	0.32
11	15-12-10	H	25740	3240	3062	60.000	0.41
12	15-12-10	N	25740	3240	3062	60.000	0.41
13	15-12-15	H	38340	4140	3962	60.000	0.27
14	15-12-15	N	38340	4140	3962	60.000	0.27
15	20-12-10	H	46320	4920	4682	60.000	0.49
16	20-12-10	N	46320	4920	4682	60.000	0.50
17	20-12-20	H	91920	7320	7082	60.000	0.10
18	20-12-20	N	91920	7320	7082	60.000	0.32

As can be seen from Table 6, the instances have different set sizes for buildings (B), tasks (T), and subcontractor (S) sets. For the homogeneous (H) and nonhomogeneous (N) cases, we compare the same test instances to see the effect of homogeneity. Therefore, we have nine test instances for each H and N problem types. Before analyzing the solution times and relative gaps, first we consider the increase in size of the problem as the cardinality of the sets are increased.

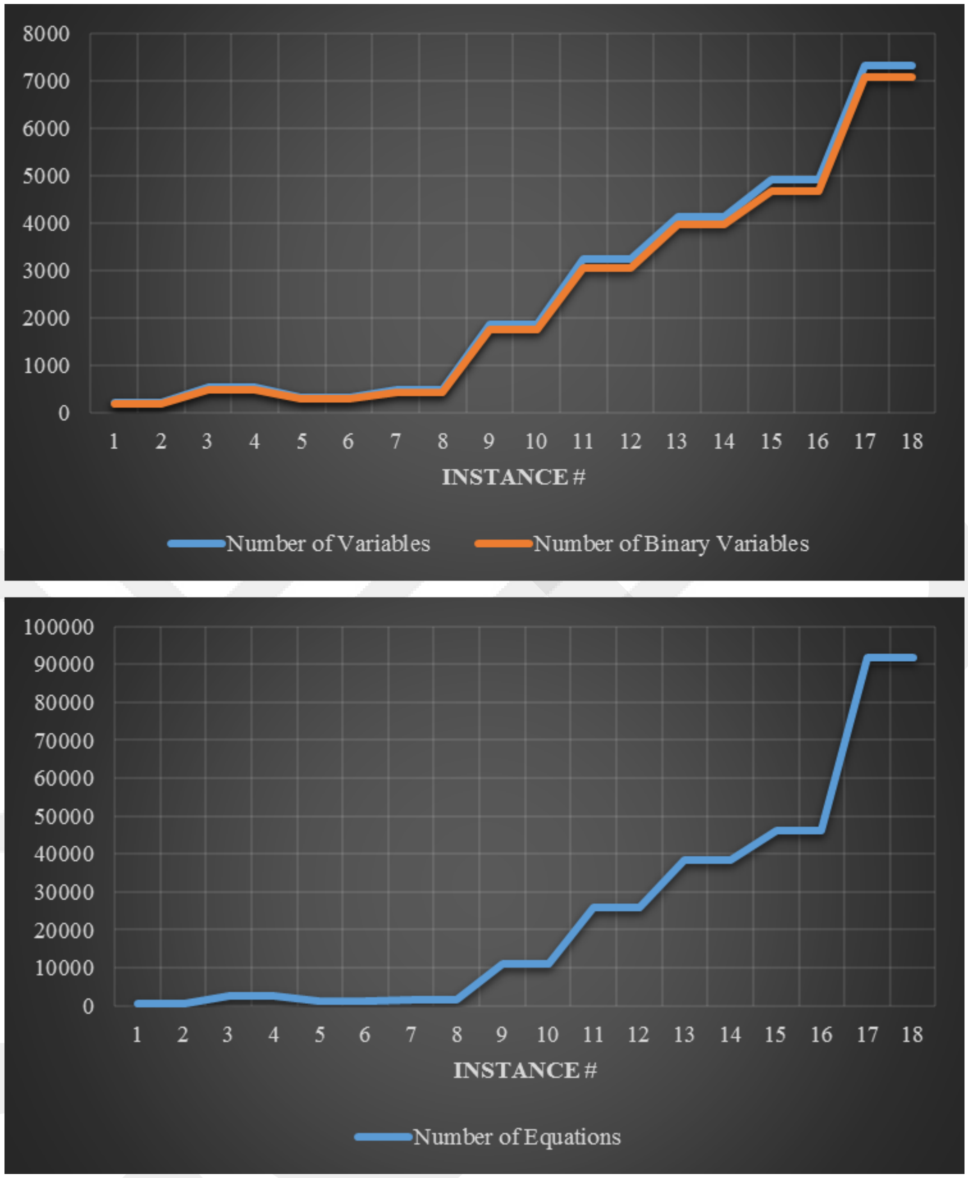

Figure 4. Size of the Problem for each Test Instance

As it is seen from Figure 4, if we increase the cardinality of the sets, then the number of equations and variables increase exponentially. Hence, as the problem size increases, the solution time also increases exponentially. In addition, on average more than 90 % of the decision variables are binary variables, which is another factor that increases the problem complexity and solution times.

As the problem is NP-hard, for larger instances the solution time is very long, hence, we limit the execution time to 3600 seconds. If the problem is solved optimally during this time, then we have zero gap and the solution time is smaller than 3600 seconds. If the problem cannot be solved optimally within allowed time limit, then the run is aborted at time=3600 seconds and the best solution is given together with the calculated optimality gap.

If we analyze the results given in Table 6, we observe that increasing the number of buildings while holding the other set sizes constant increases the solution time and optimality gap extensively. That is because all of the decision variables have an index for set B. On the other hand, if we consider the task set, again all of the decision variables depend on set T. In reality, the size of the task set is 12 as shown in Table 5. Therefore, we do not increase size of task set further, but we can see that cardinality of task set also has a similar effect as set B. Next, we consider the subcontractor set S and we observe that increasing cardinality of set S decreases the solution time or relative gap in general. That is because as more subcontractors become available, then the bottleneck related with the number of subcontractors decreases and the model make the assignments by selecting the subcontractors that have the smallest processing times. Finally, we consider the homogeneous (H) and nonhomogeneous (N) cases and observe that solution times or relative gaps generally increase in case N. This is expected because the problem is more complicated for case N.

To sum up, the problem is an NP-hard problem. For small and medium size problems, the proposed model can be used efficiently. On the other hand, for larger problems, since solution time increases exponentially some heuristic approaches or exact algorithmic methods can be developed so solve the problem in polynomial time.

5. MATHEMATICAL MODEL 2: MINIMIZATION OF TOTAL COSTS

In the previous model defined in chapter 3, we consider the minimization of makespan. This problem can be used when the construction company has several projects at hand and has limited resources to complete these projects. In this case, the company does not consider the costs at first place and tries to complete each project as soon as possible. For this case, we can use the first model. However, in most of the cases in construction projects a due date is determined and if the project cannot be completed up to this date, then the company pays penalty for each day late.

In addition to predetermined due dates, the subcontractor companies may charge different costs for the tasks. Since the task durations change from subcontractor to subcontractor, there is a tradeoff between the task durations and subcontractor costs. In this section, we consider the objective of cost minimization. Cost components are penalty costs due to lateness in project and subcontractor costs. In current problem we add due date as a constraint, however we allow the project to be completed after determined due date. The modified model is as follows:

5.1. Sets

B : $set\ of\ buildings, indexed\ by\ i\ and\ j$

T : $set\ of\ tasks\ in\ construction\ stages, indexed\ by\ t$

S : $set\ of\ subcontractors, indexed\ by\ k$

S^t : $set\ of\ subcontractors\ that\ can\ perform\ task\ t$

5.2. Parameters

$$S_{kt} = \begin{cases} 1, & if\ subcontractor\ k\ can\ perform\ task\ t: k \in S^t \\ 0, & otherwise \end{cases}$$

D_{kit} : $process\ duration\ of\ subcontractor\ k\ for\ building\ i\ and\ task\ t$

D : $project\ due\ date$

C^{pen} : $penalty\ cost\ per\ day\ lateness$

C_{kit}^{subc} : $assignment\ cost\ for\ subcontractor\ k\ to\ building\ i\ and\ task\ t$

Q : $a\ sufficiently\ large\ number, a\ lower\ bound\ can\ be\ found\ as\ follows$:

$$\sum_{k}\sum_{i}\sum_{t} S_{kt} * D_{kit} \leq Q \tag{14}$$

5.3. Decision Variables:

c_{it} $= completion\ time\ of\ building\ i\ at\ construction\ stage\ t$

$$x_{kit} = \begin{cases} 1, & if\ task\ t\ of\ building\ i\ is\ scheduled\ to\ subcontractor\ k, k \in S^{t} \\ 0, & otherwise \end{cases}$$

$$y_{ijt} = \begin{cases} 1, & if\ building\ i\ precedes\ building\ j\ for\ task\ t \\ 0, & otherwise \end{cases}$$

c $= project\ completion\ time$

l $= total\ lateness\ in\ project\ (days)$

e $= total\ earliness\ in\ project\ (days)$

5.4. Mathematical Model

$$Minimize \sum_{k\in S}\sum_{i\in B}\sum_{t\in T} C_{kit}^{subc} * x_{kit} + C^{pen} * l$$

$subject\ to$

$$c \geq c_{it}, for \; \forall \; i \in B \; and \; t \in T \tag{15}$$

$$c - D = l - e \tag{16}$$

$$\sum_{k \in S} S_{kt} * x_{kit} = 1, for \; \forall \; i \in B \; and \; t \in T \tag{17}$$

$$c_{it} - c_{i,t-1} \geq \sum_{k \in S} S_{kt} * D_{kit} * x_{kit} \, , for \; \forall \; i \in B \; and \; t \in T \tag{18}$$

$$Q(2 - x_{kit} - x_{kjt} + y_{ijt}) + c_{it} - c_{jt} \geq D_{kit}, \\ for \; \forall \; t \in T, k \in S, i \in B, and \; j \in B \; such \; that \; i < j \tag{19}$$

$$Q(3 - x_{kit} - x_{kjt} - y_{ijt}) + c_{jt} - c_{it} \geq D_{kjt}, \\ for \; \forall \; t \in T, k \in S, i \in B, and \; j \in B \; such \; that \; i < j \tag{20}$$

$$x_{kit} \in \{0,1\}, for \; \forall \; k \in S, i \in B, and \; t \in T \tag{21}$$

$$y_{ijt} \in \{0,1\}, for \; \forall \; i \in B, j \in B, and \; t \in T \tag{22}$$

$$c_{it} \geq 0, for \; \forall \; i \in B \; and \; t \in T \tag{23}$$

$$c, l, and \; e \geq 0 \tag{24}$$

In this model, we minimize the sum of total penalty costs and subcontractor assignment costs. Constraint (11) determines the completion time of the project, which is larger than the completion time of each task for each building. Constraint (12) identifies the lateness or earliness of the project. If the project is completed after the due date then lateness variable l becomes positive. Else, if the project is completed before the due date, then earliness variable e becomes positive and no penalty cost incurs. Constraints (13-19) correspond to the constraints (3-9) in Model 1. Finally, constraint (20) determines the ranges of the new decision variables.

5.5. Analysis of the Results

The GAMS code for the model defined above is given in Appendix E. The new model minimizes total subcontractor assignment and penalty costs. We allow lateness in the project by incurring a penalty cost and hence the problem never becomes infeasible even if the resources are insufficient in completing the project until due date. As a result, the objective function changes and some additional constraints are added to the problem. To test the new problem we used the test instances given in Table 6 and we add the new parameters $D, C^{pen}, and\ C_{kit}^{subc}$ to the model. Depending on the value of the parameter D, the solution time changes significantly. If D is selected to be greater than the optimum project completion time found in Model 1, then even for the largest instances the problem solved optimally within seconds. On the other hand, if D is smaller than or equal to the optimum project completion time found in Model 1, then the solution time increases. However still solution time is smaller than the Model 1 for the same test instances.

6. CONCLUSION

In this thesis, we study performance measurement and improvement in construction industry. The main purpose of the study is to review performance measurement and improvement applications in the literature and adapt these applications to Turkish Construction Industry. We divide the study into two main parts, namely performance improvement and performance measurement.

In the performance measurement part, we concentrate in performance evaluation. For that purpose, first, we conduct a detailed literature review and as a result, we see that there is no consensus on evaluating the performance of construction companies, which is also valid for Turkish Construction Industry. Hence, to provide a common means for performance evaluation we develop a balanced score card framework based on questionnaire survey. As a result, identify key management dimensions and the performance measures for evaluating each of these dimensions. In addition to that, we identify the weights of the management dimensions and weights of the performance measures within each management dimension.

In the performance improvement part, we mainly concentrate on the improvement of financial performance of the company. For that purpose, we propose two mathematical programming models for solving resource allocation and scheduling problems simultaneously considering several operational constraints. In the first model, our objective is the minimization of makespan, while in the second problem the objective is to minimize costs. Both model aims to improve financial performance of the company. In the first model, performance improvement is achieved by means of minimizing project completion time. By this way, the daily resource usage costs are minimized and available resources after the project completion can be used for other projects. The second model improves financial performance by directly minimizing the total penalty costs because of lateness and subcontractor assignment costs. Hence, both of the models can be used under different problem environments. The proposed models are tested with a set of randomly generated test instances and solution performance and problem complexities are analyzed.

As a future work, the proposed framework can be applied on several companies in Turkish construction industry and the results can be compared with the results in Literature. By this way, the strengths and weaknesses of Turkish Construction Industry can be identified and necessary measures can be taken to improve performance. On the other hand, for performance improvement we concentrate on financial performance. Hence, some other studies can be conducted for improving other management dimensions such as market measures, customer measures, internal business measures, and learning and growth.

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APPENDIX A – QUESTIONNAIRE FOR PERFORMANCE EVALUATION

Name :
Company :
Position :
E-Mail :
Phone :

Please respond the given performance measures and tick mark according to significance level of the performance measure. Please do not leave any blank spaces. (1- Not Important, 2- Slightly Important, 3- Moderately Important, 4- Important, 5- Very Important)

#	Performance Measure					
F	**Financial Measures**					
F1	Asset turnover rate	1	2	3	4	5
F2	Return on equity	1	2	3	4	5
F3	Revenue growth rate	1	2	3	4	5
F4	Operating profit	1	2	3	4	5
F5	Sales per Capita	1	2	3	4	5
M	**Market Measures**					
M1	Number of markets dominated	1	2	3	4	5
M2	Income proportion from international activities	1	2	3	4	5
M3	Number of countries that the company operates	1	2	3	4	5
M4	Income growth rate from international activities	1	2	3	4	5
C	**Customer Measures**					
C1	Customer value realization	1	2	3	4	5
C2	Regular customer proportion	1	2	3	4	5
C3	Customer cooperation	1	2	3	4	5
I	**Internal Business Measures**					
I1	Number of core businesses	1	2	3	4	5
I2	Construction works profit proportion	1	2	3	4	5
I3	Number of international businesses	1	2	3	4	5
I4	Coordination and integration of businesses	1	2	3	4	5
I5	Supply chain management	1	2	3	4	5
L	**Learning and Growth Measures**					
L1	R&D efficiency	1	2	3	4	5
L2	IT applicability	1	2	3	4	5
L3	Employee satisfaction	1	2	3	4	5
L4	Efficiency of organization and management	1	2	3	4	5
L5	Information sharing	1	2	3	4	5

APPENDIX B – QUESTIONAIRE SURVEY RESULTS

Financial Measures

Participant ID	F1	F2	F3	F4	F5	Total
1	4	4	4	5	3	20
2	3	3	3	4	3	16
3	3	3	3	3	3	15
4	4	4	4	4	4	20
5	4	4	4	3	3	18
6	3	3	3	3	3	15
7	3	4	4	4	4	19
8	4	3	4	4	4	19
9	4	4	4	4	3	19
10	3	4	4	3	3	17
11	3	4	4	4	4	19
12	4	4	4	4	3	19
13	4	3	4	4	4	19
14	4	4	3	4	4	19
15	4	4	4	5	3	20
16	3	3	4	4	4	18
17	3	3	3	3	3	15
18	4	3	4	5	3	19
19	4	4	4	3	3	18
20	4	4	3	4	4	19
21	3	4	4	4	4	19
22	4	5	4	4	4	21
23	3	4	4	4	4	19
24	3	4	4	3	3	17
25	3	4	4	4	4	19
26	4	4	4	5	3	20
27	4	4	5	4	4	21
28	4	4	3	4	4	19
29	4	4	4	4	4	20
30	3	3	3	4	3	16
31	3	3	3	4	4	17
32	4	4	4	4	4	20
33	4	4	4	3	3	18
34	4	4	4	4	4	20
35	3	3	3	4	4	17
36	4	3	4	4	4	19
37	4	5	4	4	4	21

38	3	4	4	3	3	17
39	4	4	4	4	4	20
40	4	4	3	4	3	18
41	4	5	5	4	4	22
42	4	4	3	4	4	19
43	3	4	4	4	3	18
44	4	4	4	5	3	20
45	4	5	5	4	4	22
46	4	4	3	4	4	19
47	3	4	4	3	3	17
48	4	4	4	4	4	20
49	3	3	3	4	4	17
50	4	3	4	4	4	19
51	4	4	4	4	4	20
52	4	3	3	4	4	18
Average	**3.635**	**3.788**	**3.769**	**3.904**	**3.596**	**3.738**
Weight	**0.194**	**0.203**	**0.202**	**0.209**	**0.192**	**0.199**

Minitab Item Analysis of F1, F2, F3, F4, F5

```
Correlation Matrix

       F1     F2     F3     F4
F2  0.351
F3  0.267  0.531
F4  0.391  0.061  0.124
F5  0.189  0.108  0.084  0.221

Cell Contents: Pearson correlation


Covariance Matrix

         F1       F2       F3       F4       F5
F1  0.23643
F2  0.09766  0.32692
F3  0.07089  0.16591  0.29864
F4  0.10143  0.01848  0.03620  0.28469
F5  0.04563  0.03054  0.02262  0.05845  0.24548


Item and Total Statistics

          Total
Variable  Count    Mean  StDev
F1           52   3.635  0.486
F2           52   3.788  0.572
F3           52   3.769  0.546
F4           52   3.904  0.534
F5           52   3.596  0.495
Total        52  18.692  1.639
```

Cronbach's alpha = 0.6026

Omitted Item Statistics

Omitted Variable	Adj. Total Mean	Adj. Total StDev	Item-Adj. Total Corr	Squared Multiple Corr	Cronbach's Alpha
F1	15.058	1.349	0.48112	0.26900	0.48671
F2	14.904	1.317	0.41498	0.33977	0.51503
F3	14.923	1.341	0.40345	0.29332	0.52237
F4	14.788	1.405	0.28621	0.18762	0.58529
F5	15.096	1.459	0.21757	0.06483	0.61480

Market Measures

Participant ID	M1	M2	M3	M4	Total
1	3	3	3	2	11
2	3	3	3	3	12
3	4	3	3	3	13
4	3	3	3	3	12
5	3	3	3	3	12
6	3	3	3	3	12
7	3	3	3	3	12
8	3	3	4	4	14
9	3	3	3	4	13
10	4	3	3	4	14
11	3	3	4	4	14
12	3	3	3	2	11
13	3	3	3	3	12
14	4	3	3	3	13
15	3	3	3	3	12
16	3	3	3	3	12
17	3	3	3	3	12
18	3	3	3	3	12
19	3	3	4	4	14
20	3	3	3	4	13
21	4	3	3	4	14
22	3	3	4	4	14
23	4	3	3	3	13
24	3	3	3	3	12
25	3	3	3	3	12
26	3	3	3	3	12
27	3	3	3	3	12
28	3	3	4	4	14

29	3	3	3	4	13
30	4	3	3	4	14
31	3	3	4	4	14
32	4	4	3	3	14
33	4	4	3	3	14
34	4	4	3	4	15
35	3	4	3	3	13
36	4	4	3	4	15
37	4	4	4	4	16
38	3	4	3	4	14
39	4	4	4	4	16
40	4	4	3	3	14
41	4	4	3	3	14
42	4	4	3	4	15
43	3	4	3	3	13
44	4	4	3	4	15
45	4	4	4	4	16
46	3	4	3	4	14
47	4	4	4	4	16
48	3	4	3	4	14
49	4	4	4	4	16
50	4	4	4	4	16
51	5	5	3	3	16
52	5	5	4	4	18
Average	**3.462**	**3.442**	**3.250**	**3.462**	**3.404**
Weight	**0.254**	**0.253**	**0.239**	**0.254**	**0.181**

Minitab Item Analysis of M1, M2, M3, M4

```
Correlation Matrix

       M1     M2     M3
M2  0.675
M3  0.156  0.176
M4  0.232  0.260  0.545

Cell Contents: Pearson correlation


Covariance Matrix

         M1        M2        M3        M4
M1  0.33183
M2  0.22323  0.32994
M3  0.03922  0.04412  0.19118
M4  0.07692  0.08597  0.13725  0.33183
```

```
Item and Total Statistics

           Total
Variable   Count    Mean  StDev
M1            52   3.462  0.576
M2            52   3.442  0.574
M3            52   3.250  0.437
M4            52   3.462  0.576
Total         52  13.615  1.549
```

Cronbach's alpha = 0.6746

```
Omitted Item Statistics

                        Adj.                   Squared
Omitted    Adj. Total  Total    Item-Adj.   Multiple  Cronbach's
Variable         Mean  StDev  Total Corr        Corr       Alpha
M1             10.154  1.178      0.5001      0.4586      0.5780
M2             10.173  1.167      0.5271      0.4668      0.5583
M3             10.365  1.329      0.3797      0.2983      0.6560
M4             10.154  1.211      0.4303      0.3273      0.6273
```

Customer Measures

Participant ID	C1	C2	C3	Total
1	4	4	5	13
2	4	4	4	12
3	4	4	4	12
4	4	4	4	12
5	4	4	5	13
6	4	4	4	12
7	4	4	4	12
8	4	4	5	13
9	4	3	4	11
10	4	3	4	11
11	4	3	4	11
12	4	3	4	11
13	4	4	4	12
14	4	4	4	12
15	4	4	3	11
16	4	4	4	12
17	4	4	4	12
18	4	4	4	12
19	4	4	5	13
20	4	3	3	10
21	4	4	4	12
22	4	4	4	12

23	4	4	4	12
24	4	4	4	12
25	4	3	4	11
26	4	4	4	12
27	4	4	4	12
28	4	4	3	11
29	4	4	4	12
30	4	4	4	12
31	5	4	4	13
32	4	4	4	12
33	4	4	4	12
34	4	4	4	12
35	5	4	5	14
36	4	4	4	12
37	4	4	5	13
38	4	4	5	13
39	3	3	3	9
40	4	4	3	11
41	4	4	4	12
42	4	4	4	12
43	4	4	4	12
44	4	4	4	12
45	4	4	4	12
46	4	4	4	12
47	5	4	4	13
48	3	3	3	9
49	3	3	3	9
50	4	4	4	12
51	5	4	4	13
52	4	3	4	11
Average	**4.019**	**3.808**	**4.000**	**3.942**
Weight	**0.340**	**0.322**	**0.338**	**0.209**

Minitab Item Analysis of C1, C2, C3

```
Correlation Matrix

       C1     C2
C2  0.425
C3  0.405  0.376

Cell Contents: Pearson correlation


Covariance Matrix
```

```
          C1        C2        C3
C1   0.13688
C2   0.06259   0.15837
C3   0.07843   0.07843   0.27451


Item and Total Statistics

           Total
Variable   Count     Mean   StDev
C1            52    4.019   0.370
C2            52    3.808   0.398
C3            52    4.000   0.524
Total         52   11.827   1.004
```

Cronbach's alpha = 0.6527

```
Omitted Item Statistics

                                                 Squared
Omitted    Adj. Total  Adj. Total   Item-Adj.   Multiple   Cronbach's
Variable         Mean       StDev  Total Corr       Corr        Alpha
C1             7.8077      0.7679      0.4964     0.2505       0.5320
C2             8.0192      0.7538      0.4701     0.2306       0.5521
C3             7.8269      0.6484      0.4617     0.2146       0.5955
```

Internal Business Measures

Participant ID	I1	I2	I3	I4	I5	Total
1	4	3	3	4	4	18
2	3	3	3	4	4	17
3	4	5	4	4	4	21
4	4	4	4	4	4	20
5	3	3	4	4	4	18
6	4	3	4	4	4	19
7	4	4	4	4	4	20
8	4	4	4	3	3	18
9	4	4	5	4	4	21
10	4	4	4	4	4	20
11	4	4	3	4	4	19
12	4	4	4	3	3	18
13	4	3	4	4	4	19
14	4	4	4	4	4	20
15	4	4	4	4	3	19
16	4	3	4	5	3	19
17	4	3	4	3	3	17
18	4	3	4	4	4	19

19	4	5	4	4	4	21
20	3	4	4	4	4	19
21	3	4	4	4	4	19
22	3	3	3	3	4	16
23	4	4	4	4	4	20
24	4	4	4	4	4	20
25	4	4	4	5	4	21
26	3	4	4	3	3	17
27	4	5	5	4	4	22
28	4	4	4	5	4	21
29	4	4	4	4	4	20
30	3	3	3	4	3	16
31	3	4	4	3	3	17
32	3	3	3	3	4	16
33	4	4	4	4	4	20
34	4	4	4	3	3	18
35	3	3	3	4	4	17
36	4	4	4	5	3	20
37	3	3	3	3	3	15
38	4	4	3	4	4	19
39	4	4	4	3	3	18
40	4	4	4	4	4	20
41	4	4	4	4	4	20
42	4	3	3	4	4	18
43	4	3	4	4	4	19
44	3	4	4	3	3	17
45	4	4	4	4	4	20
46	4	5	5	4	4	22
47	4	4	4	3	3	18
48	4	4	4	4	4	20
49	4	4	4	3	3	18
50	3	4	4	3	3	17
51	3	3	3	4	4	17
52	3	4	4	4	3	18
Average	**3.712**	**3.769**	**3.846**	**3.808**	**3.673**	**3.762**
Weight	**0.197**	**0.200**	**0.204**	**0.202**	**0.195**	**0.200**

Minitab Item Analysis of I1, I2, I3, I4, I5

Correlation Matrix

	I1	I2	I3	I4
I2	0.335			
I3	0.402	0.617		
I4	0.314	0.042	0.102	
I5	0.190	0.005	-0.051	0.496

Cell Contents: Pearson correlation

Covariance Matrix

	I1	I2	I3	I4	I5
I1	0.20928				
I2	0.08899	0.33786			
I3	0.09201	0.17949	0.25038		
I4	0.08069	0.01357	0.02866	0.31523	
I5	0.04110	0.00151	-0.01207	0.13198	0.22436

Item and Total Statistics

Variable	Total Count	Mean	StDev
I1	52	3.712	0.457
I2	52	3.769	0.581
I3	52	3.846	0.500
I4	52	3.808	0.561
I5	52	3.673	0.474
Total	52	18.808	1.621

Cronbach's alpha = 0.6142

Omitted Item Statistics

Omitted Variable	Adj. Total Mean	Adj. Total StDev	Item-Adj. Total Corr	Squared Multiple Corr	Cronbach's Alpha
I1	15.096	1.347	0.4914	0.2564	0.5044
I2	15.038	1.313	0.3715	0.3946	0.5605
I3	14.962	1.343	0.4288	0.4374	0.5294
I4	15.000	1.343	0.3380	0.3031	0.5780
I5	15.135	1.442	0.2379	0.2659	0.6199

Learning and Growth Measures

Participant ID	L1	L2	L3	L4	L5	Total
1	4	4	4	4	4	20
2	4	4	5	4	4	21
3	4	4	4	4	4	20
4	4	4	4	4	4	20
5	4	4	4	4	4	20
6	4	4	4	5	4	21
7	3	4	4	4	4	19
8	3	4	4	3	3	17
9	4	4	5	4	4	21
10	4	4	4	5	3	20
11	4	4	5	4	4	21
12	4	5	5	4	4	22
13	4	4	4	5	4	21
14	4	4	4	5	4	21
15	4	4	3	4	4	19
16	4	4	4	4	4	20
17	4	4	4	4	4	20
18	4	4	5	4	4	21
19	4	4	4	4	4	20
20	4	4	4	4	4	20
21	4	4	5	4	4	21
22	3	4	4	4	4	19
23	3	4	4	4	4	19
24	4	5	4	4	4	21
25	3	4	3	4	4	18
26	4	4	4	5	4	21
27	3	3	3	4	3	16
28	4	4	4	4	4	20
29	4	4	4	4	4	20
30	3	3	3	3	3	15
31	4	4	3	4	4	19
32	4	4	4	5	4	21
33	4	4	4	4	4	20
34	4	4	4	5	4	21
35	4	4	4	4	4	20
36	4	4	4	4	4	20
37	4	4	4	4	4	20
38	3	3	3	4	4	17
39	4	4	4	4	3	19
40	4	4	4	5	4	21
41	4	4	4	4	4	20
42	4	4	4	4	4	20

43	4	4	3	4	4	19
44	4	5	4	4	4	21
45	4	4	4	5	4	21
46	4	4	4	4	4	20
47	4	4	4	5	4	21
48	4	4	4	4	4	20
49	3	4	4	5	4	20
50	3	4	4	4	4	19
51	4	4	4	4	4	20
52	4	5	4	5	4	22
Average	**3.808**	**4.019**	**3.981**	**4.192**	**3.904**	**3.981**
Weight	**0.191**	**0.202**	**0.200**	**0.211**	**0.196**	**0.211**

Minitab Item Analysis of L1, L2, L3, L4, L5

```
Correlation Matrix

       L1     L2     L3     L4
L2  0.425
L3  0.372  0.422
L4  0.296  0.197  0.095
L5  0.337  0.373  0.249  0.266

Cell Contents: Pearson correlation


Covariance Matrix

         L1       L2       L3       L4       L5
L1  0.15837
L2  0.06259  0.13688
L3  0.07466  0.07881  0.25452
L4  0.05732  0.03544  0.02338  0.23680
L5  0.03997  0.04110  0.03733  0.03846  0.08861


Item and Total Statistics

          Total
Variable  Count    Mean  StDev
L1           52   3.808  0.398
L2           52   4.019  0.370
L3           52   3.981  0.505
L4           52   4.192  0.487
L5           52   3.904  0.298
Total        52  19.904  1.361
```

Cronbach's alpha = 0.6597

```
Omitted Item Statistics

                       Adj.                Squared
```

Omitted Variable	Adj. Total Mean	Total StDev	Item-Adj. Total Corr	Multiple Corr	Cronbach's Alpha
L1	16.096	1.107	0.5323	0.2879	0.5537
L2	15.885	1.132	0.5206	0.3058	0.5646
L3	15.923	1.082	0.3924	0.2288	0.6263
L4	15.712	1.143	0.2779	0.1224	0.6822
L5	16.000	1.205	0.4375	0.2056	0.6105

APPENDIX C – GAMS CODE FOR MODEL 1: MINIMIZE MAKESPAN

```
SET B set of building indexed by i and j /1*5/

ALIAS (B,i,j);

SET T set of tasks in construction stages indexed by t
/1*5/

SET S set of subcontractors indexed by k /1*5/

ALIAS (s,k);


TABLE S_kt(k,t) 1 if subcontractor k can perform task t:
0 otherwise

        1       2       3       4       5

1       0       0       1       0       0

2       0       0       0       1       0

3       1       1       1       1       0

4       1       0       0       0       1

5       1       0       0       0       1
```

TABLE D(k,i,t) process duration of subcontractor k for building i and task t

	1	2	3	4	5
1.1	3	7	59	30	14
2.1	3	7	60	29	13
3.1	4	7	60	31	13
4.1	7	7	58	28	14
5.1	5	4	63	30	13
1.2	4	7	61	32	13
2.2	5	6	59	29	14
3.2	6	8	59	27	13
4.2	8	6	60	31	12
5.2	2	4	58	28	14
1.3	5	8	59	30	12
2.3	4	7	60	30	13
3.3	8	5	59	29	12
4.3	2	5	63	31	13
5.3	5	6	60	31	14
1.4	6	6	61	29	16

2.4	5	7	58	30	16
3.4	6	5	59	30	12
4.4	7	8	61	27	13
5.4	4	5	59	30	13
1.5	8	8	61	31	13
2.5	7	7	58	30	14
3.5	8	8	58	31	14
4.5	5	9	59	33	15
5.5	5	7	62	32	15

```
PARAMETER Q: a sufficiently large number;

Q = sum((k,i,t),S_kt(k,t)*D(k,i,t)) ;

VARIABLE c(i,t):completion time of building i at construction stage t

VARIABLE x(k,i,t):1 if task t of building i is scheduled to subcontractor k and 0 otherwise

VARIABLE y(i,j,t):1 if building i precedes building j for task t and 0 otherwise

VARIABLE z: objective function value

VARIABLE m: make span-completion time of the project

BINARY VARIABLE x,y;
```

```
POSITIVE VARIABLE c,m;

FREE VARIABLE z;

EQUATIONS

ObjectiveFunction

ProjectCompletionTimeConstraint(i,t)

SubcontractorBuildingTaskAssignment(i,t)

CompletionTime(i,t)

SubcontractorOverlapping1(i,t,k,j)

SubcontractorOverlapping2(i,t,k,j)

ObjectiveFunction..z =e= m;

ProjectCompletionTimeConstraint(i,t).. m=g=c(i,t);

SubcontractorBuildingTaskAssignment(i,t)..

sum(k,S_kt(k,t)*x(k,i,t))=e=1;

CompletionTime(i,t)..

c(i,t)-c(i,t-1)=g=sum(k,S_kt(k,t)*D(k,i,t)*x(k,i,t));

SubcontractorOverlapping1(i,t,k,j)$(ord(i) lt ord(j))..

Q*(2-x(k,i,t)-x(k,j,t)+y(i,j,t))+c(i,t)-c(j,t)=g=D(k,i,t);

SubcontractorOverlapping2(i,t,k,j)$(ord(i) lt ord(j))..

Q*(3-x(k,i,t)-x(k,j,t)-y(i,j,t))+c(j,t)-c(i,t)=g=D(k,j,t);
```

```
MODEL    ConstructionScheduling /all/;

OPTION   Reslim=3600;

OPTION   Optcr=0.00;

SOLVE    ConstructionScheduling using MIP minimizing z;

DISPLAY                                    m.l,x.l,y.l,c.l;
```

APPENDIX D – MODEL 1 HOMOGENEOUS CASE

$Minimize\ m$

$subject\ to$

$$m \geq c_{it}, for\ \forall\ i \in B\ and\ t \in T \tag{25}$$

$$\sum_{k \in S} S_{kt} * x_{kit} = 1, for\ \forall\ i \in B\ and\ t \in T \tag{26}$$

$$c_{it} - c_{i,t-1} \geq \sum_{k \in S} S_{kt} * D_t * x_{kit}, for\ \forall\ i \in B\ and\ t \in T \tag{27}$$

$$Q(2 - x_{kit} - x_{kjt} + y_{ijt}) + c_{it} - c_{jt} \geq D_t, \\ for\ \forall\ t \in T, k \in S, i \in B, and\ j \in B\ such\ that\ i < j \tag{28}$$

$$Q(3 - x_{kit} - x_{kjt} - y_{ijt}) + c_{jt} - c_{it} \geq D_t, \\ for\ \forall\ t \in T, k \in S, i \in B, and\ j \in B\ such\ that\ i < j \tag{29}$$

$$x_{kit} \in \{0,1\}, for\ \forall\ k \in S, i \in B, and\ t \in T \tag{30}$$

$$y_{ijt} \in \{0,1\}, for\ \forall\ i \in B, j \in B, and\ t \in T \tag{31}$$

$$c_{it} \in \{0,1\}, for\ \forall\ i \in B\ and\ t \in T \tag{32}$$

APPENDIX E – GAMS CODE FOR MODEL 2: MINIMIZE TOTAL COSTS

```
SET B set of building indexed by i and j /1*5/

ALIAS (B,i,j);

SET T set of tasks in construction stages indexed by t
/1*5/

SET S set of subcontractors indexed by k /1*5/

ALIAS (s,k);

PARAMETER DD project due date /250/

PARAMETER C_pen penalty cost per day lateness   /10000/

TABLE C_subc(k,i,t) assignment cost for subcontractor k to
building i and task t

              1         2          3          4          5
1.1        9000     16800     141600     120000      54600
2.1        9000     16800     144000     116000      50700
3.1       12000     16800     144000     124000      50700
4.1       21000     16800     139200     112000      54600
5.1       15000      9600     151200     120000      50700
1.2       12000     16800     146400     128000      50700
2.2       15000     14400     141600     116000      54600
3.2       18000     19200     141600     108000      50700
4.2       24000     14400     144000     124000      46800
5.2        6000      9600     139200     112000      54600
1.3       15000     19200     141600     120000      46800
2.3       12000     16800     144000     120000      50700
3.3       24000     12000     141600     116000      46800
```

4.3	6000	12000	151200	124000	50700
5.3	15000	14400	144000	124000	54600
1.4	18000	14400	146400	116000	62400
2.4	15000	16800	139200	120000	62400
3.4	18000	12000	141600	120000	46800
4.4	21000	19200	146400	108000	50700
5.4	12000	12000	141600	120000	50700
1.5	24000	19200	146400	124000	50700
2.5	21000	16800	139200	120000	54600
3.5	24000	19200	139200	124000	54600
4.5	15000	21600	141600	132000	58500
5.5	15000	16800	148800	128000	58500

TABLE S_kt(k,t) 1 if subcontractor k can perform task t: 0 otherwise

	1	2	3	4	5
1	0	0	1	0	0
2	0	0	0	1	0
3	1	1	1	1	0
4	1	0	0	0	1
5	1	0	0	0	1

TABLE D(k,i,t) process duration of subcontractor k for building i and task t

	1	2	3	4	5
1.1	3	7	59	30	14
2.1	3	7	60	29	13
3.1	4	7	60	31	13
4.1	7	7	58	28	14
5.1	5	4	63	30	13
1.2	4	7	61	32	13
2.2	5	6	59	29	14
3.2	6	8	59	27	13
4.2	8	6	60	31	12
5.2	2	4	58	28	14
1.3	5	8	59	30	12
2.3	4	7	60	30	13
3.3	8	5	59	29	12
4.3	2	5	63	31	13
5.3	5	6	60	31	14
1.4	6	6	61	29	16
2.4	5	7	58	30	16
3.4	6	5	59	30	12
4.4	7	8	61	27	13
5.4	4	5	59	30	13
1.5	8	8	61	31	13

2.5	7	7	58	30	14
3.5	8	8	58	31	14
4.5	5	9	59	33	15
5.5	5	7	62	32	15

```
PARAMETER Q: a sufficiently large number;
Q = sum((k,i,t),S_kt(k,t)*D(k,i,t)) ;

VARIABLE c(i,t :completion time of building i at construction stage t

VARIABLE x(k,i,t):1 if task t of building i is scheduled to subcontractor k and 0 otherwise

VARIABLE y(i,j,t):1 if building i precedes building j for task t and 0 otherwise

VARIABLE cost: objective function value

VARIABLE comp: project completion time

VARIABLE l: total lateness in project (days)

VARIABLE e: total earliness in project (days)
```

```
BINARY VARIABLE x,y;
POSITIVE VARIABLE c,l,e,comp;
FREE VARIABLE cost;
EQUATIONS
ObjectiveFunction
SubcontractorBuildingTaskAssignment(i,t)
ProjectCompletionTimeConstraint(i,t)
LatenessEarlinessConstraint
SubcontractorBuildingTaskAssignment(i,t)
CompletionTime(i,t)
SubcontractorOverlapping1(i,t,k,j)
SubcontractorOverlapping2(i,t,k,j);
ObjectiveFunction..
Cost=e=sum((k,i,t),C_subc(k,i,t)*x(k,i,t))+C_pen*l;
ProjectCompletionTimeConstraint(i,t)..comp=g=c(i,t);
LatenessEarlinessConstraint..comp-DD=e=l-e;
SubcontractorBuildingTaskAssignment(i,t)..
sum(k,S_kt(k,t)*x(k,i,t))=e=1;
CompletionTime(i,t)..
c(i,t)-c(i,t-1)=g=sum(k,S_kt(k,t)*D(k,i,t)*x(k,i,t));

SubcontractorOverlapping1(i,t,k,j)$(ord(i) lt ord(j))..
Q*(2-x(k,i,t)-x(k,j,t)+y(i,j,t))+c(i,t)-c(j,t)=g=D(k,i,t);
```

```
SubcontractorOverlapping2(i,t,k,j)$(ord(i) lt ord(j))..
Q*(3-x(k,i,t)-x(k,j,t)-y(i,j,t))+c(j,t)-c(i,t)=g=D(k,j,t);


MODEL   ConstructionScheduling2 /all/;
OPTION  Reslim=3600;
OPTION  Optcr=0.00;
SOLVE   ConstructionScheduling2 using MIP minimizing Cost;
DISPLAY x.l,y.l,c.l;
```