T.C.
MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES IN
PURE AND APPLIED SCIENCES

AN APPROACH OF CONSTRAINT-BASED SCHEDULING FOR A CONSTRUCTION FIRM

ALPER ÇALIŞIR
(Industrial Engineering)

THESIS
FOR THE DEGREE OF MASTER OF SCIENCE
IN
INDUSTRIAL ENGINEERING PROGRAMME

SUPERVISOR
Asst.Prof.Dr. Serol BULKAN

İSTANBUL 2006

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ACCEPTANCE AND APPROVAL DOCUMENT

AN APPROACH OF CONSTRAINT-BASED SCHEDULING FOR A CONSTRUCTION FIRM

Established committee listed below, on 04.07.2006 and 2006/17-22 by the *INSTITUTE FOR GRADUATE STUDIES IN PURE AND APPLIED SCIENCES*' Executive Committee, have accepted Mr. Alper ÇALIŞIR's Master of Science thesis, titled as " AN APPROACH OF CONSTRAINT-BASED SCHEDULING FOR A CONSTRUCTION FIRM " in Industrial Engineering.

COMMITTEE

Advisor : Asst. Prof. Dr. Serol BULKAN

Member : Asst. Prof. Dr. Bahar SENNAROĞLU

Member : Asst. Prof. Dr. Arzu BALOĞLU

Date of thesis' defense before the committee: 17.07.2006

APPROVAL

Mr. Alper ÇALIŞIR has satisfactorily completed the requirements for the degree of Master of Science in Industrial Engineering at Marmara University.
Mr. Alper ÇALIŞIR is eligible to have the degree awarded at our convocation on .... Diploma and transcripts so noted will be available after that date.

Istanbul **DIRECTOR**

ACKNOWLEDGEMENT

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I also want to offer thanks to Asst.Prof.Dr. Serol BULKAN.

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ÖZET

İNŞAAT FİRMASI İÇİN KISIT TEMELLİ İŞ PROGRAMLAMASI YAKLAŞIMI

Araştırmanın amacı hızlı, rekabetçi ve kar getirecek bir teklifin oluşturulabilmesi için teklif aşamasındaki bir projenin iş planlamasının verimli yapılabilmesini sağlayacak modelin belirlenmesi ve bu modelin uygulanmasıdır.

Araştırmanın ilk aşamasında problem ve problemin diğer halleri tanımlanmıştır. Daha sonra, en rekabetçi fiyatı verecek en uygun ve hızlı yöntem belirlenmiş modeller arasından seçilmiştir. Modelin seçilmesi için ilk önce kaynak kısıtlı iş planlaması modelleri aşamalarına göre sınıflandırılmıştır ve geçmiş yapıtlar üzerinden tartışılmıştır. Anlaşılacağı üzere şeçilen en önemli kriter, modelin hızlı yanıt verebilmesi olmuştur.

Modelin seçilmesinden sonraki aşama ise, daha önce proje mühendisi olarak çalıştığım firmanın projesinde, en ekonomik ve hızlı sonuca ulaşabilmek için değerlerin ayarlanarak modelin incelenmesi olmuştur. Bunun için önce örnek proje detaylarıyla tasvir edilmiştir. En iyi çözüme ise bilgisayar programı sayesinde ulaşılmıştır. İlerleyen aşamalarda ise teklifteki, gerçekte oluşan ve model sayesinde en iyiye ulaşmak için kaynakların değiştirilmesi sonucu bulunan iş programı kıyaslanmıştır.

Sonuç olarak bir inşaat projesinin zamanında tamamlanması için gerekli iş gücünün ve günlük finansmanın önceden doğru olarak belirlenmesinin (teklif aşamasında) avantajları (kar ve süre) ortaya konmuştur.

Anahtar Kelimeler: Kaynak Kısıtlı İş Planlaması, İnşaat Sektörü, Şans Kısıtlı Programlama

Haziran, 2006 **Alper ÇALIŞIR**

ABSTRACT

AN APPROACH OF CONSTRAINT-BASED SCHEDULING FOR A CONSTRUCTION FIRM

The purpose of the research is to provide and apply a model for scheduling a construction project efficiently in stage of proposal request which should be responded quickly, competitive and also profitable when the work is taken up.

In fist step of the thesis the problem with different modes of the problem had been defined. Then, most suitable and much faster model which gives the best response for proposing competitive price had been chosen form defined models. To select a model, firstly resource constrained project scheduling models had been classified and according to their modes that it had been discussed per the literature solutions. And it's explained that fast responding factor was the most important.

After selecting the model, next step was, investigating the model on a project that I have been working on a firm as project engineer and adjusting the criteria's to find the most economic and fastest solution. For that purpose the example project had been described firstly. The optimum solution reached by computer simulation. Proposal schedule, the real application hours in construction and the results obtained by manipulating resources to reach the optimum by the estimated model had been compared.

As a conclusion it had seen the advantages (profit, time) and applicability of defining required manpower and daily finance to complete the project on time by forecasting before the project starts (at the stage of proposal).

Keywords: Resource Constrained Project Scheduling, Construction, Chance-constrained Programming

June, 2006 **Alper ÇALIŞIR**

CLAIM FOR ORIGINALITY

AN APPROACH OF CONSTRAINT-BASED SCHEDULING FOR A CONSTRUCTION FIRM

Resource constrained project scheduling is a subject very wide and discussed often. My past experience as project engineer in a construction firm showed me the lack of scheduling in practice. There is always a schedule made by engineers but in application it doesn't fit to real life. The result is usually project delay and loss of money. That makes the scheduling made in proposal request stage, very important. The purpose of the thesis is to find best solution to schedule a construction project at proposal request stage. This approach of scheduling a project from proposal request is a subject not uttered before frequently. The solution mentioned here should be quick response and accurate. As time is very short at this stage, the details of scheduling loose its importance while clarity, simplicity and velocity goes to forefront. The selected model of the thesis satisfies these requirements. Application of the model performed by the help of the firm that I have worked for. The data collected this year during the project (January and February) and the data compiled and transformed to useful form after project completion (March). The advantages (cost benefits) that the model brings will be explained in detail in later parts of the thesis.

June, 2006 **Asst.Prof.Dr. Serol BULKAN** **Alper ÇALIŞIR**

LIST OF SYMBOLS

C : Available Funding

D : Project Duration

$\mathbf{D_i}$: Unit Duration of Activity i

m : Mean

M : Number of Progress Units

N : Sample Size

$\mathbf{P_j}$: Price of Resource j

Pr[x] : Probability of the Event x

Q : System Production Rate

Q_i : Production Rate of Activity i

$\overline{Q_i}$: Fastest Possible Pace

$\underline{Q_i}$: Slowest Possible Pace

$\mathbf{R_{ij}}$: Resource j Required by Activity i

$\mathbf{RC_i}$: Resource Consumption for Individual Activities

$\mathbf{RD_{ij}}$: Daily Working Hours of the Resource j Allocated to Activity i

s : Sample Standard Deviation

$t_{\alpha/2}$: t-value

$\mathbf{T_j}$: Availability of Resource j per Day

$\bar{x}$: Sample Mean

α : Pre-specified Confidence Level

ABBREVIATIONS

CBS : Constraint-Based Scheduling
CCP : Chance Constrained Programming
CDF : Cumulative Distribution Function
CPM : Conventional Critical Path Method
DC-RCPSP : Discounted Cash Flows Problem
FF : First Fit
FFD : First Fit Decreasing
FFL : First Fit Level
GPR : General Precedence Relationships
LHS : Left-Hand Side
MM-RCPSP : Multi-Mode RCPSP
MRCPSP : Multi-Resource-Constrained Project Scheduling Problems
NPV-RCPSP : Net Present Value
OR : Operations Research
PERT : Program Evaluation and Review Technique
RCPSPS : Resource Constrained Project Scheduling Problems
RHS : Right-Hand Side
RL-RCPSP : Resource-Leveling Problem
SM-RCPSP : Single Mode Resource Constrained Project Scheduling Problems

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PART I

INTRODUCTION AND OBJECTIVES

Factors defining the price of construction project are material, labor cost and profit. As the material costs do not vary too much, the only way to have most competitive price is to minimize the labor cost. To minimize labor cost, companies should use their labor resources very effectively.

Companies should reply so many proposal requests at the same time. Proposals should be responded quickly, and the proposal should be competitive and profitable when the work is taken up. Replying all proposal requests on time, even if there are many requests are waiting for response, is very important for reliability of the company. Not replying one request will cause to be seen uninterested and will risk the future requests of the same firm. Moreover if a proposal is very high or very low in terms of the market, the reliability and the seriousness of the firm will decrease.

In first step of the thesis the problem with different modes of the problem will be defined. After most suitable and much faster model which gives the best response for proposing competitive price will be chosen form defined models. The model should give the best solution for completing the project on time by clarifying workers quantities and their skills to minimize the labor cost. In the first stage resource constrained project scheduling models will be classified and according to its modes it will be discussed per the literature solutions. It will be explained some of the procedures may be valid for a most of the modes but some of them may be valid for only a special case. Fast responding factor had been the first goal to select the model.

Next step will be investigating the model on a project that I m working on a firm as project engineer and by adjusting the criteria's to find the most economic and fastest solution. As an example project will be mechanical works of Toyota Turkey's supplier factory offices located in Adapazari Industrial Zone. Up to today three factory offices which are; Takanichi, Tsusho and Boshoku, mechanical works had been accomplished by the firm I work for. The data is taken from the last project which is the mechanical works of the offices for Takanichi Boshoku Turkey. Proposal schedule, the real application hours in construction and the results obtained by manipulating resources to reach the optimum by the estimated model will be compared.

The proposal schedule (see Appendix A) is based on experience. It is made from bill of quantities coming from drawings by considering various approaches, up on the experience. The real data is gathered at the site by meetings with site engineer and foremen. Optimum solution will be calculated by the help of simulation software on computer.

As a consequence the advantages (profit, time) had seen and applicability of defining required manpower and daily finance to complete the project on time by forecasting before the project starts (at the stage of proposal).

PART II

GENERAL BACKGROUND

Scheduling is the process of allocating resources to activities over time [1]. In a typical scheduling problem, resources are scarce and constrained in various ways (e.g., in the capacity of resources and the order of activities), and one is looking for a schedule of the activities that both satisfies the constraints and is optimal according to some criterion (e.g., the length of the schedule).

Conventional critical path method (CPM), and program evaluation and review technique (PERT) scheduling procedures start with an assumption of unlimited availability of resources for each project activity [2-4]. In other words, the analysis is based on the time requirements of the activities regardless of the resource needs of each activity. The early and late dates calculated with the critical path algorithm are based on the duration of the activities in the project and the relationships or technological constraints between them. It produces a schedule that minimizes the overall project duration. In these calculations, the issue of resource availability is either not taken into account or neglected until after the initial time-oriented calculations [5]. Many of the problems with real-life projects arise when activities require resources that are available only in limited quantities and the demands of concurrent activities cannot be satisfied [6]. Recognition of this limitation has directed many researchers towards the problem of scheduling activity networks under resource constraints.

Over the last decade, constraint-based scheduling (CBS) has become the dominant form of modeling and solving scheduling problems [7-9]. CBS separates the model - the description of activities, resources, constraints, and objectives - from the algorithms that solve the problem. This allows one to deal with a wider variety of constraints, facilitates the changing of the model, even dynamically, without changing the algorithms, and enables the reuse of the model for other tasks, such as simulation, planning, and diagnosis. Constraint solving methods such as domain reduction, constraint propagation, and backtracking search have proved to be well suited for many industrial applications [10]. Today, these methods are increasingly combined with classic solving techniques from Operations Research (OR), such as linear, integer, and mixed integer programming [11,12], to yield powerful tools for constraint-based scheduling.

II.1. RESOURCE SCHEDULING

Resource scheduling explicitly and systematically incorporates decisions about the capacity into the scheduling process. Gordon and Tulip [13] have outlined its history and development and describe the basic steps of aggregation, smoothing and leveling of resources. Matthews [14] identifies two approaches to resource scheduling as:

- Time-constrained scheduling
- Resource-constrained scheduling

Both methods begin with a time analysis (CPM) (which fails to consider capacity and therefore contains `unrealistic' dates) and proceed to resolve resource overloads by moving activities into periods when the capacity to undertake the activity exists. Time-constrained resource scheduling assumes that time constraints are fixed, and seeks to resolve capacity overloads by manipulating the timing of activities within their total float, and without affecting the initial project completion time. Resource-constrained scheduling accepts the priority of fixed resource availability, and permits not only sequencing and float times to be altered, but (if necessary) the project duration to be increased beyond the initial non-constrained project duration. In many cases therefore, time analysis and time-constrained scheduling should be considered only as intermediate steps in the process of schedule development [14]. In terms of performing resource scheduling, Gordon and Tulip [13] identify two main approaches, the `serial approach' (where priority indices are determined once, before starting the scheduling operation) and the `parallel approach' (where priority indices are updated each time an activity is scheduled). A parallel approach with allowable relaxation of `total resource limitation' and `total time limitation' was considered suitable for `construction type' projects since they tend to contain a high proportion of activities which can be split.

II.2. INTRODUCTION AND CLASSIFICATION OF RCPS PROBLEMS

Resource constrained project scheduling problems (RCPSPs) involve assigning jobs or tasks to a resource or set of resources with limited capacity in order to meet some predefined objective. Many different objectives are possible and these depend on the goals of the decision maker, but the most common of these is to find the minimum make span, i.e., the minimum time to complete the entire project. Several varieties of the RCPSP will be discussed, beginning with single-mode scheduling problems and moving on to multi-mode problems. Single-mode problems imply that each project (activity) has a single execution mode: both the activity duration and its requirements for a set of resources are assumed fixed. In multi-mode problems, each activity has to be processed in one of several modes. Each mode implies a different option in terms of (possibly) cost and activity duration for performing the activity under consideration. The RCPSP is broadly separated into the following 6 different classes:

1. Basic Single-Mode RCPSP
2. Basic Multi-Mode RCPSP
3. RCPSP problems with Non-regular objective functions
4. Stochastic RCPSP
5. Bin-packing-related RCPSP problems
6. Multi-resource-constrained project scheduling problems (MRCPSP)

The essential elements of each of these classes of project scheduling problems are later considered.

II.2.1. Basic Single-Mode RCPSP

In the single-mode RCPSP, each project (activity) has a single execution mode: both the activity duration and its requirements for a set of resources are assumed to be fixed, and only one execution mode is available for any activity. Single mode RCPSPs generally contain 4 sub-classes [15], which are characterized next. Throughout our discussion it will be assumed that a project is represented as a network of activities. The network can be represented as a graph, $G(N, A)$, where the nodes in the graph correspond to activities, and the arcs in the graph specify precedence relationships: if arc (i, j) appears in the graph, then activity i must be completed prior to performing activity j. In stating precedence conditions, two types can be considered: cases in which activity j can start at any time following completion of activity i, or cases in which activity j must start within some time window following the completion of activity i (they are called latter restrictions General Precedence Relationships, or GPR). An approach of characterizing resources in terms of their availability (capacity) will be taken to perform tasks in each of a set of time periods. Resource availability for a given resource may be the same for all periods, or it may vary from period to period. Additionally, if a task is assigned to a resource in multiple periods, the task might require the same amount of processing time in all periods, or the resource consumption to vary in different periods might be allowed. Finally, cases that require to complete a task once it is started on a machine versus cases in which a job can be stopped in the middle of processing and return to the job later can be considered, which is termed preemption. As noted, the typical approach in project scheduling minimizes the total project make span, or the total completion time of all tasks from start to finish. However, a broad array of other objectives is possible. A *regular* objective is defined as any objective with the following property: the objective function value for a given schedule is not made any worse if the completion time of a single activity is reduced without changing the activity's mode or changing the completion time of any other task [16]. Table II.1 summarizes the classification of different single-mode RCPS problems.

Basic SM-RCPSP has been extensively studied in the literature. Previous research on algorithms for providing optimal solutions typically involves the use of mathematical programming techniques and implicit enumeration, e.g., dynamic programming and branch-and-bound. A variety of branch-and-bound algorithms have been developed for this problem. Most of these use partial feasible schedules as a starting point.

Table II.1: Single-Mode RCPS Problem Classification [15]

	Basic SM-RCPSP	**SM-RCPSP with Preemption**	**General Precedence SM-RCPSP**	**General SM-RCPSP**
Objective	Min Makespan	Min Makespan	Min Makespan	Regular
Precedence Relations	P	P	GPR	GPR
Resource Availability Per Period	Constant	Constant	Constant or Time-Varying	Constant or Time-Varying
Resource Requirements Per Period	Constant	Constant	Constant or Time-Varying	Constant or Time-Varying
Preemption	No	Yes	No	No

For SM-RCPSP with Preemption Davis and Heidorn [17] developed an implicit enumeration scheme based on splitting projects into unit length process tasks. Kaplan [18] presented a dynamic programming formulation for this problem. Several branch-and-bound algorithms have also been proposed; see [15].

The General SM-RCPSP considers regular performance measures in its objective function, including:

1) Minimization of the makespan
2) Minimization the weighted delay
3) Minimization the total number of tardy activities
4) Minimization the weighted mean flow time

Branch-and-bound algorithms used in general precedence SM-RCPSP can be used for a regular objective problem as well; however, papers on this research are scarce.

II.2.2. Multi-Mode RCPSP

In a multi-mode RCPSP (MM-RCPSP), given the estimated work content for an activity, a set of allowable execution modes can be specified for the activity's execution. Each mode is characterized by a processing time and amount of a particular resource type for completing the activity. For example, one worker might finish a job in 10 hours (mode 1), whereas 2 workers might finish the same activity in 5 hours (mode 2). The product of the duration of the activity and the amount of the resource type needed is called the activities *work content*. In the previous example, in modes 1 and 2 the activity had a work content of 10 worker-hours. Resources available for completing tasks can be classified as either renewable or non-renewable. Non-renewable resources are depleted after a certain amount of consumption (or number of periods), while renewable resources typically have the same amount of availability in every period for an unlimited number of periods. As in the single-mode RCPSP, different types of MM-RCPSPs classified in Table II.2. Additional variants of the MM-RCPSP exist, such as the MM-RCPSPs with setup times; see [19]

Table II.2: Multi-Mode RCPS Problem Classification [19]

	Nonrenewable Resource MM-RCPSP	**Nonrenewable Resource MM-RCPSP**	**General MM- RCPSP**
Objective	Min Makespan	Min Makespan	Regular
Resource Type	Nonrenewable	Renewable	Nonrenewable or Renewable
Precedence Relations	P	P	GPR
Resource Availability Per Period	Constant Within a Mode	Constant Within a Mode	Constant Within a Mode
Resource Requirements Per Period	Constant Within a Mode	Constant Within a Mode	Constant Within a Mode
Preemption	No	No	No
Trade Offs	Time/Resource	Time/Resource	Time/Resource, Time/Cost, Resource/Resource

II.2.2.1. Nonrenewable Resource MM-RCPSP

A nonrenewable resource MM-RCPSP allocates a nonrenewable resource to tasks. A cost of resource *m* while processing task *i*, *cim*, is associated with this mode. If the mode set for every project can be represented as a closed interval and *cim* is an affine and decreasing function of *pi*, there is a linear time-cost tradeoff problem. If the modes are a discrete set and *cim* is decreasing in *pi*, there is a discrete time-cost tradeoff problem.

There are two related problems within this class: the budget problem (given a nonnegative budget, minimize the makespan), and the deadline problem (given a deadline for each task, minimize the total cost), which are both in the class of non-regular objective RCPSPs. For the linear time-cost tradeoff, Kelly [20] and Fulkerson [21] developed an algorithm that iteratively calculates a sequence of cuts in the AOA (activity on arc) network to compute the project cost curve. The cut can be determined by a maximum flow computation in which the capacities are derived from the slopes of the linear cost functions of the critical activities.

For the discrete case, Hindelang and Muth [22] proposed dynamic programming, and Harvey and Patterson [23] proposed an enumeration algorithm. The currently best known algorithms still rely on dynamic programming, but additionally exploit the decomposition structure of the underlying network (It is known as modular decomposition or substitution decomposition). Skutella [24] further developed approximation algorithms for this class of problems.

II.2.2.2. Renewable Resource MM-RCPSP

The renewable resource MM-RCPSP problem considers the processing time of a task as a discrete, non-increasing function of the amount of a renewable resource.

Demeulemeester, Reyck, and Herroelen presented a branch and bound procedure based on the concept of maximal activity-mode combination; see [25]. An activity-mode combination is a subset of activities executed in a specific mode; it is maximal if no other activity can be added without causing a resource conflict. Sprecher and Drexl developed a branch-and-bound procedure that relies on an enumeration scheme based on the precedence tree concept; see [26]. Several heuristic algorithms have been developed for this problem as well. The most effective is the recent generalized version of a genetic algorithm approach by Hartmann [27].

II.2.2.3. General MM-RCPSP

The general MM-RCPSP includes time/cost, time/resource and resource/resource tradeoffs, renewable and nonrenewable and double constrained resources (resources limited on both a per period and a total project basis) and a variety of regular objective functions. The modes reflect alternative combinations of resource types and resource quantities to fulfill the activities. The activities can be accelerated by raising the resource quantities (time/resource trade off or time/cost trade off), or by raising the quantities of some resources and reducing the quantities of other resources (resource/resource trade off). Sprecher and Drexl [26] extend their algorithm for the renewable resource MM-RCPSP to some regular objective problems, while Bottcher, Drexl, and Kolisch [28] provide a branch-and-bound algorithm for a partially nonrenewable resource.

II.2.3. RCPSP problems with non-regular objective functions

Some examples of non-regular objective functions are next provided. Recall that a regular objective function is one in which the objective function is never made worse by reducing the completion time of a job without increasing the completion time of any other job. A non-regular objective function violates this property. Specific problem types include the resource-leveling problem (RL-RCPSP), the maximum net present value (NPV-RCPSP) problem, and the discounted cash flows problem (DC-RCPSP). Specific non-regular objective functions include:

1) Maximize NPV (unconstrained resource problem)
2) Maximize discounted cash flows (resource-constrained problem)
3) Minimize total (weighted) resource consumption
4) Maximize smoothness of resource usage (resource leveling)

Because of the time dependent nature of these objective function costs, the objective function value can actually increase by reducing the completion time of an activity (all else being equal), and so these are non-regular objective functions.

II.2.3.1. Resource leveling problem

In the resource leveling problem, the main objective is to limit the amount of resource usage variation from period to period, which may be costly in certain contexts. Three kinds of usage functions have been considered in the literature: a resource investment function, a resource consumption deviation function, and a variation of resource utilization over time function, respectively, see [15]. Exact algorithms for this problem are based upon enumeration, integer programming or dynamic programming. Zimmermann and Engelhardt [29] devised a time-window based branch-and-bound algorithm. Several heuristic procedures based on a priority-rule method have been presented [15].

II.2.3.2. Net Present Value RCPSP

The deterministic unconstrained maximum Net Present Value (NPV) problem is sometimes referred to as the payment scheduling problem where processing each task involves a series of cash flow payments and receipts. Recently the most efficient algorithm is due to Demeulemeester [30] and is based on the concept of an early tree (which spans all activities scheduled at their earliest completion times and which corresponds to a feasible solution with a project duration equal to the critical path length); see [15].

II.2.3.3. Minimum Total Cost Problem (Deadline RCPSP)

Given a deadline for all tasks, consider the availability of an additional resource to finish the tasks on time. Deckro and Hebert [31] proposed such a problem. Assuming that an additional unit of the renewable resource $r \in R$ (where R is a set of available resources) provided in period t is available at a cost of Cr and is limited to a percentage of the regular period capacity, Kr, the objective is to find a feasible schedule with the least *additional* cost. The problem can be formulated like the MM-RCPSP problem (see [19]) with a few extensions. Based on the idea of Burgess and Killebrew [32], a heuristic for the single-mode case is proposed. This algorithm uses two lexicographically ordered priority rules, using left shifts (starting an activity earlier) and right shifts (delaying an activity) until no improvement is available in the objective function. In the multi-mode case, heuristics generally assign tasks to the lowest labeled mode, calculate the slack (the latest finishing time minus the earliest finishing time) of each project, and implement a mode-changing scheme until finding no improvement in cost [19].

II.2.4. Stochastic RCPSP

In a stochastic RCPSP, the processing time of any activity is a random variable, which follows some probability distribution [15]. This problem class, while often more realistic, leads to much greater complexity in analysis. Instead of minimizing makespan, objectives such as minimizing the *expected* makespan are considered. Since many interdependent activities are often represented in a project graph, and activity completion times are highly interdependent, the probability distribution of the total makespan is often extremely difficult or impossible to characterize, often leading to activity independence assumptions for tractable analysis.

II.2.5. Bin-packing-related RCPSP problems

A bin-packing-related RCPSP refers to a special kind of resource-constrained project scheduling problem that can be seen as analogous to a bin-packing problem. A bin-packing problem instance is specified by a standard bin size and a set of items, each of some (possibly) unique size. The objective is to pack every item in the set into a bin while minimizing the total number of bins used. Many resource-constrained scheduling problems can be viewed as generalizations (or even special cases) of the basic bin-packing problem. The analogy between the bin packing and RCPSP problems can be explained as follows. The resource capacity represents the bin size, while a task's resource consumption requirement represent an item size. In the RCPSP context, each time period can be viewed as a bin into which different tasks can be packed (of course in many of these problems, an item can be packed into consecutive bins, or equivalently schedule jobs across consecutive days). If it's supposed, however, that each task takes less than one period of resource consumption and that every task must be fully completed within a single day, then minimizing makespan of this RCPSP is equivalent to minimizing the number of bins used in an equivalent bin-packing problem. Extremely successful heuristic algorithms used for solving bin-packing problems to the RCPSP with relatively minor modifications can be adapted. Table II.3 characterizes different kinds of bin-packing related RCPSPs.

Two types of bin-packing related scheduling problems are considered. One is called the integral problem, in which a task must be completely put into a single bin. The other is called the fractional problem, where a fraction of a task can be put into different bins. This latter problem (with preemption allowed) can be solved by linear programming. Research efforts are therefore typically focused on the more difficult integer programming versions of the problem.

Garey, Graham, Johnson and Yao [33] adapted the First Fit (FF) and First Fit Decreasing (FFD) bin packing heuristics to the multi-dimensional case. Fernandez and Lueker [34] show that for any asymptotic worst-case ratio, there is a linear-time algorithm. A polynomial time approximation algorithm with asymptotic worst-case ratios equal to one exists for this problem [35].

Table II.3: Bin-Packing-Related RCPS Problem Classification [15]

	No Precedence BP-RCPSP (Multidimensional BP)	**General BP-RCPSP**
Objective	Minimize Latest Scheduled Time	Minimize Latest Scheduled Time
Resource Type	Renewable	Renewable
Precedence Relations	No	GPR
Resource Availability Per Period	With Upper Bounds	With Upper Bounds
Resource Requirements Per Period	Less Than Resource Upper Bound	Less Than Resource Upper Bound
Preemption	No	No
Trade Offs	No	No

Garey, Graham, Johnson and Yao [33] analyzed FF and FFD algorithms for this problem and proposed an FFL (first fit level) algorithm, which reorders L according to precedence levels. Srivastav, Stangier [36] developed a tight approximation algorithm for the problem with start time constraints. This method starts with a fractional solution for the system with tighter constraints and randomly rounds the fractional solution to an integral one. Jansen and Ohring [37] considered the minimum number of machines problem (which belongs in the category of time constrained problem, and the total execution time of a machine is 1). They proposed several coloring methods (the algorithm uses coloring of a conflict graph where the nodes in a color set have no conflict.) to partition jobs into independent sets before using bin-packing heuristics.

In each of the above problem classes, projects/jobs may choose from several resources, but only one operation is required for each job. By contrast, in multi-resource-constrained project scheduling problems, a job may require a set of operations, or a set of successive resources. For a given operation, several resources may be in parallel, which means the job can select any one of these resources for processing. A job might also need to complete processing on one resource before it begins processing on another resource, where successive resources are needed in series. These problems are often called machine-scheduling problems, since in manufacturing its seen machines and workstations in parallel and in series. In the manufacturing context, a resource might be a machine that can only process one job at any time. Machine and job scheduling characteristics can be broken down to several categories:

1) Identical machines in parallel;
2) Machines in parallel with different speeds: the speed of machine i is vi for all jobs;
3) Unrelated machines in parallel: speed of machine i for job j is vij;
4) Flow shop: machines are in series; every job has to be processed on each of the machines in the same sequence.
5) Job shop: a job can visit any subset of the machines in any order.

See [38] for more details on past research on more general machine scheduling problems.

II.3. SOLUTIONS

Numerous modifications to the original critical path method algorithm have been proposed for solving the scheduling problem under resource constraints. Two broad approaches have been used, namely (a) optimization by mathematical programming techniques, and (b) heuristic techniques [39,40].

II.3.1. Solutions based on mathematical optimization

These techniques seek to define the problem as a mathematical programming problem. The best solution is the one that gives the shortest project duration or the one which provides the smoothest resource profile. In some cases, these two objective functions are combined, resulting in preferred trade-offs; for example, in a slight increase in project duration with a decrease in resource level variation. However, such optimization techniques remain computationally impractical for most real-life large projects because of the enormous number of variables and constraints.

This first group formulated the problem as a mathematical optimization model. Operational research techniques used to solve the mathematical model included linear programming [41,42], mixed integer programming [43,44], branch-and-bound [45,46], and dynamic programming [47]. Möhring et al. [48] mentioned that RCPSP is one of the most intractable problems in operations research and many latest optimization techniques and local search were applied to solve it. Some of them are based on linear programming formulations including the pioneering work of Fisher [49], Blazewicz [50], Christofides et al. [51], Möhring et al. [52]. Mingozzi et al. [44] and Brucker and Knust [53] relax the non-preemption constraint and associate a variable with each subset of activities that can be processed simultaneously without violating either resource or precedence constraints. So they take into account explicitly the resource requirements of activities. Demeulemeester and Herroelen [45,54] developed a depth-first branching scheme with dominance criteria and the bounding rules. Brucker et al. [55] presented a branch-and-bound algorithm whose branching scheme applied a set of conjunctions and disjunctions to pairs of activities.

II.3.2. Solutions based on heuristics

The alternative approach is to develop heuristics which allow a process of choosing between activities that are competing for the use of a scarce resource. The inherent variables in any project scheduling process are time and resources. When these are constrained, the resulting outcomes can vary along a constraint continuum - a spectrum of combinations of time and resources with an assumption of unlimited availability at each extremity. The various heuristics and their algorithms assist in deciding upon the point on the continuum at which the schedule should end up. Many heuristic models have been developed and are available as computer packages. Each works differently, produces different schedule outcomes, and is likely to be better in some situations than in others.

A common feature of all heuristics is that they provide criteria for prioritization. Accordingly, in attempting to perfect algorithms for scheduling activities under resource constraints, theorists have designed various values to determine which activity will get the resources and which activity will be delayed.

One of the simpler examples is the work of Matthews [14] who tackled the RCPSP problem using resource allocation algorithms with different prioritization criteria for activities. Thus, activities were allocated a resource and scheduled during the earliest available period, based on one or the other of the following values:

1. Lowest total float time
2. Earliest start prioritization
3. Latest start prioritization
4. Earliest finish prioritization
5. Latest finish prioritization
6. Activity duration (ascending)
7. Activity duration (descending)
8. Activity number (ascending)
9. Activity number (descending)

The results showed that the above heuristics 1, 3 and 7 performed best (i.e. gave the shortest project duration) compared with heuristic 9 which was the worst (i.e. longest, giving a duration approximately 13% greater than the best value).

Elsayed and Nasr [39] examined a number of heuristics for allocating resources in a single-project under single- resource constraints. Each heuristic involves the prioritization of activities based on values (ACTIM, ACTRES, TIMRES, GENRES, ROT, ACROS, TIMROS and TIMGEN) calculated for each activity. Some of these values are weighted and some are more complex combinations of several simpler ones. The ACTIM value of an activity is calculated as the maximum length of time that the activity `controls' throughout the critical path network; the ACTRES value is the sum of the products of the time and resources that the activity `controls' through the network; TIMRES and GENRES are weighted combinations of the ACTIM and ACTRES values; ROT is determined by the maximum sum, on any one path that the activity controls, of the ratios of resources to time; ACROS is the maximum resource value on any one path that the activity controls through the network; TIMROS and TIMGEN are respectively, weighted combinations of the ACROS and ACTIM, and TIMROS and GENRES values. The experiments carried out by Elsayed and Nasr [39] demonstrated that TIMROS and TIMGEN out-performed the others, in terms of meeting resource constraints within the shortest project duration.

The previously referenced work compared the relative performance of different heuristics against one another; however, Davis and Patterson [56] compared the effectiveness of alternative heuristic sequencing rules relative to a mathematically optimized solution using `bounded enumeration' procedure [57-59]. The comparison between optimum and heuristic-based solutions was performed over a group of (single-project, multi-resource) test problems. The heuristic sequencing rules selected were used in a parallel approach, in which activity priority is determined during scheduling rather than before. The heuristics were:. Minimum job slack (MINSLK)

. Resource scheduling method (RSM)
. Minimum late finish time (MINLFT)
. Greatest resource demand (GRD)
. Greatest resource utilization (GRU)
. Shortest imminent operation (SIO)
. Most jobs possible (MJP)
. Select jobs randomly (RAN)

In the resource scheduling method (RSM), priority is given to the activity with the minimum time between its own earliest finish time (EFT) and the latest start time (LST) of the succeeding activity.

In Davis and Patterson's experiment [56], MINSLK, MINLFT and RSM performed the best, whereas GRU, GRD, SIO and MJP were poor performers (compared even to RAN) in minimizing project duration. The results also revealed that certain project and resource characteristics can affect the performance of a particular heuristic sequencing rule. These characteristics include:

. The ratio of average resource requirements per activity to the amount available
. The ratio of average total float per activity to the critical path length (average float ratio)
. The ratio of number of activities to number of precedence relationships (project complexity)

Further investigation into the performance of heuristic sequencing rules was carried out by Boctor [60], whose intention was to introduce some efficient multi-heuristic procedures. Tests were performed on a number of small (5-20 activities) and large (38-111 activities) projects, using up to three resource types. The measures used to assess the efficiency of each heuristic were:

1. the average percentage increase in project duration above the optimum duration or the critical path length;
2. the number of times each heuristic produced the optimum or the shortest duration.

The results confirmed earlier findings that MINSLK, MINLFT and RSM were the most efficient rules. When combinations of heuristics were employed sequentially, the most efficient combinations were always found to include the MINSLK rule, and the probability of getting the best solution was proportional to the number of heuristics combined. Boctor [60] also observed that serial heuristics are, on an average, five times faster to perform than parallel ones, although RSM requires three times the processing time of other parallel heuristics.

Kolisch [59] was critical of the logic behind the commonly used RSM priority rule and suggested an improved model known as improved RSM (IRSM). He also developed two new priority rules: worst case slack (WCS) and average case slack (ACS). Kolisch showed that on an average, the three new rules out-performed the other heuristics, including LFT and MINSLK.

Moselhi and Lorterapong [58] proposed a model for assigning scarce resources to activities collectively rather than individually. The new algorithm was coded in BASIC language along with four highly regarded heuristic rules: MINSLK, MINLFT, GRD, and Shortest Duration (SHD). A total of 31 CPM-type multi-resource-constrained project networks were taken from the literature and used to examine the performance of the new algorithm against existing heuristic rules (including RSM) and a number of available optimal solutions. The proposed algorithm proved superior (i.e. resulted in shorter project durations) in the majority of cases.

In response to the problems associated with a multiplicity of resource constraints, Nkasu [5] developed an iterative heuristic scheduling method known as Computer Sequencing Approach to Multi-Resource-Constrained Scheduling (COMSARS). The method attempts to produce schedules that minimize the total project completion time as well as minimize the total idle resources, thereby facilitating project-cost savings. It reports a chronological listing of all the activities that start and finish in conformity with the constraints imposed by both, the activity precedence relationships and the resource availabilities. Further, COMSARS produces the resource aggregation profiles in terms of their availabilities, requirements, actual utilization, and levels of idleness at various identifiable milestones throughout the entire project duration.

As Davis and Patterson [56] have noted, the performance of a particular heuristic should be investigated with regard to the project and resource characteristics that may affect it. This issue is addressed in a study by Ulusoy and Ozdamar [61] in which a new heuristic rule, weighted resource utilization and precedence (WRUP) is compared with the widely used rules.

II.3.3. Evolutionary computation techniques

Some metaheuristic algorithms were also proposed for RCPSP. They include the genetic algorithm, the simulated annealing, the tabu search, the ant colony optimization [62,63], the path relinking, and hybrid algorithms. The following studies incorporate genetic algorithms: [64-74]. Some simulated annealing algorithms were proposed by Boctor [75], Lee and Kim [67], Cho and Kim [76], Bouleimen and Lecocq [77,78] and Jeffcoat and Bulfin [73]. Methods based on tabu search were presented in [79-85]. Palpant et al. [86] presented a local search strategy, in which a subpart of the current solution is fixed and the other part defines a subproblem solved by a heuristic or an exact method. Merkle et al. [87] presented an ant colony optimization by using the summation of the values in the pheromone set for this problem. Kochetov and Stolyar [66] proposed an evolutionary algorithm that combines the genetic algorithm, the path relinking and the tabu search. Valls et al. [88] presented a simple technique named justification that can be applied in many methods to improve the quality of solution without generally requiring more computing time. They also designed a peak crossover operator within a hybrid genetic algorithm with justification [89] and this algorithm presented the best results to RCPSP as stated in Kolisch and Hartmann's experimental evaluation of state-of-the-art heuristics [90].

The investigation of Hartmann and Kolisch [91] and its updated version [90] conducted an elaborate study on state-of-the-art heuristic and metaheuristic methods. They presented performance comparisons among heuristic and metaheuristic methods in their study by applying these methods to different standard instance sets, namely J30, J60 and J120, generated by ProGen in the PSPLIB [92]. As shown by the latest experimental evaluation [90], metaheuristic methods outperform heuristic methods. For 26 methods sorted with respect to the performance of evaluating 1000, 5000 and 50,000 schedules, the best four methods for J30 and the best five methods for J60 and J120 are all metaheuristic methods. The recent benchmark results [71,91,93] show that the genetic algorithms proposed by Alcaraz and Maroto [71] ,Hartman [94], and [95] are the best performing methods currently available for RCPSP.

PART III

RESEARCH

III.1. RESEARCH METHOD

The purpose of the research is to identify the manpower and the finance of this manpower required to complete the work on time. A method which will be used to provide the best competitive price for the contractor will be sought. As a real life example, this method will be tested in mechanical works of Toyota Turkey's supplier factory offices located in Adapazari Industrial Zone. In order to achieve this goal the method will be used, is to realize the RCSP models and solutions which are derived from Section II literature research. Within these models, the one which gives the near optimum solution and which has the fastest response time will be chosen, and the results will be compared with the actual.

III.1.2 Resources

In this section, total required manpower together with their skills and daily finance of this manpower which are two main resources of the project will be examined. Resources employed in repetitive projects, such as labor and equipment, are often to limited availability. This leads to a practical concern of how distribute the limited resources among various activities so that the project can be completed within a minimal period of time.

III.1.2.1. Man-hours

Man-hours are gathered from site engineer and foremen at site. Bill of Quantities are obtained from as-built drawings, measurements and counts from the office as listed in Appendix B. Actual manpower and their skills are also written in the table for each work. The worker quantities are distributed according to the manpower at that time. There is no necessity to follow that numbers. The time period of the work may change by playing the manpower quantity, for this reason the data coming from this table will be transformed to time bases in the latter stages and will be stated man-hours bases. The sequences of the jobs should not be in the same manner, one job may start before the other finishes. The important thing is the job will be completed when the man-hours of that are finished.

III.1.2.2. Finance

Installation costs of materials gathered from as-built projects and site counts been taken from Mechanical Works Unit Prices Book Year 2006 of Ministry of Public Works and Settlement [96] and written in Appendix C for each material. The total installation cost calculated as 21.200 YTL. Since the prescribed period of the project is 53 days, daily manpower cost constrained as 400 YTL. Please see Appendix A for prescribed work schedule.

III.1.3. Resource Availability

In Appendix D, one month sample of actual work hours of workers has been given to show the availability of manpower. There are days of over time but also some workers are absent some days. This working hours are represented for showing only the availability, it's unknown that they have worked on that project or another project. What is known is they have worked for the firm, they were absent or they have worked on over time. In latter section these values will be used with their standard variation.

III.2. RESEARCH MATERIALS

As stated before to gather the bill of quantities as-built drawings are used. The drawings drawn by the site engineer can be seen be electronically in AutoCAD 2004 format. The drawings for office are totally 7 sheets and filed separately as air conditioning, sanitary (vitreous and plumbing) and fire fighting.

Installation costs are taken from Mechanical Works Unit Prices Book Year 2006 of Ministry of Public Works and Settlement. As the quality of the materials is not related to this issue, it's skipped.

The prescribed work schedule done by employer in excel format used for evaluation and not altered. The prescribed duration is also taken from that schedule. Please see Appendix A.

The application of the model namely the resolution of the linear programming will be done using Lingo 9 software.

III.3. SELECTED MODEL

As described in tables before, there are 5 manpower skills resources; these are installation foreman, assembler, helper, painter, HVAC foreman. Since the duration of the job may vary from the number of workers, multi-mode model should be used.

Together with the finance the quantity of the resource types becomes six and constraints number is not more than 40, linear programming can be used to resolve the problem. The selected model will be linear programming as to get the optimum solution.

Availability of manpower may vary over time; it cannot be hired always same quantity of workers everyday due to illness, dismissals and vacations. Because of these variations probability based model will be correct for relying worker quantities. For this reason the model will be stochastic.

Since the article published last year by Tung Yang and Chi-Yi Cha [41] is up to date, satisfies the requirements stated above, it's chosen and explained below in details. Model starts with deterministic but in latter it will be explained how to alter stochastic model.

III.3.1. Deterministic optimization model

Within repetitive projects, scheduling is usually done by considering crews ‘‘flowing through’’ the whole project, similar to manufacturing assembly lines . In repetitive construction projects, the product being built tends to be stationary, whereas every crew proceeds from location to location and complete work that is prerequisite to starting work by the following crew.

The flow model of repetitive projects leads to the use of production lines whose slopes represent individual production rates. To accelerate the project, a well grounded treatment is to ‘‘balance’’ the production lines (i.e., to make all the lines have the same slope) as decreed in the line-of-balance procedure. Fig. II.1 illustrates a balanced situation where three consecutive activities A, B, and C are repetitively performed from unit 1 to unit u. Given the duration of the first unit (calculated by CPM), the rate of construction is then the result of dividing the remaining number of units (u-1) by the difference between project deadline and the duration of the first unit. Once the rate of construction has been calculated, the start times of activities on different units and the number of each required crew can be computed.

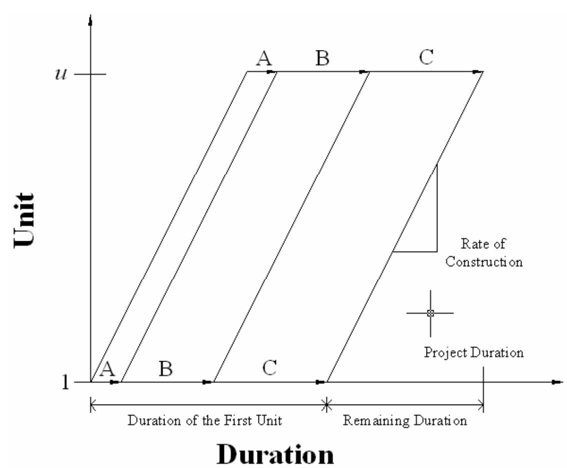


Figure III.1 Balanced Condition

The traditional approach of average rate in the line-of-balance procedure is underpinned by the assumption that resource availability is unlimited. When the supply of resources is constrained, a challenge emerges: how to efficiently allocate the working hours of available resources to various activities when a resource may work for different activities (e.g., carpenters construct both column forms and exterior doors) and an activity may employ multiple types of resources (e.g., earth moving needs both bulldozers and dump trucks). These issues, unfortunately, can not be resolved by the traditional line-of-balance procedure. It is therefore the goal of the proposed model to incorporate limited supply conditions of resources and funding in the line-of-balance procedure.

In what follows, a deterministic optimization model is introduced, which is a variant of Perera's model [97], for scheduling repetitive projects with the consideration of limited resource and financial availability. The following model extends Perera's by introducing new coefficients that are used to elucidate the logic behind the model. In the next section, one step further is taken to consider the situation when the availability can not be expressed merely by a single estimate.

The general objective of the deterministic model is to minimize the project duration, which can be computed as follows:

$$D = D_1 + \frac{(M-1)}{Q}, \tag{III.1}$$

where D is the project duration; M is the number of progress units; and D_1 is the duration of the first unit. Since M is a constant, to minimize the project duration is equivalent to maximizing the system production rate, Q (measured in unit/day), which can be expressed as

$$Q = \frac{M-1}{D-D_1}. \tag{III.2}$$

The objective is thereby

$$\text{Maximize } Q. \tag{III.3}$$

The constraints comprise six sets of equations. The first set describes that the system production rate is governed by the slowest activity. This is the underlying concept of bottleneck in the Theory of Constraint.

$$Q \le Q_i \quad \forall i, \tag{III.4}$$

where Q_i denotes the production rate of activity i (measured in unit/day).

The second set defines coefficients of resource consumption for individual activities (RC_i)

$$RC_i = D_i Q_i \quad \forall i . \qquad \text{(III.5)}$$

Since the unit duration of activity i (D_i, measured in day/unit) is a known constant, the coefficient of resource consumption is directly proportional to the production rate of activity i (Q_i, measured in unit/day). The mechanism is that an increase in the production rate of an activity would require more resources working at different units simultaneously. As a result of multiplication, the coefficient of resource consumption is unitless.

In the third set, the daily working hours of the resource j allocated to activity i (RD_{ij}, measured in resource-hour/day) is derived by dividing the working hours of resource j required by activity i (R_{ij}, measured in resource-hour/unit) by the unit duration of activity i (D_i, measured in day/unit). The equation is

$$RD_{ij} = \frac{R_{ij}}{D_i} \quad \forall i, j . \qquad \text{(III.6)}$$

The fourth set of constraints ensures the feasibility of resources. That is, the daily working hours of each resource (sum of the allocated amounts for different activities, i = (1,2,. . .,n) should be less or equal to the available amount

$$\sum_{i=1}^{n} \left(RD_{ij} \times RC_i \right) \leq T_j \quad \forall j , \qquad \text{(III.7)}$$

where T_j denotes the availability of resource j per day (measured in resource-hour/day). Substitute the lefthand side (LHS) of (7) by (5) and (6), the constraint can be rewritten as

$$\sum_{i=1}^{n} \left(R_{ij} Q_i \right) \leq T_j \quad \forall j . \qquad \text{(III.8)}$$

Aggregating the costs of all the resources (j = 1,2,. . .,m), the fifth set considers the financial feasibility by limiting the daily cost to be less or equal to the available funding

$$\sum_{J=1}^{m}\left(\sum_{i=1}^{n} R_{ij} Q_i \times P_j\right) \le C \,, \qquad \text{(III.9)}$$

where P_j is the unit price of resource j (measured in \$/resource-hour) and C is the available funding.

The last set of constraints defines the upper and lower bounds of the production rate for each activity. The former may be caused by technical constraints, such as limits on equipment capacity or crew productivity whereas the latter, being always positive, may be the result of economical consideration

$$\underline{Q_i} \le Q_i \le \overline{Q_i} \quad \forall i \,, \qquad \text{(III.10)}$$

where the upper bound $\overline{Q_i}$ represents the fastest possible pace at which activity i can be performed and the lower bound $\underline{Q_i}$ denotes the slowest possible pace.

To sum up, the deterministic model is

Maximize Q. (III.11)

Subject to

$$Q \le Q_i \quad \forall i \,, \qquad \text{(III.12)}$$

$$\sum_{i=1}^{n}\left(R_{ij} Q_i\right) \le T_j \quad \forall j \,, \qquad \text{(III.13)}$$

$$\sum_{J=1}^{m}\left(\sum_{i=1}^{n} R_{ij} Q_i \times P_j\right) \le C \,, \qquad \text{(III.14)}$$

$$\underline{Q_i} \le Q_i \le \overline{Q_i} \quad \forall i \,. \qquad \text{(III.15)}$$

In the deterministic model, Q_i are the decision variables. The required input includes T_j (available working hours of resource j), C (available funding), R_{ij} (necessary working hours of resource j for activity i), P_j (unit price of resource j), and $\overline{Q_i}$ and $\underline{Q_i}$ (upper and lower bounds of the production rate for activity i).

III.3.2. Stochastic optimization model

To deal with the uncertainty associated with the supply of resources, (13) is modified to a probabilistic constraint

$$\Pr\left[\sum_{i=1}^{n} R_{ij}Q_i \le T_j\right] \ge \alpha_j^T \quad \forall j, \tag{III.16}$$

where Pr[·] is the probability of the event in [·]; T_j is now a random value with a distribution of uncertainty; α_j^T is a pre-specified confidence level. So a solution set is feasible if and only if the probability measure of the set is at least α_j^T. In other words, the constraint will be violated at most (1-α_j^T).of time.

Similarly, (14) is modified to address the uncertainty inherent in the supply of funding

$$\Pr\left[\sum_{j=1}^{m}\left(\sum_{i=1}^{n} R_{ij}Q_i \times P_j\right) \le C\right] \ge \alpha^C, \tag{III.17}$$

where C is a random value; α^C is a pre-specified confidence level, which represents the lowest limit on the probability of the constraint being satisfied. Again, the constraint will be violated at most (1-α^C) of time.

The stochastic model can be solved by chance constrained programming (CCP), which was first developed by Charnes and Cooper [98] and has been since applied to a wide variety of practical problems, such as investment portfolio selection , railway reservation, and water reservoir management.

The basic technique of CCP is to convert the stochastic constraints to their respective deterministic equivalents. For (16), if the distribution density of T_j can be estimated, the deterministic equivalent is to replace the right-hand side (RHS) by $\tilde{T}_j$ such that

$$\int_{\tilde{T}_j}^{+\infty} \varphi_j(T_j)\,dT_j = \alpha_j^T, \tag{III.18}$$

where α_j^T is the distribution density function of Tj.

Suppose the cumulative distribution function (CDF) of T_j, denoted by $\psi_j(T_j)$, is continuous and strictly monotonic, $\tilde{T}_j$ can be computed directly based on the inverse of the CDF.

$$\tilde{T}_j = \psi_j^{-1}(T_j, 1-\alpha_j^T). \quad \text{(III.19)}$$

Thus, the deterministic equivalent of (16) is

$$\sum_{i=1}^{n} R_{ij} Q_i \le \psi_j^{-1}\left(T_j, 1-\alpha_j^T\right) \quad \forall j. \quad \text{(III.20)}$$

By the same token, the probabilistic constraint (17) can be converted to the following deterministic equivalent

$$\sum_{j=1}^{m}\left(\sum_{i=1}^{n} R_{ij} Q_i \times P_j\right) \le \psi^{-1}\left(C, 1-\alpha^C\right). \quad \text{(III.21)}$$

Since (20) and (21) are linear combinations of the decision variables, the deterministic equivalent of the stochastic model is still a linear programming problem. So it can be solved in polynomial time by the use of very efficient linear programming techniques, such as simplex or interior point methods.

In summary, the general form of the deterministic equivalent of the proposed chance-constrained programming model is

$$\text{Maximize}\, Q, \quad \text{(III.22)}$$

Subject to

$$Q \le Q_i \quad \forall i, \quad \text{(III.23)}$$

$$\sum_{i=1}^{n} R_{ij} Q_i \le \psi_j^{-1}\left(T_j, 1-\alpha_j^T\right) \quad \forall j ,$$

(III.24)

$$\sum_{j=1}^{m}\left(\sum_{i=1}^{n} R_{ij} Q_i \times P_j\right) \le \psi^{-1}\left(C, 1-\alpha^C\right), \tag{III.25}$$

$$\underline{Q_i} \le Q_i \le \overline{Q_i} \quad \forall i . \tag{III.26}$$

The formulation in (24) and (25) is applicable for commonly-used types of distributions, such as normal, lognormal, beta, gamma, uniform, or triangular. When T_j and C are normally distributed, the RHS of both constraints can be reduced to a combination of the estimated mean and standard deviation

$$\sum_{i=1}^{n} R_{ij} Q_i \le m_i^T + k\left(1-\alpha_j^T\right)\sigma_j^T \quad \forall j , \tag{III.27}$$

$$\sum_{j=1}^{m}\left(\sum_{i=1}^{n} R_{ij} Q_i \times P_j\right) \le m_c + k\left(1-\alpha^C\right)\sigma_C , \tag{III.28}$$

where m is the mean; k(·) is the normal distribution value corresponding to lower-tail probability of (·); σ is the standard deviation.

For other types of distributions, the computation of the RHS of (24) and (25) is straightforward when the inverse CDF can be expressed as a closed form (e.g., uniform and triangular distributions). Otherwise, numerical algorithms are readily available to approximate the inverse value, such as normal or lognormal and beta distributions .

Despite the advantages, CCP is not without its own limitation. As shown by Elmaghraby et al. [99], CCP is not suitable for event realization in activity networks, i.e., project evaluation and review technique (PERT) analysis. This is primarily because traditional CCP relies on an implied assumption that all the constraints shall be independent. This assumption cannot be justified in PERT analysis because in an activity network (activity-on-arrow) the realization of an event is dependent on all the activities entering that particular node. In the model, however, the assumption can be valid if the availability of all the resources and funding is independent, e.g., when they are supplied by different sources.

PART IV

RESULTS

IV.1. PREPARATION OF THE DATA

In this section the results of the models will be examined. But to reach the results transform collected data should be transformed to a useful form. There are five group of work: sanitary, plumbing, heating, HVAC and fire fighting. These groups have different resource requirements. Their resource requirements are manpower with different skills, which are: installation foreman, assembler, HVAC foreman, painter and helper. In all groups helpers needed, on the contrary foremen are needed for special groups. For example HVAC foremen are only required in HVAC. However installation foremen are required wherever pipe laying is available, which are sanitary installations, all plumbing, heating (heating pipes) and sprinkler system pipes. Painter is required for black pipe painting. In sanitary drinking water pipes are galvanized so they don't need to be painted. Assembler is required for specific equipment installations. Helpers are unskilled workers; they work under control of foremen. They are required for every work especially for heavy duty works where foreman doesn't want to force him self. Foremen explain how to execute the work to helpers and control the work after completed. And finally what is not mentioned in tables is the site engineer is responsible of distributing works to foremen and control overall progress of job. Project planning is also prepared by site engineer in daily bases.

In Appendix B as the requirements had been given as day bases, they should be converted to hour based data in order to use in the model. And the raw data coming from part III has been transformed to man-hours and listed as follows in Table IV.1.

Table IV.1 Compiled Man-hours

NO	ITEM	QUALIFICATION	MAN-HOUR
A	**SANITARY**		
1	Installations	Inst. Foreman	56
		Assembler	56
		Helper	384
2	Drains	Diamond Drilling Machine	6
		Inst. Foreman	40
		Helper	72
3	Accessories	Assembler	29
		Helper	24
B	**Plumbing**		
1	PVC plastic pipes	Inst. Foreman	64
		Helper	192
2	Galvanized Steel Pipes	Inst. Foreman	176
		Helper	528
C	**Heating**		
1	First process for steel pipes	Inst. Foreman	16
		Helper	16
2	Steel Pipes	Inst. Foreman	56
		Helper	168
3	Pipe anti-rust and painting	Painter	32
4	Pipe Insulation	Inst. Foreman	40
		Helper	40
5	Radiators	Assembler	32
		Helper	64
D	**HVAC**		
1	Galvanized Steel Ducts	HVAC Foreman	240
		Helpers	1200
2	Fan Installations	Assembler	8
		Helper	8
3	Grills & Diffusers	HVAC Foreman	24
		Helper	48

Table IV.1 (Continues)

NO	ITEM	QUALIFICATION	MAN-HOUR
4	Roof-top A/C base plate installation	Assembler	8
		Helper	8
5	Roof-top A/C installation	Assembler	3
		Winch	3
E	**Fire-fighting**		
1	Sprinklers pre-process	Inst. Foreman	24
		Helper	24
2	Sprinklers steel pipes	Inst. Foreman	128
		Helper	256
3	Pipe painting	Painter	32
4	Sprinklers branching	Foreman	32
		Helper	32
5	Sprinklers final installations	Inst. Foreman	32
		Helper	64
6	Piping for fire cabinet	Inst. Foreman	4
		Helper	4
7	Fire cabinet installation	Assembler	2
		Helper	2

As summary, total man-hours for activities are as follows in Table IV.2. Diamond drilling machine and winch hours are negligible in comparison to other resources, that's why both have been removed from the table.

Table IV.2 Resource Amount and Unit Duration of Activities

Activity		**Resource (resource-hour/unit)**				
		Installation Foreman	Assembler	Helper	Painter	HVAC Foreman
A	Sanitary	102	85	480	-	-
B	Plumbing	240	-	720	-	-
C	Heating	112	32	288	32	-
D	HVAC	-	19	1264	-	267
E	Fire Fighting	188	34	382	32	-

Unit prices of workers taken from accounting department of the firm are as follows in Table IV.3.

Table IV.3 Unit Prices of Resources

Resources	Unit prices (YTL/resource-hour)
Installation Foreman	8
Assembler	5,5
Helper	4
Painter	5
HVAC Foreman	8,5

The availability of manpower has been taken from point plan of accounting department to pay wages of workers. From one month sample (see Appendix D) these values has been derived and listed as follows in Table IV.4.

Table IV.4 Supply Conditions of Resources and Funding

Resource Type	Supply Conditions		
	Mean	Coef.* of Variation (%)	SD
Installation Foreman	17,387	23,837	4,145
Assembler	8,484	37,258	3,161
Helper	83,645	11,353	9,496
Painter	8,097	24,151	1,955
HVAC Foreman	8,161	31,810	2,596

*Coef: Coefficient

When only sample standard deviation is know the confidence interval is calculated by:

$$\bar{x} \pm t_{\alpha/2} \frac{s}{\sqrt{n}} \qquad \text{(IV.1)}$$

$\bar{x}$: sample mean

n: sample size

s: sample standard deviation

$t_{\alpha/2}$: t-value with an area of α/2 to its right ($t_{\alpha/2}$ can be obtained from Appendix E.).

$t_{\alpha/2}$ for n=31 (df (degree of freedom) =30) is 1,697.

n=31 for all samples in Appendix D makes $\sqrt{31}$ =5,568

$$\bar{x} \pm t_{\alpha/2}\frac{s}{\sqrt{n}} = \bar{x} \pm 1{,}697\frac{s}{5{,}568} = \bar{x} \pm s \times 0{,}305$$

is the value will be used in following cases.

IV.2. CASES

In this section different cases of the problem will be discussed. The values of supply condition will be altered to reach the best possible case.

IV.2.1. Actual Case

Table IV.4 will be used to solve the problem. Here, the coefficient of variation is used to estimate the level of uncertainty associated with the supply condition because it is a simple and direct measure of variability. If the required confidence level for every constraint is 90%, the chance-constrained programming model has the following deterministic equivalent:

Maximize Q;

Subject to;

$Q \leq Q_1$,
$Q \leq Q_2$,
$Q \leq Q_3$,
$Q \leq Q_4$,
$Q \leq Q_5$,

Installation Foreman:
102*Q1+240*Q2+112*Q3+188*Q5 ≤ **17.387+4.145***(-0.305);
Assembler:
85*Q1+32*Q3+19*Q4+34*Q5 ≤ **8.484+3.161***(-0.305);
Helper:
480*Q1+720*Q2+288*Q3+1264*Q4+382*Q5 ≤ **83.645+9.496***(-0.305);

Painter:

32*Q3+32*Q5 ≤ **8.097+1.955***(-0.305);

HVAC Foreman:

267*Q4 ≤ **8.161+2.596***(-0.305);

Funding:

(102*Q1+240*Q2+112*Q3+188*Q5)*8+(85*Q1+32*Q3+19*Q4+34*Q5)*5.5+(480*Q1+720*Q2+288*Q3+1264*Q4+382*Q5)*4+(32*Q3+32*Q5)*5+(267*Q4)*8.5≤ **400**;

$Q_1 \geq 0$;

$Q_2 \geq 0$;

$Q_3 \geq 0$;

$Q_4 \geq 0$;

$Q_5 \geq 0$.

The optimal solution set is:

$\{Q_1, Q_2, Q_3, Q_4, Q_5\}$={0.018871, 0.018871, 0.018871, 0.018871, 0.018871}.

In mechanical works there is a rule of ordering jobs. Plumbing, heating, fire-fighting and sanitary should follow in order for technical reasons.

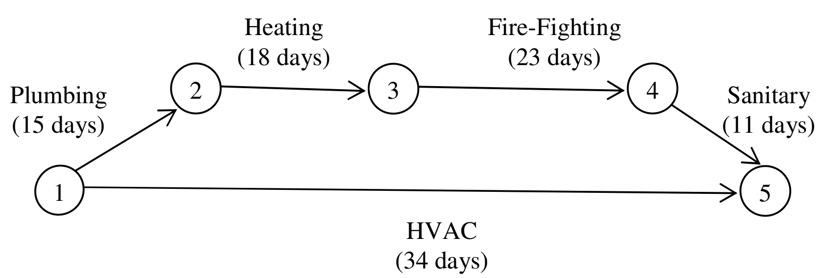


Figure IV.1 CPM

By CPM method the duration to complete first of five offices calculated D_1=67 days. It's the actual completion time of recently build office (Boshoku) which had been completed mid of the February with a delay of half a month from employer schedule. By the way the completion time of five offices according to the following formula:

$$D = D_1 + \frac{(M-1)}{Q}, \qquad \text{(IV.2)}$$

is 279 days. This makes the average completion time of one office 56 days which is higher than employer's request which was 53 days.

Increasing daily funding up to 533 YTL, will give an optimal solution set: $\{Q_1, Q_2, Q_3, Q_4, Q_5\}$={0.025113, 0.025113, 0.025113, 0.025113, 0.025113}. The completion time of five offices becomes 227 days with an average of 45 days which is lower than employer's request.

IV.2.2. Fixed Resources

It's assumed that there is no variation of resource supply. Working hour for one worker is eight hours and it's fixed.

Table IV.5 Fixed Resources

Resource Type	Supply Conditions
Installation Foreman	16
Assembler	8
Helper	80
Painter	8
HVAC Foreman	8

Maximize Q;

Subject to;

$Q \leq Q_1$;
$Q \leq Q_2$;
$Q \leq Q_3$;
$Q \leq Q_4$;
$Q \leq Q_5$;

Installation Foreman:
102*Q1+240*Q2+112*Q3+188*Q5 ≤ **16** ;

Assembler:

85*Q1+32*Q3+19*Q4+34*Q5 ≤ **8 ;**

Helper:

480*Q1+720*Q2+288*Q3+1264*Q4+382*Q5 ≤ **80** ;

Painter:

32*Q3+32*Q5 ≤ **8** ;

HVAC Foreman:

267*Q4 ≤ **8** ;

Funding:

(102*Q1+240*Q2+112*Q3+188*Q5)*8+(85*Q1+32*Q3+19*Q4+34*Q5)*5.5+(480*Q1+720*Q2+288*Q3+1264*Q4+382*Q5)*4+(32*Q3+32*Q5)*5+(267*Q4)*8.5≤ **400 ;**

$Q_1 \geq 0$;

$Q_2 \geq 0$;

$Q_3 \geq 0$;

$Q_4 \geq 0$;

$Q_5 \geq 0$;

The optimal solution set is the same as initial one because of the project duration has been constrained by funding, as it's seen. Increasing funding caused the decrease of the duration. That means there are more worker available than may be hired.

IV.2.3 Availability Limits of Resources

For each resource type, minimum availability limit keeps the average unit duration 53 days which is obtained by 265 total project day. The system production rate which gives project duration 265 days is 0,0202. If linear programming software Lingo is used to find for which founding constraint is needed to obtain this value, it's found finally 429 YTL per day.

This value (429 YTL) may be used to optimize worker quantities. Each resource will be decreased by one by one keeping same coefficient of variation using Lingo to find optimum worker quantities for 429 YTL. Table IV.4 giving initial values for resource availability is modified to Table IV.6.

If the values of Table IV.6 are formularized the function will be:

Maximize Q;

Subject to;

$Q \leq Q_{1;}$

$Q \leq Q_{2;}$

$Q \leq Q_{3;}$

$Q \leq Q_{4;}$

$Q \leq Q_{5;}$

Installation Foreman:

102*Q1+240*Q2+112*Q3+188*Q5≤**14.1+3.361***(-0.305);

Assembler:

85*Q1+32*Q3+19*Q4+34*Q5≤**3.9+1.453***(-0.305);

Helper:

480*Q1+720*Q2+288*Q3+1264*Q4+382*Q5≤**65.8+7.470***(-0.305);

Painter:

32*Q3+32*Q5≤**1.4+0.338***(-0.305);

HVAC Foreman:

267*Q4≤**6+1.909***(-0.305);

Funding:

(102*Q1+240*Q2+112*Q3+188*Q5)*8+(85*Q1+32*Q3+19*Q4+34*Q5)*5.5+(480*Q1+720*Q2+288*Q3+1264*Q4+382*Q5)*4+(32*Q3+32*Q5)*5+(267*Q4)*8.5≤**429**;

Q1 ≥0;

Q2 ≥0;

Q3 ≥0;

Q4 ≥0;

Q5 ≥0;

Which gives same system production rate of {0,02023} despite of the decrease of each labor resource availability.

Table IV.6 Resources Availability Limits

Resource Type	Supply Conditions		
	Mean	Coef. of Variation (%)	SD
Installation Foreman	14,1	23,837	3,361
Assembler	3,9	37,258	1,453
Helper	65,8	11,353	7,470
Painter	1,4	24,151	0,338
HVAC Foreman	6,0	31,81	1,909

To compare availability limits to initial values see Table IV.7.

Table IV.7 Resources Availability Limits Comparison

Resource Type	Supply Conditions	
	Available Mean	Required Mean
Installation Foreman	17,387	14,1
Assembler	8,484	3,9
Helper	83,645	65,8
Painter	8,097	1,4
HVAC Foreman	8,161	6

IV.2.4 Changing Confidence Level

In past examples the confidence level used was %90. If confidence level is increased to %95, the formulation of confidence interval changes as follows:

$$t_{\alpha/2} = 2,042$$

$$n = 31$$

$$\bar{x} \pm t_{\alpha/2} \frac{s}{\sqrt{n}} = \bar{x} \pm 0,367 \times s$$

Changing confidence level to %95 doesn't effect the system production rate of 400 YTL per day founding constraint. But increasing founding per day to 429 increase system production rate to 0,0202. This is the same value of confidence level of %90. Now the optimum quantities of labor will be seeked by decreasing one by one and simulating by Lingo software.

If confidence level is decreased to %99, the formulation of confidence interval changes as follows:

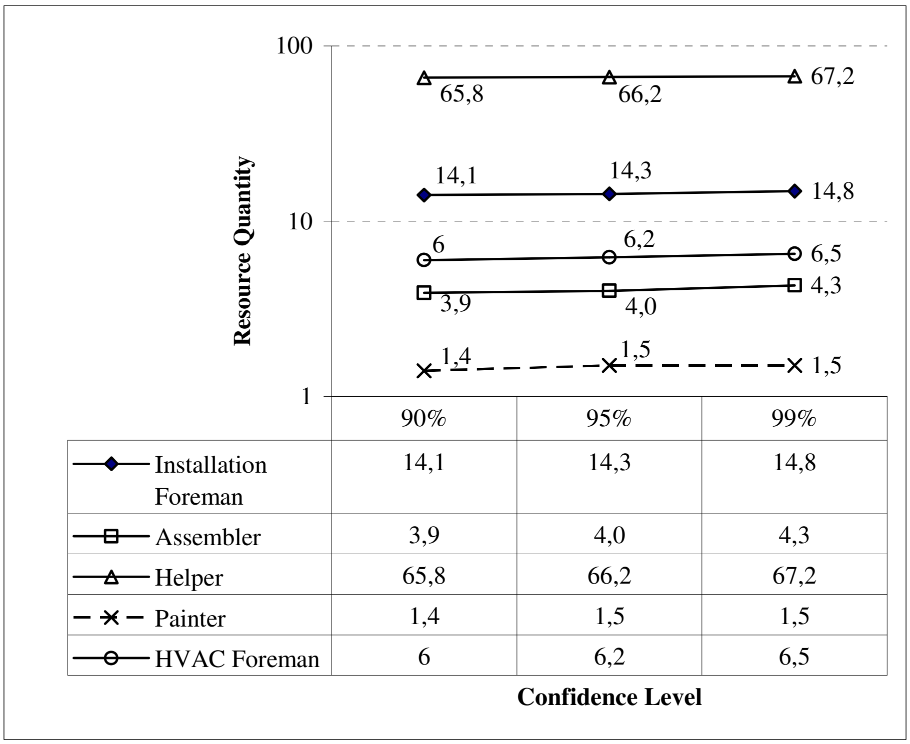
$$t_{\alpha/2} = 2,750$$

$$\bar{x} \pm t_{\alpha/2} \frac{s}{\sqrt{n}} = \bar{x} \pm 0,494 \times s$$

After calculated availability limit for confidence level %99 all levels are compared in Table IV.7.

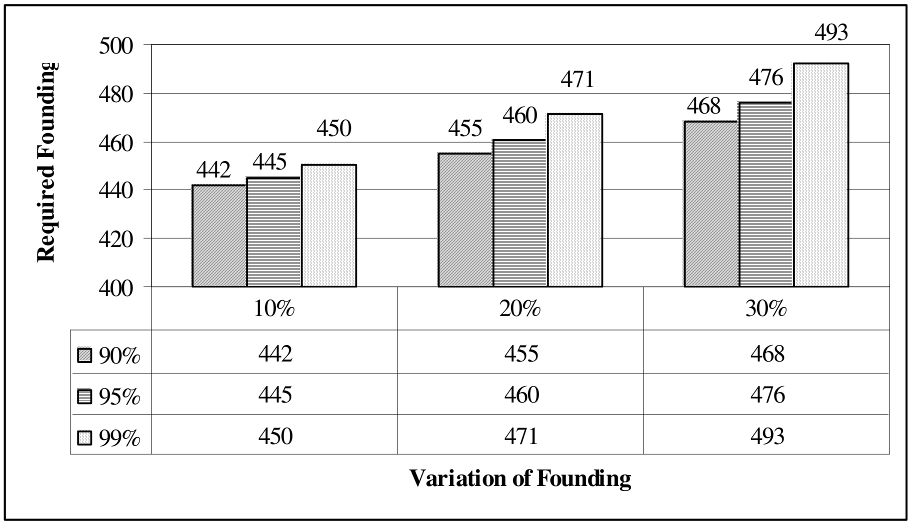
Table IV.8 Confidence Levels Comparison

Resource Type	Supply Conditions			
	Available Mean	Required Mean for %90	Required Mean for %95	Required Mean for %99
Installation Foreman	17,4	14,1	14,3	14,8
Assembler	8,5	3,9	4,0	4,3
Helper	83,6	65,8	66,2	67,2
Painter	8,1	1,4	1,5	1,5
HVAC Foreman	8,2	6	6,2	6,5



IV.2.5 Variation of Founding

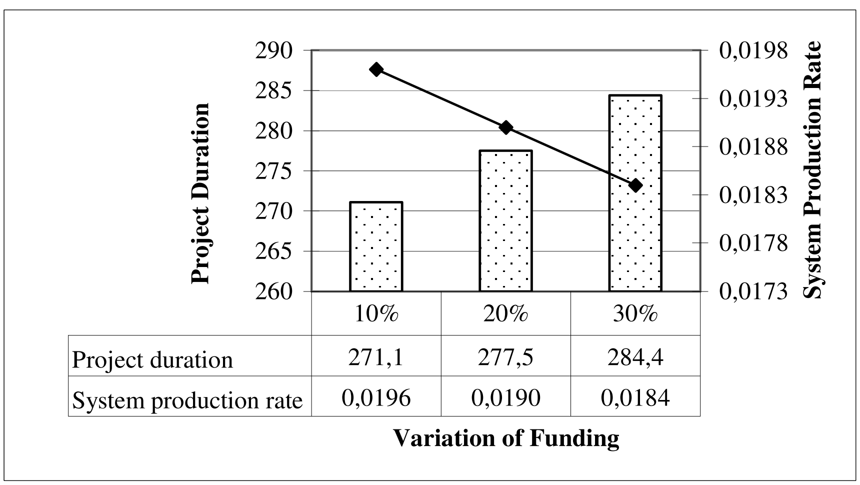
The exact currency flow of founding is not available but a funding variation may be estimated to stay in confidence by considering the same sample size is same as working hours. In following Figure IV.2 required funding for each confidence levels is seen as (90%, 95%, 99%) over each variation (%10, %20, %30).



	10%	20%	30%
90%	442	455	468
95%	445	460	476
99%	450	471	493

Figure IV.2 Variation of Founding

It's considered how to increase daily funding to prevent a project delay. Now it will be assumed that if funding isn't increased what will happen to project duration in case of variation of funding. The confidence level will be 90% as initial and the availability of workers will be best possible case of 90% confidence level found in Table IV.7. The effect of variation of funding will be as follows in Figure IV.3.



	10%	20%	30%
Project duration	271,1	277,5	284,4
System production rate	0,0196	0,0190	0,0184

Figure IV.3 Effect of Variation of Funding

PART V

DISCUSSIONS AND EVALUATIONS

Repetitive construction projects utilize various resources (labor and equipment) and require funding. While the amounts of resources and funding are subject to certain limits, their supply conditions may also be exposed to uncertainty in today's dynamic and complex business environment. Such uncertainty requires caution and should be incorporated into the decision-making process. To achieve this goal, a chance constrained programming model had been presented, derive its deterministic equivalent, and solve the equivalent by classical linear programming techniques.

Two values are reached to discuss by examining Part IV's results; first sufficiency of availability of workers or equipments, secondly availability of funding. It had seen that the availability quantity of workers may change by adjusting confidence level. This availability differences (Table IV.7) may seen to be few but because of they are calculated daily bases, by the length of the project, adding each days delay to each other may cause a big delay at the end. That will affect all related systems and the firm. Only one hour of less estimated of daily man-hour causes six days of delay for a fifty day's project. Keeping confidence level too high will cause over load of workers and high labor cost and also by calculating high proposal price may result of rejection from the employer. The selection of confidence level is very important because of these reasons.

There are two important problems to take care of in funding a resource. First mistake made is ignoring variation of funding and causing excessive delay of the project. The excessive delay of the project will victimize workers, employer and by decreasing productivity it may reduce profit or it may cause lost of money. Second case is wrong selecting of variation and confidence level of funding. This case may result of high or low proposal prices. Because of high proposal price or very low proposal price (seriousness and accuracy of the proposal) the employer may reject the proposal. In case of acceptance by the employer of low priced proposal (under the cost of the project) the will of executing the work in good quality will be defected. Poor quality of craftsmanship will defect also the reliability of the firm. By the result of the cases of part IV (Figure IV.2) application of suggested model prevents very high or very low price proposals and also not applying or ignoring funding variations (Figure IV.3) may cause a wrong project scheduling.

At the earlier stages of proposal request keeping confidence level and variation of funding at high level for negotiating purpose and discounting by reducing in latter stages may give an advantage of price.

It had seen before that increasing confidence level will increase the availability request of workers and equipment. Identifying worker and equipment availability requirements by different cases (changing confidence level) (Table IV.7) will be helpful to take preventive measure at the starting point of the project. The confidence level may also be considered as a risk factor. Selecting a confidence level is also selecting the risk to be taken.

The quick response of the model simulation electronically by computer software provides an easy comparison of risks taken by the firm. The simulation software may be used to obtain data to manage the decision making process. Evaluation of the data may simplify correct decisions.

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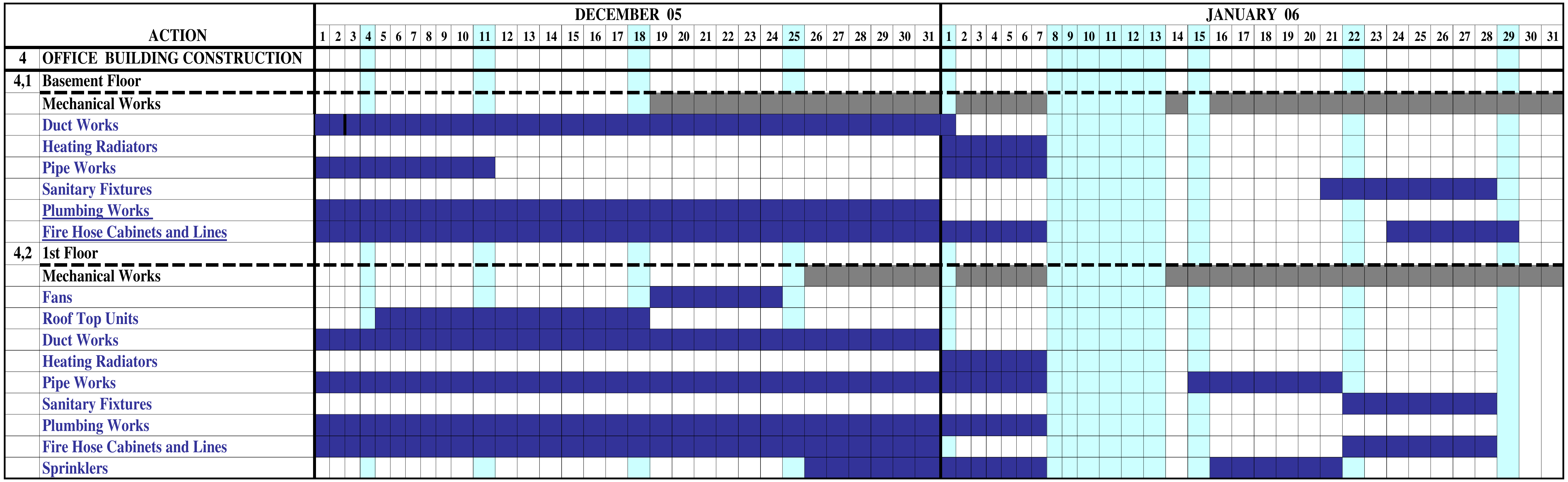
APPENDIX A

Table A.1 TID 2 Work Schedule



APPENDIX B

Table B.1 Man-hours

NO	ITEM	UNIT	QUAN.*	QUALIFICATION	DURATION
A	**SANITARY**				
A.1	**First Floor**				
1	Installations				
	-Closet &r reservoir -Lavatory -Urinal	Pcs Pcs Pcs	4 5 2	1 Inst. Foreman† 1 Assembler 4 Helpers	2 days
2	Drains				
	-Drilling	Pcs	6	1 Diamond Drilling Machine	6 h
	-Floor Drains	Pcs	2	1 Inst. Foreman 1 Helper	1 day
3	Accessories				
	-Mirror	Pcs	5	1 Assembler	4 h
	-Paper holder -Automatic Liquid soap -Paper dispenser	Pcs Pcs Pcs	4 2 2	1 Assembler 1 Helper	1 day
A.2	**Basement**				
1	Installations				
	-Closet & reservoir - Squat Toilet - Shower tub -Lavatory -Urinal	Pcs Pcs Pcs Pcs Pcs	2 7 6 13 4	1 Inst. Foreman 1 Assembler 4 Helpers	5 days
2	Drains				
	-Drilling -Floor Drains	Pcs Pcs	13 3	2 Inst. Foremen 4 Helpers	2 days

* QUAN: Quantity
† Inst. Foreman: Installation Foreman

Table B.1 (Continues)

NO	ITEM	UNIT	QUAN.	QUALIFICATION	DURATION
3	Accessories				
	-Mirror	Pcs	13	1 Assembler	9 h
	-Paper holder -Automatic Liquid soap -Paper dispenser	Pcs Pcs Pcs	9 7 2	1 Assembler 2 Helpers	1 day
B	**Plumbing**				
1	PVC plastic pipes -DN100 -DN125 -DN150	 m m m	 61 47 20	2 Inst. Foremen 6 Helpers	4 days
2	Galvanized Steel Pipes -1/2" -3/4" -1" -1 1/4" -Fittings	 m m m m %	 10 39 127 19 30	2 Inst. Foremen 6 Helpers	11 days
C	**Heating**				
1	-First process for steel pipes			1 Inst. Foreman 1 Helpers	2 days
2	Steel Pipes -2 1/2" -2" -1 1/2" -1 1/4" -1" -3/4" -1/2" -Fittings	 m m m m m m m %	 29 71 32 51 49 73 38 30	1 Inst. Foreman 3 Helpers	7 days
3	Pipe anti-rust and painting -2 1/2" -2" -1 1/2" -1 1/4" -1" -3/4" -1/2"	 m m m m m m m	 29 71 32 51 49 73 38	1 Painter	4 days

Table B.1 (Continues)

NO	ITEM	UNIT	QUAN.	QUALIFICATION	DURATION
4	Pipe Insulation				
	-2 1/2"	m	29		
	-2"	m	71		
	-1 1/2"	m	32	1 Inst. Foreman	5 days
	-1 1/4"	m	51	1 Helper	
	-1"	m	39		
	-3/4"	m	29		
	-1/2"	m	33		
5	Radiators				
	-PKKP 600 180	Pcs	2		
	-PKKP 600 160	Pcs	12		
	-PKKP 600 140	Pcs	4		
	-PKKP 600 120	Pcs	13	1 Assembler	4 days
	-PKKP 600 100	Pcs	3	2 Helpers	
	-PKKP 600 80	Pcs	8		
	-PKKP 600 60	Pcs	2		
	-PKKP 600 50	Pcs	2		
	-PKKP 900 70	Pcs	2		
D	**HVAC**				
1	Galvanized Steel Ducts			1 HVAC Foreman	
	-Ducts	m^2	1120	5 Helpers	30 days
	-Duct Insulation	m^2	550		
2	Fan Installations				
	-Cell Fan	Pcs	1	1 Assembler	1 day
	-AxC 315 B	Pcs	5	1 Helper	
	-AxB 7x4 T4	Pcs	1		
3	Grills				
	-40x50	Pcs	18		
	-30x60	Pcs	11		
	-30x50	Pcs	23		
	-25x50	Pcs	5	1 HVAC Foreman	
	-20x30	Pcs	10	2 Helpers	3 days
	-15x30	Pcs	8		
	Diffusers				
	-45x45	Pcs	12		
	-37.5x37.5	Pcs	13		
	-30x30	Pcs	14		

Table B.1 (Continues)

NO	ITEM	UNIT	QUAN.	QUALIFICATION	DURATION
4	Roof-top A/C base plate installation	Pcs	2	1 Assembler 1 Helper	1 day
5	Roof-top A/C installation	Pcs	2	1 Assembler 1 winch	3 h
E	**Fire-fighting**				
1	Sprinklers pre-process			1 Inst. Foreman 1 Helper	3 days
2	Sprinklers steel pipes 3/4" 1" 1 1/4" 2 1/2 3" Fittings	 m m m m m %	 112 71 47 19 64 30	2 Inst. Foremen 4 Helpers	8 days
3	Pipe painting 3/4" 1" 1 1/4" 2 1/2 3"	 m m m m m	 112 71 47 19 64	1 Painter	4 days
4	Sprinklers branching	Pcs	79	1 Inst. Foreman 1 Helper	4 days
5	Sprinklers final installations	Pcs	79	1 Inst. Foreman 2 Helpers	4 days
6	Piping for fire cabinet -1"	 m	 5	1 Inst. Foreman 1 Helper	4 h
7	Fire cabinet installation	Pcs	1	1 Assembler 1 Helper	2 h

APPENDIX C

Table C.1 Installation Costs

NO	ITEM	UNIT	QUAN.	UNIT COST (YTL)	TOTAL (YTL)
A	**SANITARY**				
1	Installations				
	-Closet & reservoir	Pcs	6	26,6	159,6
	- Squat Toilet	Pcs	7	32,6	228,2
	- Shower tub	Pcs	6	38	228
	-Lavatory	Pcs	18	37,96	683,28
	-Urinal	Pcs	6	35,9	215,4
	-Urinal Separator	Pcs	5	6	30
2	Drains				
	-Drilling	Pcs	19	0,5	9,5
	-Floor Drains	Pcs	5	3	15
3	Accessories				
	-Mirror	Pcs	18	2	36
	-Paper holder	Pcs	13	1	13
	-Automatic Liquid soap	Pcs	9	2	18
	-Paper dispenser	Pcs	4	2	8
B	**Plumbing**				
1	PVC plastic pipes				
	-DN100	m	61	1,3	79,3
	-DN125	m	47	1,3	61,1
	-DN150	m	20	1,5	30
2	Galvanized Steel Pipes				
	-1/2"	m	10	1,4	14
	-3/4"	m	39	1,6	62,4
	-1"	m	127	1,8	228,6
	-1 1/4"	m	19	2	38
	-Fittings	%	30		102,9

Table C.1 (Continues)

NO	ITEM	UNIT	QUAN.	UNIT COST (YTL)	TOTAL (YTL)
C	**Heating**				
1	-First process for steel pipes			Included in steel pipes installation cost.	
2	Steel Pipes				
	-2 1/2"	m	29	2,3	66,7
	-2"	m	71	2,2	156,2
	-1 1/2"	m	32	2,1	67,2
	-1 1/4"	m	51	2	102
	-1"	m	49	1,8	88,2
	-3/4"	m	73	1,6	116,8
	-1/2"	m	38	1,5	57
	-Fittings	%	30		196,23
3	Pipe anti-rust and painting				
	-2 1/2"	m	29	0,52	15,08
	-2"	m	71	0,31	22,01
	-1 1/2"	m	32	0,31	9,92
	-1 1/4"	m	51	0,31	15,81
	-1"	m	49	0,31	15,19
	-3/4"	m	73	0,31	22,63
	-1/2"	m	38	0,31	11,78
4	Pipe Insulation				
	-2 1/2"	m	29	1,2	34,8
	-2"	m	71	1	71
	-1 1/2"	m	32	1	32
	-1 1/4"	m	51	0,8	40,8
	-1"	m	39	0,8	31,2
	-3/4"	m	29	0,8	23,2
	-1/2"	m	33	0,8	26,4

Table C.1 (Continues)

NO	ITEM	UNIT	QUAN.	UNIT COST (YTL)	TOTAL (YTL)
5	Radiators				
	-PKKP 600 180	Pcs	2	7,4	14,8
	-PKKP 600 160	Pcs	12	4,4	52,8
	-PKKP 600 140	Pcs	4	4,4	17,6
	-PKKP 600 120	Pcs	13	4,4	57,2
	-PKKP 600 100	Pcs	3	4,4	13,2
	-PKKP 600 80	Pcs	8	4,4	35,2
	-PKKP 600 60	Pcs	2	4,4	8,8
	-PKKP 600 50	Pcs	2	4,4	8,8
	-PKKP 900 70	Pcs	2	4,4	8,8
D	**HVAC**				
1	Galvanized Steel Ducts				
	-Ducts	m^2	1120	11,77	13.182,4
	-Duct Insulation	m^2	550	4	2200
2	Fan Installations				
	-Cell Fan	Pcs	1	137	137
	-AxC 315 B	Pcs	5	9	45
	-AxB 7x4 T4	Pcs	1	9	9
3	Grills				
	-40x50	Pcs	18	4	72
	-30x60	Pcs	11	4	44
	-30x50	Pcs	23	4	92
	-25x50	Pcs	5	4	20
	-20x30	Pcs	10	4	40
	-15x30	Pcs	8	4	32
	Diffusers				
	-45x45	Pcs	12	4	48
	-37.5x37.5	Pcs	13	4	52
	-30x30	Pcs	14	4	56
4	Roof-top A/C base plate installation	Pcs	2	Included in roof-top A/C installation	
5	Roof-top A/C installation	Pcs	2	137	274
E	**Fire-fighting**				
1	Sprinklers pre-process			Included in sprinklers steel pipes	

Table C.1 (Continues)

NO	ITEM	UNIT	QUAN.	UNIT COST (YTL)	TOTAL (YTL)
2	Sprinklers steel pipes				
	3/4"	m	112	1,6	179,2
	1"	m	71	1,8	127,8
	1 1/4"	m	47	2	94
	2 1/2	m	19	2,3	43,7
	3"	m	64	2,9	185,6
	Fittings	%	30		189,09
3	Pipe painting				
	3/4"	m	112	0,31	34,72
	1"	m	71	0,31	22,01
	1 1/4"	m	47	0,31	14,57
	2 1/2	m	19	0,52	9,88
	3"	m	64	0,52	33,28
4	Sprinklers branching	Pcs	79	Included in sprinklers final installations	
5	Sprinklers final installations	Pcs	79	2	158
6	Piping for fire cabinet	m	5		
	-1"			2,11	10,55
7	Fire cabinet installation	Pcs	1	95	95
				TOTAL (YTL)	**21.200,43**

APPENDIX D

Table D.1 Resource Availability Sample

WORKER	WORKING HOURS PER DAY																													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
Inst. Foreman #1	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	4	8
Over time										1				5			3		2			3	2		7	5	2	3	4		
Inst. Foreman #2	8	8	8	8	8	8	8	8	8	8	8	8	8	X	X	X	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Overtime		2		8	2	1	2		4									8					2			5					
Assembler	8	8	8	8	8	8	8	8	X	X	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Over time		4		8		3						1	4												8	3					
Helper #1	8	8	4	8	8	8	8	8	8	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Overtime									4																						
Helper #2	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Overtime																				1			2								
Helper #3	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Overtime		2		8		4		3			8			3				8		1		2	2	2	8	5				1	
Helper #4	8	8	8	8	8	8	2	8	8	8	8	4	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Overtime	2																					1	1	1	8					2	
Helper #5	8	8	8	8	8	8	8	8	8	8	8	8	8	X	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Overtime	2			8					3									8													
Helper #6	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	4	8	8
Overtime														1		2		4		4	1		4	2				1			
Helper #7	8	8	8	8	8	8	8	8	8	8	8	8	8	6	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Overtime				8		4					8							8					2		8	1					
Helper #8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	X	8	8	8	8	8
Overtime																															
Helper #9	8	8	8	8	8	8	8	6	8	8	8	8	8	8	8	4	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Overtime																		4			3									2	
Helper #10	X	X	X	X	X	8	8	8	8	X	8	8	8	8	8	8	8	8	8	8	8	6	8	8	8	8	8	8	8	8	8
Overtime						4	2		4					4						1	1	3				5	4	3	4	4	
Painter	7	8	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	X	8	8	8	8	8	8	8	8	8
Overtime																					1		4				4		4		
HVAC Foreman	8	8	8	8	8	8	8	8	8	X	8	8	8	8	8	8	8	8	8	8	8	8	X	8	8	8	8	8	8	8	8
Overtime						4	3		1					4														4	4	1	

APPENDIX E

Table E.1 Inverse T-Distribution Table

df $\alpha \rightarrow$ ↓	**0.1**	**0.05**	**0.025**	**0.01**	**0.005**	**0.001**	**0.0005**
Infinity	1.282	1.645	1.960	2.326	2.576	3.091	3.291
1	3.078	6.314	12.706	31.821	63.656	318.289	636.578
2	1.886	2.920	4.303	6.965	9.925	22.328	31.600
3	1.638	2.353	3.182	4.541	5.841	10.214	12.924
4	1.533	2.132	2.776	3.747	4.604	7.173	8.610
5	1.476	2.015	2.571	3.365	4.032	5.894	6.869
6	1.440	1.943	2.447	3.143	3.707	5.208	5.959
7	1.415	1.895	2.365	2.998	3.499	4.785	5.408
8	1.397	1.860	2.306	2.896	3.355	4.501	5.041
9	1.383	1.833	2.262	2.821	3.250	4.297	4.781
10	1.372	1.812	2.228	2.764	3.169	4.144	4.587
11	1.363	1.796	2.201	2.718	3.106	4.025	4.437
12	1.356	1.782	2.179	2.681	3.055	3.930	4.318
13	1.350	1.771	2.160	2.650	3.012	3.852	4.221
14	1.345	1.761	2.145	2.624	2.977	3.787	4.140
15	1.341	1.753	2.131	2.602	2.947	3.733	4.073
16	1.337	1.746	2.120	2.583	2.921	3.686	4.015
17	1.333	1.740	2.110	2.567	2.898	3.646	3.965
18	1.330	1.734	2.101	2.552	2.878	3.610	3.922
19	1.328	1.729	2.093	2.539	2.861	3.579	3.883
20	1.325	1.725	2.086	2.528	2.845	3.552	3.850
21	1.323	1.721	2.080	2.518	2.831	3.527	3.819
22	1.321	1.717	2.074	2.508	2.819	3.505	3.792
23	1.319	1.714	2.069	2.500	2.807	3.485	3.768
24	1.318	1.711	2.064	2.492	2.797	3.467	3.745
25	1.316	1.708	2.060	2.485	2.787	3.450	3.725
26	1.315	1.706	2.056	2.479	2.779	3.435	3.707
27	1.314	1.703	2.052	2.473	2.771	3.421	3.689
28	1.313	1.701	2.048	2.467	2.763	3.408	3.674
29	1.311	1.699	2.045	2.462	2.756	3.396	3.660
30	1.310	1.697	2.042	2.457	2.750	3.385	3.646
60	1.296	1.671	2.000	2.390	2.660	3.232	3.460
120	1.289	1.658	1.980	2.358	2.617	3.160	3.373
Infinity	1.282	1.645	1.960	2.326	2.576	3.091	3.291

RESUME

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