OPTIMAL SCOPE OF WORK FOR INTERNATIONAL INTEGRATED SYSTEMS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

MUSTAFA ALP ERTEM

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
INDUSTRIAL ENGINEERING

JUNE 2005

Approval of the Graduate School of Natural and Applied Science.

Prof. Dr. Canan Özgen
Director

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

Prof. Dr. Çağlar Güven
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Canan Sepil
Supervisor

Examining Committee Members

Assoc. Prof. Dr. Levent Kandiller	(METU, IE)	
Assoc. Prof. Dr. Canan Sepil	(METU, IE)	
Asst. Prof. Dr. Sedef Meral	(METU, IE)	
Asst. Prof. Dr. Rıfat Sönmez	(METU, CE)	
Dr. Seçil Savaşaneril	(METU, IE)	

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name : Mustafa Alp Ertem

Signature :

ABSTRACT

OPTIMAL SCOPE OF WORK FOR
INTERNATIONAL INTEGRATED SYSTEMS

Ertem, Mustafa Alp
M.S., Department of Industrial Engineering
Supervisor : Assoc. Prof. Dr. Canan Sepil

June 2005, 72 pages

This study develops a systems integration project scheduling model which identifies the assignment of activity responsibilities that minimizes expected project implementation cost, considering the project risk. Assignment of resources to the individual jobs comprising the project is a persistent problem in project management. Mostly, skilled labor is an essential resource and both the time and the cost incurred to perform a job depend on the resource to which job is assigned.

A systems integration project includes implementation issues in the areas of shipping, installation, and commissioning. Implementation problems lead to project delays, increased costs, and decreased performance, leading to customer dissatisfaction with the systems integrator. Activities can be performed in one of three ways: by the integrator, by the customer, or jointly between the integrator and customer. In this study we select the performer (mode) of each activity comprising the project network while taking into consideration the varying cost, duration and extreme event probability of each activity among different modes-integrator, joint work and customer.

Use of the model will permit customers and integrators to mutually agree on an appropriate assignment of responsibilities in the contract. Systems integrators can also use the model to improve their implementation services offerings. An experimental design and a Monte-Carlo simulation study were conducted to see the effects of the parameters of the problem on the selection of modes.

Keywords: project scheduling, multi-mode time/cost trade-off problem, systems integration projects, quantitative risk analysis, implementation issues.

ÖZ

ULUSLARARASI ENTEGRE SİSTEMLER İÇİN
OPTİMUM İŞ KAPSAMI

Ertem, Mustafa Alp
Yüksek Lisans, Endüstri Mühendisliği Bölümü
Tez Yöneticisi : Doç. Dr. Canan Sepil

Haziran 2005, 72 sayfa

Bu çalışma, proje uygulama maliyetinin beklenen değerini, proje riskini de dikkate alarak minimize eden bir sistem entegrasyon projesi modeli tanımlamaktadır. Proje yönetiminde sık rastlanan bir sorun kıt kaynakların projeyi oluşturan özel işlere atanmasıdır. Bu kaynakları çoğunlukla bireyler (vasıflı işgücü) temsil ederler. Bir işi yapmak için harcanan zaman ve katlanılan maliyet, işin hangi kaynağa atandığına bağlıdır.

Bir sistem entegrasyonu projesi nakliyat, kurulum ve kabul alanlarındaki uygulama konularını içerir. Uygulama sorunları; proje gecikmelerine, artan maliyetlere, azalan performansa yol açar, bu da sistem entegratörünün müşterilerinde memnuniyetsizliğe sebep olur. Aktiviteler şu üç yoldan biriyle yapılabilir; entegratör tarafından, müşteri tarafından veya entegratör ve müşterinin ortak çalışmasıyla. Bu çalışmada, her yola göre değişen maliyet, süre ve olağanüstü olay olasılıkları dikkate alınarak proje ağını oluşturan her aktivitenin gerçekleştiricisi seçilmiştir.

Modelin kullanımı müşteri ve entegratörün beraberce sözleşmedeki sorumlulukların uygun atanmasına imkan verecektir. Sistem entegratörleri, bu modeli uygulama hizmetlerini geliştirmek için de kullanabilirler. Farklı

parametrelerin değişik yolların seçimindeki etkisini görebilmek için deneysel bir tasarım ve Monte-Carlo simülasyon çalışması yapılmıştır.

Anahtar Kelimeler: proje çizelgeleme, çok-yollu zaman/maliyet ödünleşme problemi, sistem entegrasyon projeleri, sayısal risk analizi, uygulama konuları

ACKNOWLEDGEMENTS

I would like to express my sincere thanks to my supervisor Assoc. Dr. Canan Sepil for the understanding, support, guidance and patience she provided.

I also wish to thank Assoc. Dr. Thomas Lacksonen – who was a visiting professor in Industrial Engineering Department during 2003-3004 academic year - for his motivating and encouraging support at the beginning of this study.

My special thanks and appreciation goes to my sister Ayşegül, her husband Mustafa and my "brother" Fatih Genişel for the hospitality they provide in Ankara after my years in Istanbul.

My sincere gratefulness is for my father and my mother for the great support they provide during my whole education.

TABLE OF CONTENTS

PLAGIARISM.. iii

ABSTRACT.. iv

ÖZ.. vi

ACKNOWLEDGMENTS... viii

TABLE OF CONTENTS... ix

LIST OF TABLES.. xi

LIST OF FIGURES.. xiii

CHAPTER

1. INTRODUCTION 1
2. LITERATURE REVIEW 6
   2.1 Project Scheduling and Resource Constrained Project Scheduling Problem (RCPS) 6
   2.2 Risk Analysis (RA) and Quantitative RA 9
   2.3 Uncertainty and Risk Analysis in Project Scheduling.................. 10
      2.3.1 Sensitivity Analysis 10
      2.3.2 Probabilistic Treatment of Project Analysis Involving Risk 11
   2.4 Time/Cost Trade-Off Problem.. 12
   2.5 Multimode Resource Constrained Project Scheduling Problem and Subcontracting.. 13
3. SYSTEMS INTEGRATION PROJECT SCHEDULE 15
   3.1 System design phase 15
   3.2 System shipment phase 17
   3.3 System installment phase 17
   3.4 System commissioning phase 18
   3.5 Problem Definition 19
   3.6 Mathematical formulation... 20
   3.7 Solution approach.. 22
4. CASE STUDY 24
   4.1 Data 25

4.2 Scenarios 25

4.3 Solution and results 30

5. COMPUTATIONAL EXPERIMENTS.. 35

5.1 Experimental Design 35

5.2 Simulation Study 43

6. CONCLUSION 52

REFERENCES..55

APPENDICES

A. 3rd Simulation Run's Data and IP for Experiment 111................ 58

B. Experimental Design Results for 243 experiments...................... 63

C. Visual Basic Code For Simulation Study...................................... 70

LIST OF TABLES

TABLES

1 First-world integrator data 27

2 First-world integrator with developing country distributor data............... 27

3 Developing country customer data 28

4 First-world country customer data 28

5 First-world int. and developing country customer joint activity data....... 29

6 First-world integrator/developing country distributor and 29

7 First-world integrator or integrator/distributor and first-world country customer joint activity data.. 30

8 Solution summary for four scenarios of ISPS problem............................. 33

9 Source data based on the integrator's case study data 36

10 Penalty Cost as a percentage of Average Daily Cost.............................. 37

11 Factors in 243 experiments.. 38

12 243 experiments' results (% of all experiments).................................... 39

13 Cost weight of each activity based on the source data 45

14 Results of the simulation study for Exp.111 (‰ of all runs) 47

15 Criticality of each activity in simulation study for Ex111(% of all runs). 47

16 Result of the Experimental Design for 111th experiment 47

17 Experiment 111's Factor Levels 47

18 Results of the simulation study for Exp.132 (‰ of all runs) 48

19 Criticality of each activity in simulation study for Ex132(% of all runs). 48

20 Result of the Experimental Design for 132nd experiment 48

21 Experiment 132's Factor Levels 48

22 Results of the simulation study for Exp.51 (‰ of all runs) 49

23 Criticality of each activity in simulation study for Ex51 (% of all runs).. 49

24 Result of the Experimental Design for 51st experiment 49

25 Experiment 51's Factor Levels 49

26 Results of the simulation study for Exp.114 (‰ of all runs) 50
27 Criticality of each activity in simulation study for Ex114 (% of all runs) 50
28 Result of the Experimental Design for 114th experiment 50
29 Experiment 114's Factor Levels 50

LIST OF FIGURES

FIGURES

1 Integrated systems project schedule 16

2 Sample integrated system 24

3 International integration scenarios 26

4 Sample probability trees for Scenario 1 32

5 Cp's effect on mode selection 40

6 ProbExtr's effect on mode selection 40

7 ExtrFac's effect on mode selection 41

8 JointDurIncFac's effect on mode selection 41

9 CustomerDurIncFac's effect on mode selection 42

10 JointCostDecFac's effect on mode selection 42

11 CustCostDecFac's effect on mode selection 43

12 ISPS problem network used in simulation runs. 44

13 Flowchart used in simulation runs. 46

CHAPTER 1

INTRODUCTION

A project involves an integrated set of activities directed to the accomplishment of a desired objective, such as the delivery of a system or a product, under certain constraints. A project generally has a minimum set of features including a specific objective to be achieved within certain technical specifications, starting and ending times, budget and consumption of resources. Project management is the discipline that aims to carry out the project to successful completion with effective use of people, resources, systems and techniques. The goal of project management is to accomplish the project before the designated deadline within the budget limits and utilizing the available resources efficiently.

The planning and control of large projects is a difficult and important problem of modern enterprise that many network planning techniques have tried to handle. Practical application of these techniques leads, however, to many complexities. During the planning phase of a project, project management must solve series of technical problems involving time, cost and resource aspects.

The scheduling problems involve the allocation of scarce resources to project activities, which may depend on several factors. Generally, a scheduling problem involves the preparation of a timetable as to when certain activities start and end, which resource-duration modes will be employed, if there are any, under the consideration of the resource constraints. Resource-constrained project scheduling problem is one of the operational research problems that has received great interest. The evolution of the research is towards more realistic models of resource-constrained project scheduling problems involving multiple-category resources, multiple performing modes of activities, multiple project performance measures and the incorporation of uncertainty in time parameters (Hapke et al.,1994).

Drexl (1991) states that:

> A recurring problem in project management involves the allocation of scarce resources to the individual jobs comprising the project. In many situations the resources correspond to individuals (skilled labor). This naturally leads to an assignment type of project scheduling problem, i.e. a project has to be processed by assigning one of several individuals to each job.

Both the time and the cost incurred to perform a job depend on the resource to which job is assigned. Objective is to find the least expensive schedule under which the project is completed by the given time horizon.

Automation, downsizing and globalization were all key trends in manufacturing and distribution of the 1990s that are still affecting business today. Their impact has changed the way manufacturing and distribution systems integration projects are performed.

Key business strategies for manufacturing and business success have changed as lean manufacturing concepts are expanded. Cost was the primary objective through the 1970s, with quality added in the 1980s, and delivery added in the 1990s (Chase et.al. 1998). Properly applied, increased automation can help companies achieve all of these objectives. Therefore, increasingly sophisticated integrated systems were designed to meet ever more demanding customer expectations.

Downsizing of staff was one result of the business process re-engineering trend in the 1990s. For today's engineering projects, companies typically hire a third-party systems integrator to perform systems design work in support of their own project engineers. A systems integrator provides a full set on engineering services to take a project from problem definition stage to system acceptance. Additionally, the system integrator can manage the project resources and take financial responsibility for system performance (ISCC of MHIA, 1992).

Globalization involved the delivery of products and services between countries. Many companies have moved to or added production facilities in countries with lower operating costs. Distribution centers are spreading across the world to provide timelier service to global customers. Exports of machinery and transport equipment increased at 8% per year in the 1990s. By 2002, 24.7% of the world's goods and services were exported (WorldBank Stat.,2005). Machinery accounted for $2.57 trillion in exports, or 41.5% of the world's merchandise trade (WTO Stat., 2004). Systems integration services are also global. Sixteen of the top twenty integrators with a United States presence are headquartered overseas (MMH, 2004). These large integrators are from the United States, Western Europe, and the Pacific Rim. With many projects in developing countries, systems integration projects have a global scope.

These trends have changed the scope of systems integration projects. Research has focused on the design and analysis of integrated systems. As a result, systems integrators usually design systems that meet customer specifications. But a systems integration project also includes implementation issues in the areas of shipping, installation, and commissioning. Implementation problems lead to project delays, increased costs, and decreased performance, leading to customer dissatisfaction with the systems integrator (Lacksonen, 2002). This feature has been the major driving force of this study and the main concern for the rest of the review and development effort presented in the chapters that follow.

Activities can be performed in one of three ways: by the integrator, by the customer, or jointly between the integrator and customer. The major contribution of this study is to select the performer (mode) of each activity constructing the project network while taking into consideration the varying cost, duration and extreme event probability of each activity among different modes-integrator, joint work and customer.

Generally, integrator work has a higher cost and lower risk, while customer work has lower cost and higher risk. The customer ultimately defines the scope of work, but since costs and risks are generally shared in the contract, it is in the interest of both parties to identify the single best scope of work. A proper division of responsibilities will reduce implementation risks and customer dissatisfaction.

This study develops a systems integration project scheduling model which identifies the assignment of activity responsibilities that minimizes expected project implementation cost, considering the project risk. Customers and integrators would mutually agree on an appropriate assignment of responsibilities in the contract by using this model. Systems integrators can also use the model to improve their implementation services offerings.

Project Scheduling, Resource Constrained Project Scheduling Problem (RCPSP), Risk Analysis, Time/Cost Trade-off Problem, Multi-Mode RCPSP and Subcontracting issues are covered as a literature survey in Chapter 2.

The basic schedule that formed a basis to the study, namely Systems Integration Project Schedule is explained in the 3rd Chapter. The Zero-One

Integer Programming Solution to the Integrated Systems Project Scheduling Problem is formulated in the last two section of this chapter.

In the following chapter, a case study is presented which was performed to the data based on a project where a Japanese systems integrator working with a Turkish distributor providing an integrated system to a large Turkish vehicle manufacturer.

In the 5th chapter, the effects of the parameters of the problem on the selection of modes were considered with an Experimental Design and a Monte-Carlo Simulation Study. Finally, the conclusions regarding the study are presented in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Project Scheduling and Resource Constrained Project Scheduling Problem (RCPS)

The allocation of restricted resources such as money, time and labor to activities of the project while optimizing the use of these resources and finishing the project on time and in budget limits is defined as project scheduling.

As the objective function of project scheduling problems, there are time-based objectives of minimizing makespan, mean lateness, mean completion time, total or weighted tardiness, and etc. Time-based objectives often conflict with cost-based objectives such as maximizing project's net present value (NPV), minimizing the total cost of resources, overhead, tardiness penalties, and etc. A general situation found in practice is the necessity of completing the project by its due date and also maximizing revenue (Ozdamar and Ulusoy, 1993).

As for the constraints in project scheduling models, precedence constraints represent the technological network and resource limitations. Resource constraints complicate the representation of the problem and the more accurately they describe the actual problem, the more difficult they become to handle (Ozdamar and Ulusoy 1993). Resource Constrained Project

Scheduling Problem (RCPSP) is known as the problem of allocating resources to activities under limited resource units with the objective of minimizing makespan or maximizing the Net Present Value.

There are two alternative preemption assumptions that can be made for the problem. In the first one, where preemption is allowed, an activity can be interrupted to allow the execution of another one. In the non-preemptive case, activities cannot be interrupted after they are initiated.

The research on the traditional resource-constrained project scheduling problem consists of solutions incorporating optimization techniques based on branch and bound, and zero-one integer programming methods and heuristics.

Detailed categorizations of these approaches are presented by Davis (1973), and Icmeli, Erenguc and Zappe (1993). Comparisons among optimization methods and dispatching rules are found in the literature and best performing dispatching rules are specified. Optimal solutions cannot be obtained in large size problems because of the combinatorial complexity of the problem.

The time/cost trade-off problem is composed of activities that are subject to technological precedence constraints where they require a certain amount of resources and the resources are scarce.

The way in which resources are consumed by activities also represents a distinguishing factor. An activity mode is an operating option that can be selected in the scheduling process. It contains information on its operating duration and the amounts of resources it requires during its realization (Ozdamar and Ulusoy 1993). At the scheduling phase, the procedure derives a solution which specifies how each activity should be performed, that is, which mode should be selected and when each mode should be scheduled (Talbot, 1982).

Talbot (1982) formulated the resource constrained project scheduling problem enabling one to handle different kind of resources, to identify several alternative ways, or modes, of accomplishing each activity in the project and allowing minimization of either the project duration or its execution cost. Talbot described the nature of the time-resource trade-off problem and formally defined using a zero-one integer programming approach. He then developed an implicit enumeration solution technique for finding the schedule of jobs that minimizes project completion time. However, Talbot's solution technique cannot be used to solve real life large scale problems.

Mori and Tseng (1997) also consider the general class of nonpreemptive multi-mode resource constrained project scheduling problems and propose a genetic algorithm for these problems. They compare their algorithm with a stochastic scheduling method proposed by Drexl and Gruenewald (1993) and suggest that the genetic algorithm is superior to the stochastic scheduling method. The algorithm is based on the incorporation of problem-specific knowledge of the application domain in the genetic algorithm.

The stochastic nature of this method proposed by Drexl and Gruenewald (1993) emerges from using some criteria measuring the impacts of job selection and mode assignment in a probabilistic way. Drexl and Gruenewald compare the performance of their method with the so reported best performing deterministic scheduling rules and conclude that stochastic scheduling method is highly superior to other well-known existing deterministic scheduling rules.

2.2 Risk Analysis (RA) and Quantitative RA

Risk management currently has an important aspect on project management activities. There are quantitative and qualitative techniques which are applied to analyze the risk associated with the project activities.

Quantitative techniques are normally mathematically and/or computationally based and provide numerical probabilities, or frequencies, of the consequences and likelihood of identified risks. The values used in these techniques are obtained from historical databases or are estimates; they still contain some extent of uncertainty, due to the possible use of subjectively attained values (Baker et.al., 1998).

Quantitative techniques used for the analysis of risks in major projects are (Baker et.al., 1998):

- EMV(Expected Monetary Value)
- ENPV(Expected Net Present Value)
- Algorithms
- Decision matrix
- Decision tree
- Bayesian theory
- Stochastic decision tree
- Break-even analysis
- EMV with Delphi
- RADR (Risk adjusted discount rate)
- Stochastic dominance
- Simulation
- Portfolio theory

Qualitative techniques are usually employed at the beginning to identify and rank risks. Those risks with a high or intermediate rank may be further analyzed through quantitative techniques. The results of a quantitative technique are compared against company criteria and decisions made as to whether the risks are acceptable or not (Baker et.al., 1998).

2.3 Uncertainty and Risk Analysis in Project Scheduling

Risk and uncertainty are inherent in the general problem of project scheduling because all the decisions depend on estimates about uncertain future. Thus, risk and uncertainty have occupied the attention of a great many theoreticians and practitioners. A conventional approach to deal with the uncertainty in project scheduling is the use of stochastic methods. PERT (Program Evaluation and Review Technique) models have been widely used as an alternative to stochastic approaches. In PERT, expected project completion time is estimated using optimistic, most likely and pessimistic activity durations. Such an approach, however, has certain disadvantages based on its assumptions (Gallagher, 1987). Sensitivity analysis and probabilistic treatment to the problem are two approaches used in the following chapters to deal with the risk and uncertainty in project scheduling.

2.3.1 Sensitivity analysis

Uncertainty means that more things can happen than will happen. Purpose of the sensitivity analysis is to specify the possible range for a variable and to find how sensitive the project profitability to changes in this variable. Variables do not usually change one at a time. Therefore many companies try to cope with this problem by examining the effect on the project of alternative plausible combinations of variables. In other words, they will estimate the performance measure of the project under different scenarios and compare the estimate with the base case.

In sensitivity analysis, one can find infinity of combinations of the variables for which the project is justified, and infinity of combinations for which it is not. The more combinations of variables one tries, the less clear the picture of the project becomes. The only way to obtain an overall, synthetic picture of the project is to proceed with a probability analysis (Pouliquen, 1970).

2.3.2 Probabilistic Treatment of Project Analysis Involving Risk

To formally incorporate uncertainty about future events into a logical decision process it is necessary to utilize probability theory (Fabrycky and Thuesen, 1980). Probability theory consists of an extensive body of knowledge concerned with the quantitative treatment of uncertainty. By using probability theory it is possible to uniquely define events so that no ambiguities exist and so that each statement made within the theory is explicit and clearly understood. Probability theory allows uncertainty to be represented by a number so that the uncertainty of different events can be compared. Additionally, the structure of probability theory prevents the introduction of extraneous notions without full knowledge of the decision maker.

Sensitivity and probability analysis should not be considered as alternatives for each other. They can be considered as complementary to each other, i.e., each renders significance to other. Since constructing a probability distribution for each individual variable in the analysis is exhaustive and time consuming, the probability analysis should concentrate on only variables that have been identified by sensitivity analysis as being critical in determining the performance measure (Sarıaslan, 1989).

Almost all applications of probability theory to real-life decision making require the estimation of prior, or subjective, probabilities. Unfortunately, decision makers are extremely bad at estimating probabilities - with a strong tendency to over optimism. Because of this, the use of methods in risk analysis should be undertaken only with the greatest of care (Harrison, 1973).

2.4 Time/Cost Trade-Off Problem

Time/cost trade-off is deciding on whether to put more money into an activity and shorten the duration or to make the duration longer to stay within budget limits (Icmeli, Erenguc and Zappe 1993).

Common network planning techniques such as PERT and CPM (Critical Path Method), essentially concern with the time aspect only. These methods aim to minimize project duration, assuming that the various resources required for project completion are available. The various resource problems that may appear during project scheduling can be divided into three classes: time/cost trade-off, resource leveling and resource allocation (Herroelen, 1972).

Time/cost trade-off problems may appear when there are no constraints imposed on the availability of the resources. The problem then consists of reducing project completion time by adding additional resources to certain activities, so that execution of these activities may be accelerated. When this is the case there are many different ways in which activity durations may be selected so that project completion times of the resulting schedules are all equal. However, each schedule may yield a different value of total project direct cost. It would therefore be desirable to have some method for determining the least costly schedule for any given project duration. Several such methods have been developed, each of which hinge upon various assumptions about the form of the activity direct cost-duration relationship (Herroelen, 1972). In time/cost trade-off problems, there may be different modes of performing the activities, with different costs and the least costly schedules are sought.

Resource leveling problem occurs when one aims to keep the resource usage as much as possible to a constant rate and resource allocation problem occurs when total resource usage is restricted to a given limit (Herroelen, 1972).

Control on the processing times of activities can be interpreted as allocation of nonrenewable resource to the activities, where a larger allocation to an activity (i.e., a higher cost input) reduces processing time. The planner then aims at either minimizing the project makespan subject to a fixed upper bound on the resource (the budget problem), or at minimizing the total allocation subject to a given bound on the makespan (the deadline problem). As the allocation is usually measured in money, these problems are commonly referred to as time/cost trade-off problems (Brucker et.al., 1999).

2.5 Multimode Resource Constrained Project Scheduling Problem and Subcontracting

Within the classical resource-constrained project scheduling problem (RCPSP), the activities of a project have to be scheduled such that the makespan of the project is minimized. Thereby, technological precedence constraints have to be observed as well as limitations of the renewable resources required to accomplish the activities. Once started, an activity may not be interrupted. This problem has been extended to a more realistic model, the multimode resource constrained project scheduling problem (MRCPSP). Here, each activity can be performed in one out of several modes. Each mode of an activity represents an alternative way of combining different levels of resource requirements with a related duration. Following Slowinski (1980), renewable, nonrenewable, and doubly constrained resources are distinguished. While renewable resources have limited per-period availability such as manpower and machines, nonrenewable resources are limited for the entire project such as the budget of the project. Doubly constrained resources are limited both for each period and of the whole project. The objective is to find a mode and a start time for each activity such that the schedule is makespan minimal and feasible with respect to the precedence and resource constraints (Hartmann and Drexl, 1998).

Paul and Gutierrez (2000) address the problem of designing a contract mechanism to allocate the component subprojects of a large project to a pool of contractors. They state that while allocating the subprojects-which might be an activity on project network- to contractors, one should answer the question of whether to subcontract the activities individually or aggregate the activities in some fashion into packages and subcontract the packages. In the case of a homogeneous project consisting of serial subprojects, they show that disaggregating the project and assigning the subprojects to the contractors on a piecemeal basis reduces the variance of project duration while leaving the mean unchanged. On the other hand, in the case of a homogeneous project consisting of parallel subprojects, aggregating the subprojects and assigning the aggregated project to one of the contractors reduces mean project duration. Although the results of the study are related to the project duration, they claim that it can be extended to the cost analysis of the problem.

CHAPTER 3

SYSTEMS INTEGRATION PROJECT SCHEDULE

A generic systems integration schedule is used as a basis for the project. The schedule was developed based on the case study described in Chapter 4 (Figure 1). Large integrated projects may have several similar schedules, one for each major sub-system.

There are 17 activities in the defined systems integration project schedule which are divided into phases with milestones. The milestones are important because, one cannot progress to the following steps unless he comes to the end of a phase –which is described by a milestone.

The generic schedule is related to the systems development life cycle of the Integrated Systems and Controls Council (ISC) of Material Handling Industry of America (MHIA). The ISC schedule Phase I is *Project definition*. For our purposes, the systems integration schedule starts when an order is placed and the contract is signed. This model is designed for use in contract development, so earlier project definition activities are not considered. The ISC schedule Phase II is *Developing the solution*, which parallels the *Design system* phase. The ISC schedule Phase III is *Building the system*, which is divided into *Ship system* and *Install system* phases. The ISC schedule Phase IV is *Commissioning and maintaining the system*, which parallels the *Commission system* phase.

3.1 System design phase

The first and obviously most critical activity is the system design itself. For this study, it is assumed that the customer has chosen the systems integrator to perform at least the design phase, or there would be no need for the systems integrator. This activity is often the longest duration activity in the project, and includes functional specification definition, preliminary design, and detailed design. Here, the customer approves the designs during design reviews.

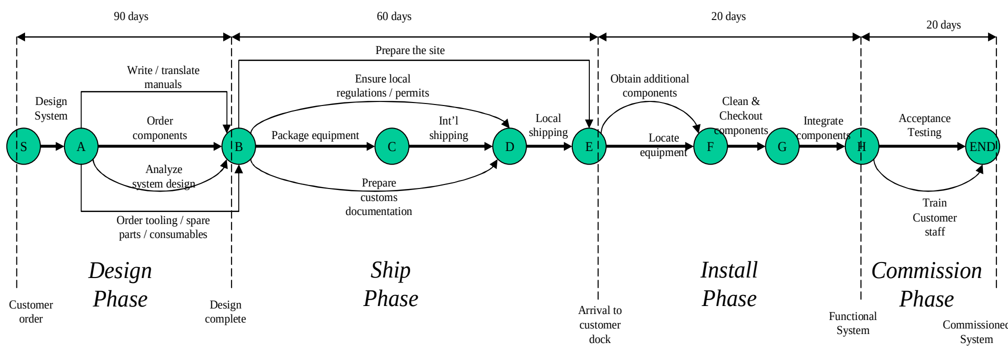


Figure 1: Integrated systems project schedule

As the design is being completed, several other activities must be performed. The system consists of a combination of off-the-shelf components, custom designed components, tooling, fixtures, and spare parts. All items must be ordered and manufactured by suppliers. Additionally, system documentation and manuals must be developed. Some components may come with prepared documents, but custom components and the integrated systems must have their own documentation completed. For international customers, translation of parts of the installation, operation, and maintenance manuals is required. Finally, the system design must be analyzed in the systems integrator's facility. Analysis includes physical testing of components, fixtures, and pilot integrations, and simulation testing of overall system performance. Here again, the customer approves the testing process and results.

These activities must generally be completed before the customer approves the system design and permits shipment of the system to the customer.

The five activities in the design phase are:

1) Design system
2) Order components
3) Order tooling/spares/consumables
4) Write / translate manuals
5) Analyze system design

3.2 System shipment phase

Several activities must occur for the system to arrive safely at the customer site's dock. Components gathered at the integrator's site must be properly packaged for shipment. For components shipped directly from international suppliers and systems integrator components shipped to an international customer, customs documentation must be prepared. International shipping and local shipping means must be selected, procured, scheduled and tracked. Simultaneously, the customer site must be prepared to receive the equipment, by constructing space, clearing space, and/or preparing equipment locations.

The six activities in ship system phase are:

6) Package equipment
7) Prepare customs documentation
8) International shipping
9) Local shipping
10) Ensure local regulations / permits
11) Prepare the site

3.3 System installment phase

Several sequential activities occur in installing a system at the customer site. First, the individual components must be physically located on the customer's site. At this point, missing parts, replacement parts, and miscellaneous hardware may need to be procured to complete the installation. Next, individual components are cleaned and checked out to insure that there was no damage during shipping and to introduce the customer to the components. Then, individual components are operated to verify that they are performing up to specification. Finally the entire system is integrated with existing customer hardware and software, and the integrated system is initially operated. The install phase is completed when the integrated system demonstrates its functionality.

The four activities in the install system phase are:

12) Obtain additional parts
13) Locate equipment
14) Clean & Checkout components
15) Integrate components

3.4 System commissioning phase

The last phase of the project is to commission the system, which includes acceptance testing and training. Acceptance testing involves running a pre-determined series of tests to verify that the system meets all functional specifications. The three components of training are engineer/programmer training, maintenance/service training, and operator/floor worker training. The level of training depends on the customer's existing familiarity with the system. Training usually occurs on the customer site. The project ends when the customer takes ownership of the system and signs off that all tests specified in the original contract have been successfully performed. Post-commissioning activities such as maintenance and service contract work are not part of the systems integration schedule.

The two activities in the commission system phase are:

16) Acceptance Testing

17) Train customer staff

3.5 Problem Definition

The problem is a time-cost trade-off problem within project scheduling problems. In a time-cost trade-off problem, there may be different modes to perform an activity with different durations and costs. It is assumed that the owner of the project has enough resources to fund the project. Resource constraints are beyond the scope of this thesis. The focus is on minimizing the costs and risks by using different modes for each activity. Risk is defined here with the inclusion of a probability that the duration of an activity increases due to an extreme event. Integrator working alone, Customer working alone or Integrator & Customer working joint are three types of modes considered in this study. Every activity explained in this chapter has a different cost and a different duration for each mode.

It is assumed that the integrator performs activities with less duration, low risk, but high costs; whereas the customer performs the activities with less cost, but long duration and high risk. And Joint Work is in between these. There is also a fixed cost of the project. Expressed as a daily cost, it is the opportunity cost of not giving the system into service, and is included as the penalty cost. The problem, then, is to determine the mode for each activity that minimizes the total cost while satisfying the precedence constraints.

The following section gives a mathematical formulation and, after that, a solution approach to the above problem is given.

3.6 Mathematical formulation

Given the problem definition the mathematical formulation of the problem is as follows:

Given the following network:

$G(N, A)$: Project network

$i, j \in N$: Nodes in network, $i = 1, ..., n$

n: number of nodes in the network

$ij \in A$: Activities in network, represented by an arc.

Define the following decision variables:

$$X_{ijr} = \begin{cases} 1, \text{ if mode } r \text{ is selected for activity } ij & \forall ij,\ r = 1,2,3 \\ 0, \text{ otherwise.} \end{cases}$$

Y_i = occurrence time of node i, $i = 1 ... n$

Define the following random variables and constants:

$p_{ij}(X_{ijr})$ = probability that extreme event occurs in activity ij in mode r, $\forall ij$, $r = 1,2,3$

Cp = Penalty cost of delaying the project one day.

$C_{ij}(X_{ijr})$ = cost of activity ij in mode r, $\forall ij$, $r = 1,2,3$

$D_{ij}(X_{ijr})$ = duration of activity ij in mode r, $\forall ij$, $r = 1,2,3$

Here in this study, it assumed that;

$C_{ij}(X_{ijr})$ and $D_{ij}(X_{ijr})$ have the following Bernoulli distributions:

$C_{ij}(X_{ijr})$ is a random variable denoting the cost of activity *ij in mode r* which incurs the following costs:

$c^n_{ij}(X_{ijr})$ = normal cost of activity ij in mode r

$c^e_{ij}(X_{ijr})$ = extreme event cost of activity ij in mode r

and $D_{ij}(X_{ijr})$ is a random variable denoting the cost of activity *ij in mode r* which incurs the following costs:

$d^n_{ij}(X_{ijr})$ = normal duration of activity *ij* in mode *r*

$d^e_{ij}(X_{ijr})$ = extreme event duration of activity *ij* in mode *r*

$$P[C_{ij}(X_{ijr}) = c^n_{ij}(X_{ijr})] = 1 - p_{ij}(X_{ijr})$$

$$P[C_{ij}(X_{ijr}) = c^e_{ij}(X_{ijr})] = p_{ij}(X_{ijr}) \quad \forall ij,\ r = 1,2,3$$

$$P[D_{ij}(X_{ijr}) = d^n_{ij}(X_{ijr})] = 1 - p_{ij}(X_{ijr})$$

$$P[D_{ij}(X_{ijr}) = d^e_{ij}(X_{ijr})] = p_{ij}(X_{ijr}) \quad \forall ij,\ r = 1,2,3$$

From this, one can calculate the expected value of $C_{ij}(X_{ijr})$:

$$E[C_{ij}(X_{ijr})] = c^n_{ij}(X_{ijr})[1 - p_{ij}(X_{ijr})] + c^e_{ij}(X_{ijr})[\,p_{ij}(X_{ijr})] \qquad [1]$$

The minimum project duration, *T*, is a constant and can be calculated as follows. Assign the times t_{ijmin} to graph *G* and find the critical path and project duration, where

$t_{ijmin} = \underset{r=1,2,3}{Min} \{ d^n_{ij}(X_{ijr}) \}$, and

$T = \sum_{\forall ij} t_{ij\,\min}$, where the summation is over activities on the critical path.

The project duration is the occurrence time of the last node, Y_n. The project duration is a random variable. Its expected value cannot be concisely expressed mathematically, but is defined below. It is calculated using probability trees.

$E[Y_n]$ = Expected project duration

The integrated systems project scheduling [ISPS] model can be expressed as:

$$Min \quad \sum_{r} \sum_{\forall ij} E[C_{ij}(X_{ijr})] + (E[Y_n] - T)Cp \qquad [2]$$

subject to:

$$\sum_{r=1}^{3} X_{ijr} = 1 \qquad \forall ij \qquad [3]$$

$$Y_i + D_{ij}(X_{ijr}) - Y_j \leq 0 \qquad \forall ij,\ r = 1,2,3 \qquad [4]$$

$$Y_1 = 0 \qquad [5]$$

$$X_{ijr} \in \{0,1\} \qquad \forall ij,\ r = 1,2,3$$

$$Y_i \geq 0 \qquad i = 1,\ldots,n$$

The objective function [2] minimizes the expected activity costs plus the expected project delay costs. Constraint [3] insures that exactly one mode is assigned to each activity. Constraints [4] and [5] insure that all precedence constraints in the project network are maintained.

3.7 Solution approach

The network has 17 activities with one to three possible assignments each, for a total of 1,417,176 possible combinations. Network decomposition and dominance rules can be used to reduce the number of combinations to evaluate.

The network decomposes into the 4 phases, which can be optimized independently, since each network is individual. Practically, the milestones at the end of each phase represent design reviews and/or payment dates. So other systems integration networks are likely to have similar decoupling points.

A mode assignment to an activity can be dominated by another mode in one of two ways. If a mode assignment cannot make the activity critical, then one only compares expected activity costs. However, if a mode assignment can make an activity critical, one must compare expected activity costs and all parameters that affect the expected cost of project delay.

Define:

EF_i = early occurrence time of node i when times t_{ijmin} are assigned to graph G

S_{ij} = available time for activity ij without incurring project delay (Note that for more complicated networks, free slack rather than total slack computations must be used).

$S_{ij} = EF_j - EF_i$

Compare 2 modes s and t on activity ij, X_{ijs} and X_{ijt}:

Dominance rule 1:

For $d^e_{ij}(X_{ijs}) \leq S_{ij}$,

If $E[C_{ij}(X_{ijs})] \leq E[C_{ij}(X_{ijt})]$ then mode $X_{ijt} = 0$.

Dominance rule 2:

For $d^e_{ij}(X_{ijs}) > S_{ij}$,

If $E[C_{ij}(X_{ijs})] \leq E[C_{ij}(X_{ijt})]$

and $d^n_{ij}(X_{ijs}) \leq d^n_{ij}(X_{ijt})$

and $d^e_{ij}(X_{ijs}) \leq d^e_{ij}(X_{ijt})$

and $p_{ij}(X_{ijs}) \leq p_{ij}(X_{ijt})$, then mode $X_{ijt} = 0$.

The ISPS model is solved with the following approach.

1. Eliminate any dominated alternatives using dominance rules 1 and 2.
2. Solve each phase of the network by explicitly calculating the expected costs of all combinations of remaining alternatives and selecting the lowest cost combination.

CHAPTER 4

CASE STUDY

4.1 Data

Data is based on a project where a Japanese systems integrator working with a Turkish distributor provides an integrated system to a large Turkish vehicle manufacturer. The system consist of a series of vertical machining centers, automated tool changers, a conveyorized pallet handling system, part loading stations, and a cell controller. A picture of a similar system is shown in Figure 1.

The following assumptions were used to estimate the data:

- First-world engineers earn $70,000 and work 2000 hours in a year.
- Developing country engineers earn $14,000 and work 2000 hours in a year (McGraw, 2003).

Figure 1: Sample integrated system

- Skilled laborers earn about half as much as engineers, $18 per hour in first-world and $3 per hour in a developing country.
- Skilled laborers always come from the customer's country.
- Customers take 50% longer than integrators to perform a task (with exceptions).
- Joint work takes 20% less time but 20% more staff than integrators to perform a task (with exceptions).
- Travel costs are required for integrators in *Prepare site, Install system* phase's and *Commission system* phase's activities.
- Travel costs for integrator distributors working on-site are $100 per day.
- Travel costs for first-world integrators working on-site are $200 per day (state.gov, 2004).
- Overhead rates are 50% for customers and 100% for integrators.
- *Design system, Write manuals, Test system, Package equipment* and part of the *Train customer staff* activities must be done by the system integrator.
- The integrator distributor can do all activities in *Ship system, Install system*, and *Commission system* phases (except *Package equipment*).
- The probability of an extreme element for a joint work activity is 5% or 20%.
- The probability of an extreme element is double for customers doing activities requiring design-specific knowledge and integrators doing on-site activities alone (with exceptions).
- An extreme element increases activity time and cost by about 50%.
- The cost of delaying the overall project one day is $4000 (double profit with 2-year payback).

4.2 Scenarios

Assume that the system integrator is based in a first-world country and that the customer may be in a first-world country or a developing country. Four international scenarios exist, as shown in Figure 2.

1. A systems integrator works with a developing country customer.
2. A systems integrator uses a developing country distributor to work with a developing country customer.
3. A systems integrator works with a first-world customer.
4. A systems integrator uses a first-world country distributor to work with a first-world country customer.

Data were collected on each resource for the entire schedule, resulting in 9 unique data sets. Seven data sets are shown in Tables 1 to 7. Data set 1 and 9 are not shown, because for scenario 3, the integrator costs are slightly higher for 3 activities than in Table 1 and for scenario 4, the integrator/distributor durations and costs are the same as Table 1 and the probabilities are the same as Table 2. The durations are in days and the costs are in US$ in all data in this thesis.

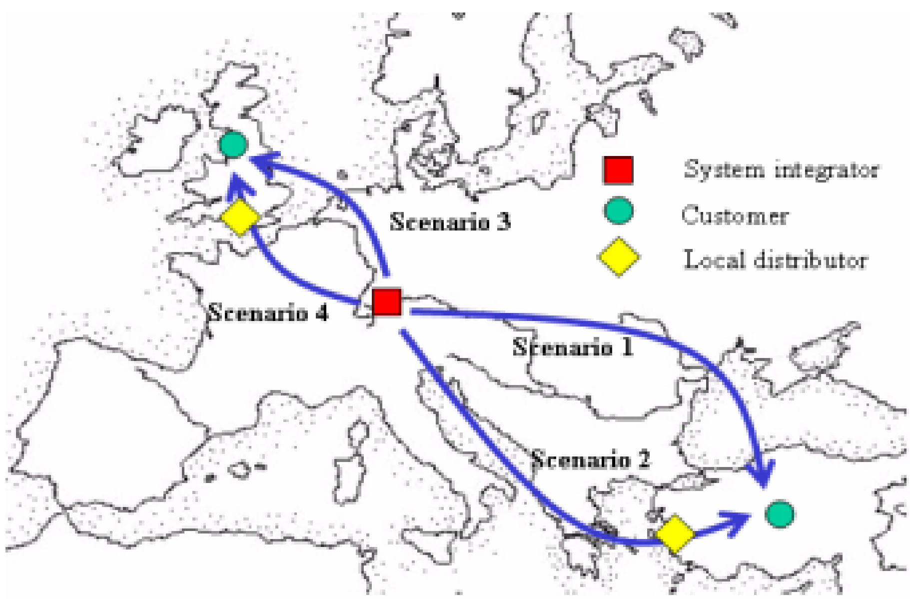


Figure 2: International integration scenarios

Table 1: First-world integrator data

Activity	D^n	C^n	P	D^e	C^e
Design system	60	N/A	N/A	90	N/A
Order components	31	2,240	10%	45	3,360
Order tooling/spares/consumables	28	1,680	10%	42	2,800
Write / translate manuals	20	11,200	5%	30	16,800
Analyze system design	25	42,000	10%	37	62,160
Package equipment	1	1,120	5%	2	2,240
Prepare customs documentation	2	2,240	10%	3	3,360
International shipping	30	3,360	5%	45	5,600
Local shipping	3	1,120	20%	5	2,240
Ensure local regulations / permits	15	3,360	20%	23	5,600
Prepare the site	15	26,400	10%	23	40,480
Obtain additional parts	3	2,280	10%	5	3,800
Locate equipment	5	5,000	10%	8	8,000
Clean & checkout components	4	7,040	5%	6	10,560
Integrate components	5	7,600	10%	8	12,160
Acceptance testing	25	38,000	10%	37	56,240
Train customer staff	15	22,800	5%	23	34,960

Table 2: First-world integrator with developing country distributor data

Activity	D^n	C^n	P	D^e	C^e
Design system	60	N/A	N/A	90	N/A
Order components	31	2,240	10%	45	3,360
Order tooling/spares/consumables	28	1,680	10%	42	2,800
Write / translate manuals	20	11,200	5%	30	16,800
Analyze system design	25	42,000	10%	37	62,160
Package equipment	1	1,120	5%	2	2,240
Prepare customs documentation	2	448	10%	3	672
International shipping	30	672	5%	45	1,200
Local shipping	3	224	10%	5	448
Ensure local regulations / permits	15	672	10%	23	1,120
Prepare the site	15	9,960	10%	23	15,272
Obtain additional parts	3	636	5%	5	1,060
Locate equipment	5	2,260	10%	8	3,616
Clean & checkout components	4	2,656	5%	6	3,984
Integrate components	5	2,120	10%	8	3,392
Acceptance testing	25	10,600	10%	37	15,688
Train customer staff	15	6,360	5%	23	9,752

Table 3: Developing country customer data

Activity	D^n	C^n	P	D^e	C^e
Design system	N/A	N/A	N/A	N/A	N/A
Order components	N/A	N/A	N/A	N/A	N/A
Order tooling/spares/consumables	31	504	20%	45	756
Write / translate manuals	N/A	N/A	N/A	N/A	N/A
Analyze system design	N/A	N/A	N/A	N/A	N/A
Package equipment	N/A	N/A	N/A	N/A	N/A
Prepare customs documentation	3	504	20%	5	840
International shipping	32	504	10%	45	840
Local shipping	3	168	10%	5	336
Ensure local regulations / permits	15	840	10%	23	1,344
Prepare the site	23	8,004	10%	35	12,180
Obtain additional parts	5	420	5%	8	672
Locate equipment	5	1,320	5%	8	2,112
Clean & checkout components	6	2,088	10%	9	3,132
Integrate components	8	1,344	20%	12	2,016
Acceptance testing	37	6,216	20%	55	9,240
Train customer staff	N/A	N/A	N/A	N/A	N/A

Table 4: First-world country customer data

Activity	D^n	C^n	P	D^e	C^e
Design system	N/A	N/A	N/A	N/A	N/A
Order components	N/A	N/A	N/A	N/A	N/A
Order tooling/spares/consumables	31	2,520	20%	45	3,780
Write / translate manuals	N/A	N/A	N/A	N/A	N/A
Analyze system design	N/A	N/A	N/A	N/A	N/A
Package equipment	N/A	N/A	N/A	N/A	N/A
Prepare customs documentation	3	2,520	20%	5	4,200
International shipping	32	2,520	10%	45	4,200
Local shipping	3	840	10%	5	1,680
Ensure local regulations / permits	15	4,200	10%	23	6,720
Prepare the site	23	44,160	10%	35	67,200
Obtain additional parts	5	2,100	5%	8	3,360
Locate equipment	5	7,500	5%	8	12,000
Clean & checkout components	6	11,520	10%	9	17,280
Integrate components	8	6,720	20%	12	10,080
Acceptance testing	37	31,080	20%	55	46,200
Train customer staff	N/A	N/A	N/A	N/A	N/A

Table 5: First-world integrator and developing country customer joint activity data

Activity	D^n	C^n	P	D^e	C^e
Design system	N/A	N/A	N/A	N/A	N/A
Order components	30	1,372	10%	45	2,576
Order tooling/spares/consumables	27	1,288	10%	42	1,932
Write / translate manuals	20	6,440	5%	30	9,660
Analyze system design	N/A	N/A	N/A	N/A	N/A
Package equipment	N/A	N/A	N/A	N/A	N/A
Prepare customs documentation	2	1,288	10%	3	2,408
International shipping	30	2,492	5%	45	4,816
Local shipping	3	728	10%	5	1,932
Ensure local regulations / permits	15	2,492	10%	23	4,816
Prepare the site	12	12,288	5%	18	18,432
Obtain additional parts	3	1,604	5%	5	2,532
Locate equipment	4	2,576	5%	6	5,120
Clean & checkout components	3	3,324	5%	5	5,540
Integrate components	4	3,712	10%	6	5,568
Acceptance testing	20	16,040	10%	30	21,100
Train customer staff	20	7,160	5%	30	18,560

Table 6: First-world integrator / developing country distributor and developing country customer joint activity data

Activity	D^n	C^n	P	D^e	C^e
Design system	N/A	N/A	N/A	N/A	N/A
Order components	30	1,372	10%	45	2,576
Order tooling/spares/consumables	27	1,288	10%	42	1,932
Write / translate manuals	20	6,440	5%	30	9,660
Analyze system design	N/A	N/A	N/A	N/A	N/A
Package equipment	N/A	N/A	N/A	N/A	N/A
Prepare customs documentation	2	392	10%	3	616
International shipping	30	700	5%	45	1,232
Local shipping	3	280	10%	5	588
Ensure local regulations / permits	15	700	10%	23	1,232
Prepare the site	12	5,712	5%	18	8,568
Obtain additional parts	3	508	5%	5	888
Locate equipment	4	1,480	5%	6	2,380
Clean & checkout components	3	1,680	5%	5	2,800
Integrate components	4	1,520	10%	6	2,280
Acceptance testing	20	5,080	10%	30	7,400
Train customer staff	20	4,420	5%	30	7,600

Table 7: First-world integrator or integrator/distributor and first-world country customer joint activity data

Activity	D^n	C^n	P	D^e	C^e
Design system	N/A	N/A	N/A	N/A	N/A
Order components	30	2,380	10%	45	3,920
Order tooling/spares/consumables	27	1,960	10%	42	2,940
Write / translate manuals	20	9,800	5%	30	14,700
Analyze system design	N/A	N/A	N/A	N/A	N/A
Package equipment	N/A	N/A	N/A	N/A	N/A
Prepare customs documentation	2	1,960	10%	3	3,080
International shipping	30	3,500	5%	45	6,160
Local shipping	3	1,400	10%	5	2,940
Ensure local regulations / permits	15	3,500	10%	23	6,160
Prepare the site	12	27,120	5%	18	40,680
Obtain additional parts	3	1,940	5%	5	3,540
Locate equipment	4	7,520	5%	6	11,300
Clean & checkout components	3	8,040	5%	5	13,400
Integrate components	4	6,400	10%	6	9,600
Acceptance testing	20	19,400	10%	30	29,500
Train customer staff	20	20,600	5%	30	32,000

4.3 Solution and results

The ISPS model was solved for the four scenarios. Network decomposition reduced the number of combinations from 1,417,176 to 342 combinations. Then the dominance rules further reduced the combinations to 28, 14, 9, and 9 combinations for the four scenarios respectively. Microsoft *Excel* © was used to solve the probability trees and find expected costs.

For example, compare *s* = integrator/distributor (Table 6 data) and *t* = developing world customer (Table 7 data) on activities *Prepare customs documentation* and *International shipping* activities. For *ij* = *Prepare customs documentation,* S_{ij}=31 days, the minimum time for package equipment and international shipping. Extreme duration for integrator/distributor, $d^e_{ij}(X_{ijs})$, is 3 days, so it can never become critical. Therefore, only compare expected costs and since expected costs for integrator/distributor is lower than for customer, the customer can be eliminated (X_{ijt} = 0).

For *ij* = *International shipping* activity, S_{ij}=30 days for this critical activity. Extreme duration for integrator/distributor, $d^{e}_{ij}(X_{ijs})$, is 45 days, so it can become critical. Now one must compare all the parameters that may increase project duration. Integrator/distributor has higher costs, lower normal duration, lower extreme duration, and lower probability than customer, so the customer cannot be eliminated.

Sample probability trees for the *Design* phase of Scenario 1 are shown in Figure 4. In this phase, there are four parallel activities-*Order Components(2nd), Order tooling/spares/consumables(3rd), Write/translate manuals(4th) and Analyze system design(5th).* The *Design System(1st)* activity is not considered, because it is assumed to be in the responsibility of the integrator in this thesis. The 4th activity can never become critical, because its extreme duration is at most 30 days, which is equal to the normal duration of the 2nd activity. When dominance rules are applied to this phase, Joint Work is selected to perform the 2nd and 4th activities, Integrator is selected to perform 5th activity, and Integrator alternative for the 3rd activity is eliminated. Thus, Customer and Joint Work alternatives are left for the 3rd activity, and the calculations for these two alternatives are seen in sample probability trees. Here, the cost of project delay outweighs the activity cost savings of the customer, so *Order tooling/parts* will be performed jointly.

3rd activity performed by customer									
2-extreme								prob.	duration
45	10%							10,00%	45
2-normal		3-extreme							
30	90%	45	20%					18,00%	45
		3-normal		5-extreme					
		31	80%	37	10%			7,20%	37
				5-normal		4-either			
				25	90%	30	100%	64,80%	31
Activity costs				$52.664				expected	35,35
Penalty cost				$21.408				delay	5,35
Total cost				**$74.072**					

3rd activity performed by joint work									
2-extreme								prob.	duration
45	10%							10,00%	45
2-normal		3-extreme							
30	90%	42	10%					9,00%	42
		3-normal		5-extreme					
		27	90%	37	10%			8,10%	37
				5-normal		4-either			
				25	90%	30	100%	72,90%	30
Activity costs				$53.462				expected	33,15
Penalty cost				$12.588				delay	3,15
Total cost				**$66.050**	**Lower cost - select**				

Figure 3: Sample probability trees for Scenario 1

Optimal solutions for the four scenarios are summarized in Table 8.

Table 8: Solution summary for four scenarios of ISPS problem

Scenario Supplier type Customer country	Scenario 1 Integrator Developing	Scenario 2 Distributor Developing	Scenario 3 Integrator First-world	Scenario 4 Distributor First-world
Activity				
Design system	Integrator	Integrator	Integrator	Integrator
Order components	Joint	Joint	Joint	Joint
Order tooling/spares/consumables	Joint	Joint	Joint	Joint
Write / translate manuals	Joint	Joint	Joint	Joint
Analyze system design	Integrator	Integrator	Integrator	Integrator
Package equipment	Integrator	Integrator	Integrator	Integrator
Prepare customs documentation	Customer	Joint	Joint	Joint
International shipping	Joint	Integrator	Integrator	Integrator
Local shipping	Customer	Customer	Customer	Customer
Ensure local regulations / permits	Customer	Integrator	Joint	Integrator
Prepare the site	Customer	Joint	Joint	Joint
Obtain additional parts	Joint	Joint	Joint	Joint
Locate equipment	Joint	Joint	Joint	Joint
Clean & checkout components	Joint	Joint	Joint	Joint
Integrate components	Joint	Joint	Joint	Joint
Acceptance testing	Joint	Joint	Joint	Joint
Train customer staff	Joint	Joint	Joint	Joint
Expected project duration	101.13	102.95	101.05	101.05
Expected activity cost	$103,259	$ 77,756	$188,386	$188,194
Expected project delay cost	$ 24,520	$ 31,800	$ 24,200	$ 24,200
Expected total cost	$127.779	$109.556	$188.386	$188.194

Several observations can be made about the selected modes for the given data sets:

- In the *Design* phase, all activities are done by the integrator or jointly.
- The *Ship* phase contains the most significant expected cost tradeoffs between all three modes.
- The *Install* and *Commission* phases are exclusively done jointly.

- The two first-world scenarios have almost identical solutions, as the distributor provides minimal cost and risk advantage over the integrator.
- In scenario 1, more activities are done by the customer, as there are the most cost savings.
- Critical activities are always given to the mode with the lowest risk (probability of extreme events).
- Non-critical activities may be given to either low risk or low cost resources.

Several observations can be made about the solutions. As mentioned previously, the *Design system* activity is not included in these numbers.

- Scenario 2 has the lowest activity cost, with scenario 1 about 33% higher.
- The first-world scenarios have 47% and 71% higher total cost than the corresponding developing country scenarios.
- The minimum project duration with no delays is 95 days. Scenario 2 has the riskiest selections; with about 2 days (or about 30%) more expected delay.
- For a developing world customer, using a distributor (scenario 2) reduced total expected cost by about 16% versus not using a distributor (scenario 1).
- For a first-world customer, there is almost no advantage to using a distributor, with a 0.1% cost savings and no change in project duration. (Note: service activities are not part of this analysis).

CHAPTER 5

COMPUTATIONAL EXPERIMENTS

5.1 Experimental Design

In this chapter, we considered the effects of the parameters of the problem on the selection of modes. Here, the types of modes considered for each activity are the following; the integrator; the customer; and the integrator and the customer working jointly. The distributor is not included here, the customer is assumed to be working with a distributor without changing the cost and duration values of the customer.

Before considering the parameters, few assumptions related with the modes will be explained:

1. The durations of activities are assumed to increase as the modes are ranged from integrator to joint and from joint to customer. This is true both for normal durations as well as extreme durations. This assumption is like the three discrete durations of PERT type problems.
2. The costs of activities are assumed to increase as the modes are ranged from customer to joint and from joint to integrator. This is true both for normal costs as well as extreme costs.
3. The probability of having extreme events $p_{ij}(X_{ijr})$ is assumed to be a constant value independent of the activities as well as the modes used.

With these assumptions, the factors that are considered to be important on the choice of modes are;

Cp : Daily penalty cost ($)

ProbExtr : Probability of an extreme event for each mode.

ExtrFac : Duration increase factor for extreme events.

(Extreme Duration = Normal Duration*ExtrFac)

DurIncFac : Duration increase factor between modes.

(Joint Duration = Integ Duration*DurIncFac)

(Customer Duration = Integ Duration* DurIncFac)

CostDecFac : Cost decrease factor between modes.

(Joint Cost = Integ cost*CostDecFac)

(Customer Cost = Integ cost*CostDecFac)

A design with 243 experiments is implemented to the data in the case study. Integrator's normal duration and cost data are taken as given; customer and joint work's data is created based on this data.

Table 9 shows the source data.

Table 9: Source data based on the integrator's case study data

		Design				Ship						Install				Com'sn	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
ACTIVITY	Design system	Order components	Order tooling/spares/consumables	Write / translate manuals	Analyze system design	Package equipment	Prepare customs documentation	International shipping	Local shipping	Ensure local regulations / permits	Prepare the site	Obtain additional parts	Locate equipment	Clean & Checkout components	Integrate components	Acceptance Testing	Train customer staff
Normal Duration	60	31	28	20	25	1	2	30	3	15	15	3	5	4	5	25	15
normal cost	NA	2.240	1.680	11.200	42.000	1.120	2.240	3.360	1.120	3.360	44.400	2.280	11.000	11.840	7.600	38.000	22.800
ExtrCost	NA	3.360	2.800	16.800	62.160	2.240	3.360	5.600	2.240	5.600	68.080	3.800	17.600	17.760	12.160	56.240	34.960

In this study, for each of the 5 factors, 3 levels are selected and 243 (3^5) experiments are created. Because of the complexity of the problem, each phase is taken as a whole and the activities are not divided. Durations and costs are calculated phase by phase. The Penalty cost is calculated using t_{ijmin} values of the source data, where t_{ijmin} is the minimum possible completion time of each phase. It is calculated as 31 days for Design Phase, 34 days for Ship Phase, 14 days for Install Phase and 25 days for Commission Phase. Minimum completion time of the project is 164 days, 104 days is the sum of t_{ijmin} values and 60 days is the first activity, Design System-which is assumed to be performed by the Integrator in all circumstances.

Expected Durations are calculated using the Normal and Extreme durations. Expected Costs are also calculated using the Normal and Extreme costs. Expected Cost is then added to the Penalty Cost to find the Total Cost of each phase. Since phase generalization is assumed in this study, the mode with minimum total phase cost is selected to perform all activities in the same phase.

The penalty cost is determined by considering the average daily cost of activities. Table 10 shows the Cp values considered and their relation to the daily cost of activities. Total Cost is calculated as $206,204 and Average Daily Cost is calculated as $1,257 using the total cost and minimum completion time of the project.

Table 10: Penalty Cost as a percentage of Average Daily Cost

	LEVELS		
Cp	1000	1500	2000
% of Average Daily Cost	80%	119%	159%

The factors considered, and the levels for these factors are shown in Table 11. Here, the levels are selected after a series of experiments, and within these ranges the mode decisions differ much.

Table 11: Factors in 243 experiments

	Factors	LEVELS		
Integrator	Cp	1000	1500	2000
	ext.fac	1,3	1,5	1,7
	prob.extr	0,05	0,1	0,2
Joint	durincfac	1,2	1,3	1,4
	cost.dec	0,4	0,5	0,6
Customer	durincfac	1,4	1,5	1,6
	cost.dec	0,2	0,3	0,4

Table 12 shows the results of the experimental design. Here, for each level of a factor the percentage of mode usages are indicated. While Cp increases, phases performed by the Customer decrease and Integrator's share increases. At the given levels, ProbExtr and ExtrFac have an effect in the distribution between Joint Work and Customer, but they cannot change the Integrator's share significantly. While ProbExtr and CostDec for Joint Work increases, the share of Customer passes to Joint Work. While ExtrFac and CostDec for Joint Work increases, the share of Joint Work passes to Customer.

In DurIncFac for Joint Work we see that with higher levels, Joint Work's share passes to Customer and Integrator providing higher proportion to Customer. Similar result can be concluded in DurIncFac for Customer, that is Customer's share passes to Joint Work and Integrator providing higher proportion to Joint Work.

Table 12: 243 experiments' results (% of all experiments in all phases)

FACTORS	LEVELS	joint	integrator	customer
Cp	1000	0,34	0,00	0,66
	1500	0,40	0,09	0,52
	2000	0,45	0,21	0,35
ProbExtr	5%	0,19	0,09	0,72
	10%	0,39	0,09	0,52
	20%	0,60	0,11	0,28
ExtrFac	1,3	0,61	0,08	0,31
	1,5	0,42	0,08	0,50
	1,7	0,21	0,13	0,66
Joint DurIncFac	**1,2**	0,65	0,03	0,33
	1,3	0,38	0,10	0,51
	1,4	0,16	0,16	0,68
Customer DurIncFac	1,4	0,22	0,08	0,70
	1,5	0,40	0,10	0,49
	1,6	0,56	0,11	0,32
Joint CostDec	**0,4**	0,61	0,08	0,31
	0,5	0,40	0,08	0,52
	0,6	0,17	0,14	0,69
Customer CostDec	0,2	0,19	0,09	0,72
	0,3	0,39	0,09	0,52
	0,4	0,60	0,11	0,28

The results of the experimental design are given in Appendix B, from where Table 12 is drawn.

Graphics drawn from the data in Table 12 are depicted on Figure 5 through Figure 11.

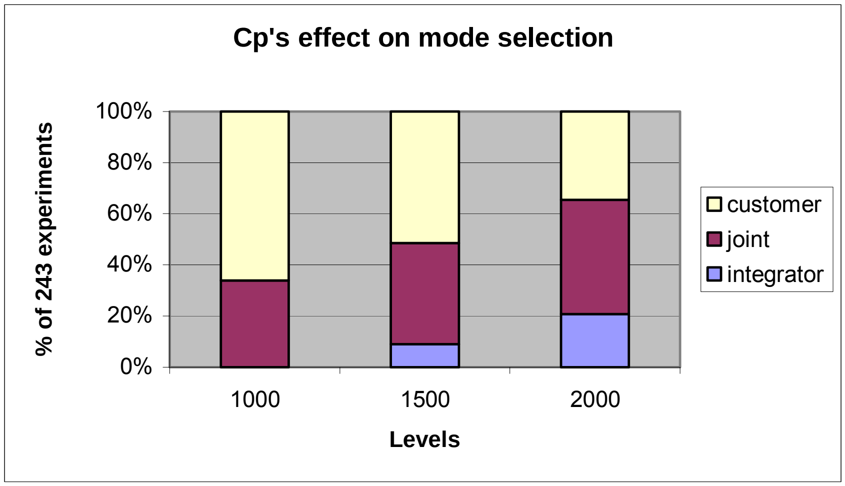


Figure 5: Cp's effect on mode selection

In Figure 5, while Cp increases, phases performed by the Customer decrease and Integrator's share increases. Here, we can see that if we penalize longer makespan of Customer with higher daily costs, then Integrator takes the responsibility of activities.

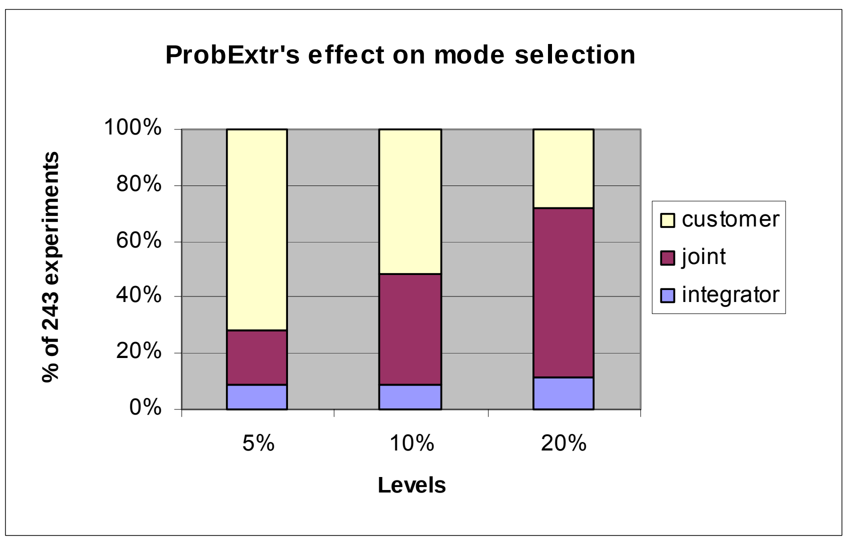


Figure 6: ProbExtr's effect on mode selection

In Figure 6, at the given levels, ProbExtr has an effect in the distribution between Joint Work and Customer, but it cannot change the Integrator's share significantly. While ProbExtr increases, the share of Customer passes to Joint Work.

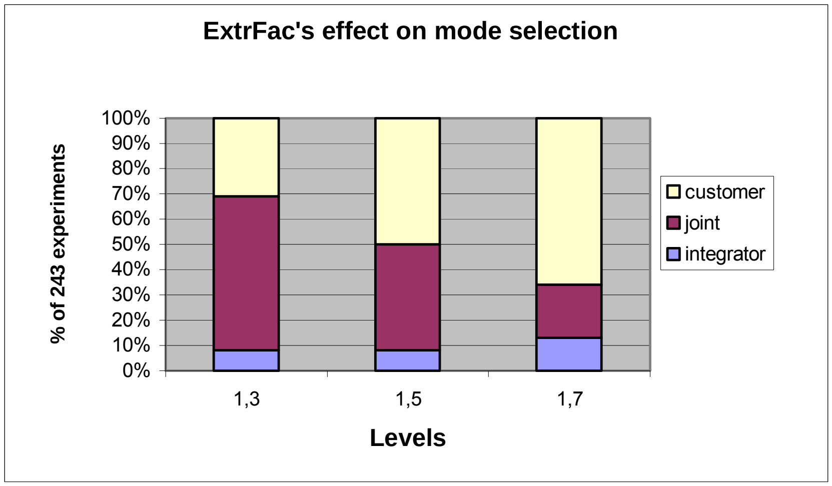


Figure 7: ExtrFac's effect on mode selection

In Figure 7, it can be seen that ExtrFac has an effect in the distribution between Joint Work and Customer. While ExtrFac increases, the share of Joint Work passes to Customer.

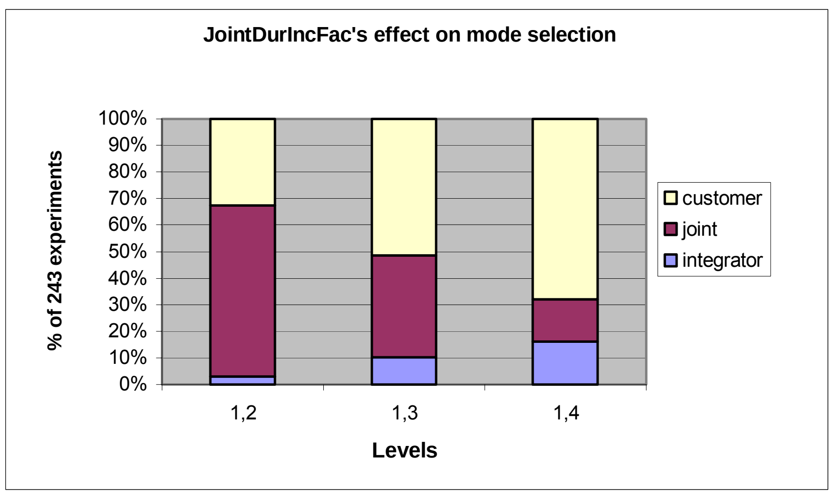


Figure 8: JointDurIncFac's effect on mode selection

In Figure 8, in DurIncFac for Joint Work we see that with higher levels, Joint Work's share passes to Customer and Integrator, providing higher proportion to Customer. This is a result of the longer durations of Joint Work in higher factor levels.

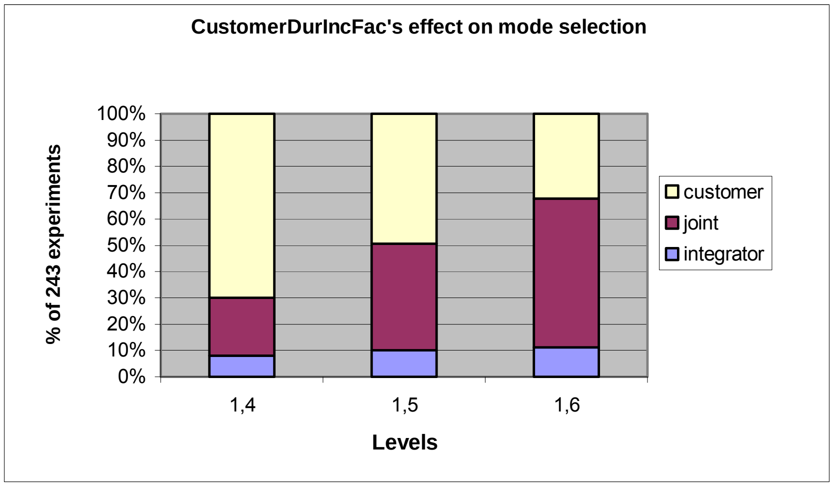


Figure 9: CustomerDurIncFac's effect on mode selection

As in the Joint Work, in Figure 9, we see that with higher levels, Customer's share passes to Joint Work and Integrator, providing higher proportion to Joint Work. This is a result of the longer durations of Customer in higher factor levels.

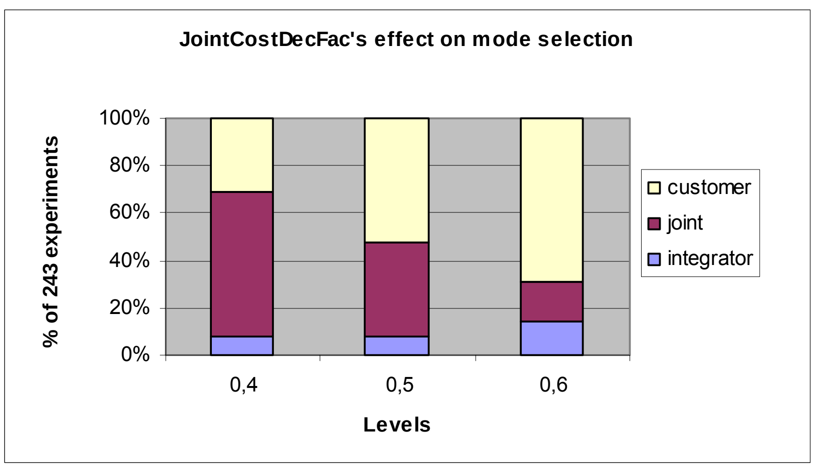


Figure 10: JointCostDecFac's effect on mode selection

In Figure 10, while CostDecFac for Joint Work increases, the share of Joint Work passes to Customer. This is a result of the higher costs of Joint Work in higher factor levels.

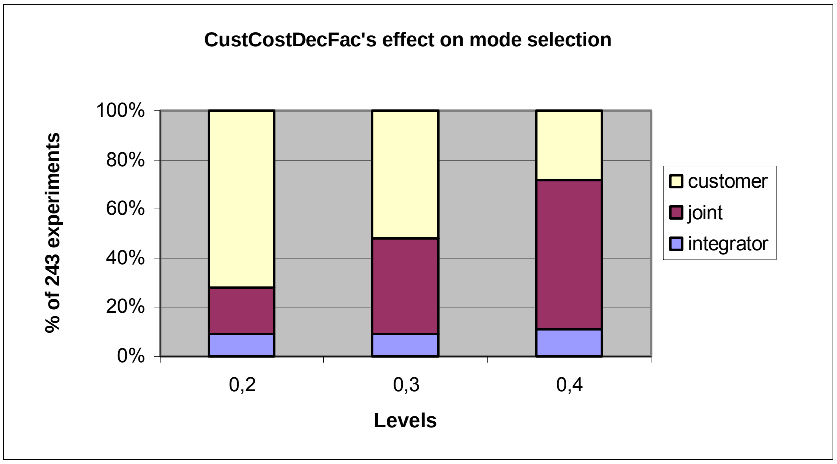


Figure 11: CustCostDecFac's effect on mode selection

In Figure 11, while CostDecFac for Customer increases, the share of Customer passes to Joint Work. This is a result of the higher costs of Customer in higher factor levels.

5.2 Simulation Study

For 4 selected experiments from the 243 experiments, a Monte-Carlo simulation study is conducted. In this study, it has been aimed to see how the exact result of the ISPSP (Integrated Systems Project Scheduling Problem) differs in phase generalization.

Experiment 111, 132, 51 and 114 are chosen to be solved to optimality. Experiment 111 and 132 are selected randomly, but experiment 51 and 114 are selected to see the effect of one factor variation with experiment 132. The basic difference of this study from the previous study is that, an instance is created for this experiment by using the binomial distribution for determining the extreme event occurrence probability and the corresponding durations and costs of activities are generated.

To solve the ISPS problem, dummy nodes and arcs are created. Figure 12 shows the schedule with dummy-nodes.

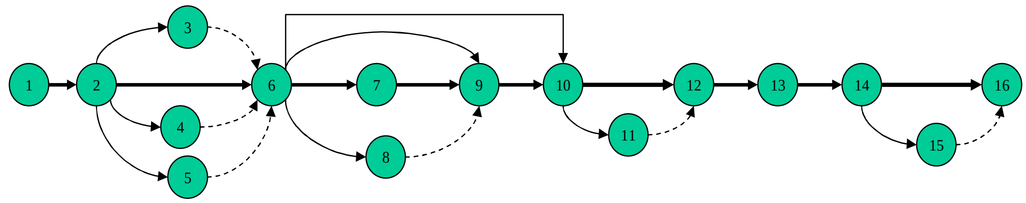


Figure 12: ISPS problem network used in simulation runs.

1000 instances are created using the Monte-Carlo simulation. Number of replications is seen to represent the variance in the factors. Each instance is then solved to optimality with the Excel Premium Solver Platform 6.0 using “the Standart LP/Quadratic Solution Method”. The Premium Solver uses an improved implementation of the Simplex method with bounds on the variables. The Visual Basic code used in this study is given in Appendix C.

The IP model solved in this phase is the model

$$Min \sum_{r} \sum_{\forall ij} C_{ij}(X_{ijr}) + ([Y_n] - T)Cp \qquad [6]$$

subject to the constraints [2], [3], [4] and [5].

Here, it can be seen that expected values are not taken in the objective function [6].

The data and IP used in Experiment 111 for 3rd run is explicitly shown in Appendix A.

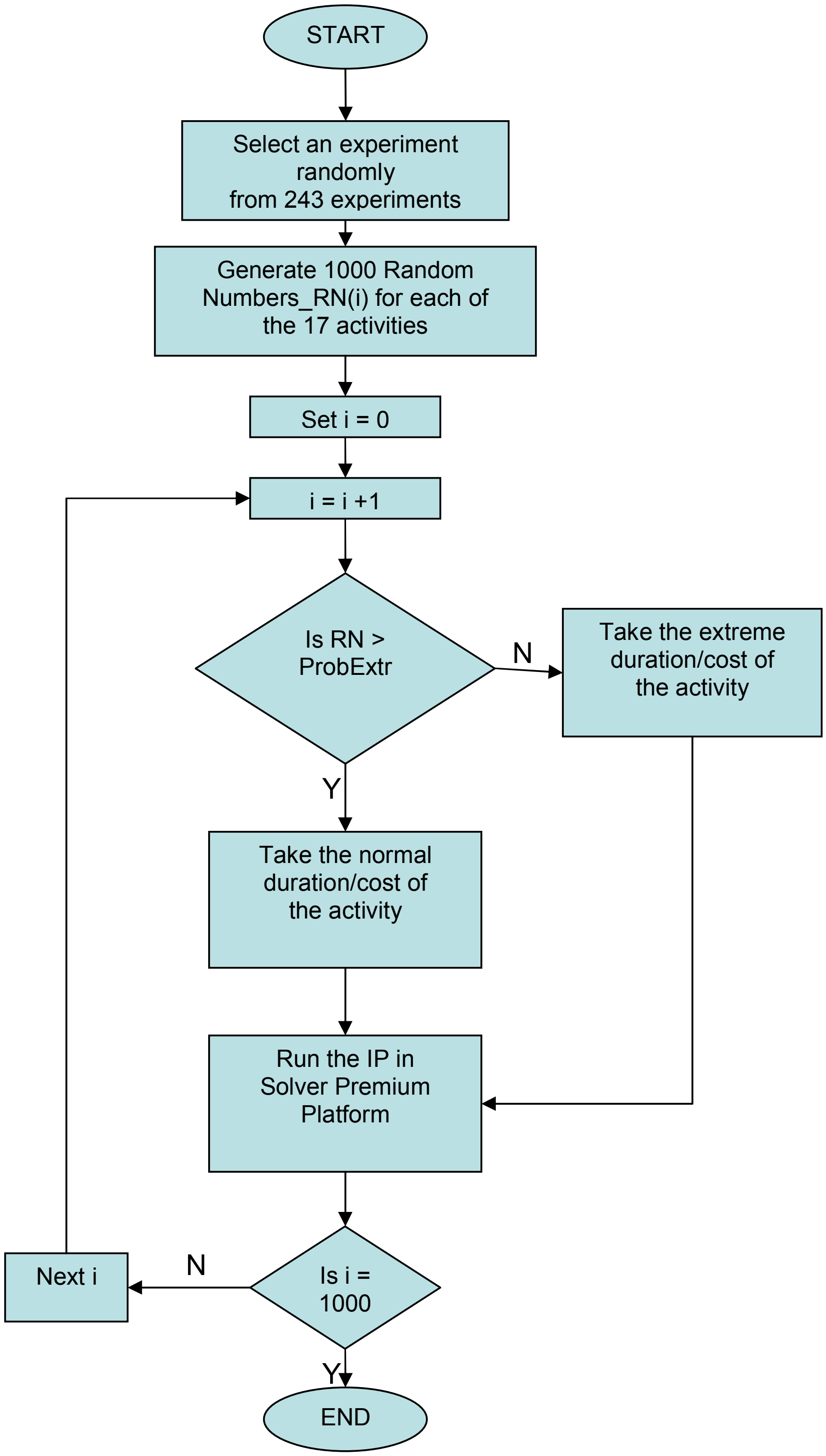
The cost weight of each activity based on the source data are shown in Table 13.

Table 13: Cost weight of each activity based on the source data

		Design				Ship						Install				Com'sn	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
ACTIVITY	Design system	Order components	Order tooling/spares/consumables	Write / translate manuals	Analyze system design	Package equipment	Prepare customs documentation	International shipping	Local shipping	Ensure local regulations / permits	Prepare the site	Obtain additional parts	Locate equipment	Clean & Checkout components	Integrate components	Acceptance Testing	Train customer staff
Normal Cost	NA	1%	1%	5%	20%	1%	1%	2%	1%	2%	22%	1%	5%	6%	4%	18%	11%
Phase Totals	NA	28%				27%						16%				29%	

Figure 13 shows the flowchart of the Monte-Carlo simulation.

Figure 13: Flowchart used in simulation runs.



In Monte-Carlo simulation study for Experiment 111 average cost is 112,371$ and average duration is 204 days. Table 14 shows the results of the simulation study for experiment 111.

Table 14: Results of the simulation study for Exp.111 (‰ of all runs)

			Design				Ship						Install				coms'n	
	Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Resource	integ	1000	839	176	0	0	0	0	1000	1000	0	0	0	0	0	0	0	0
	Joint	0	0	661	0	0	794	0	0	0	0	0	0	0	0	202	1	0
	Cust	0	161	163	1000	1000	206	1000	0	0	1000	1000	1000	1000	1000	798	999	1000

Criticality index and standard deviation of each activity for 111th experiment in simulation study is shown in Table 15.

Table 15: Criticality of each activity in simulation study for Exp.111(% of all runs)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
ACTIVITY	Design system	Order components	Order tooling/spares/consumables	Write / translate manuals	Analyze system design	Package equipment	Prepare customs documentation	International shipping	Local shipping	Ensure local regulations / permits	Prepare the site	Obtain additional parts	Locate equipment	Clean & Checkout components	Integrate components	Acceptance Testing	Train customer staff
number	1000	160	0	135	705	1000	0	1000	1000	0	0	0	1000	1000	1000	1000	0
% of tot	100%	16%	0%	14%	71%	100%	0%	100%	100%	0%	0%	0%	100%	100%	100%	100%	0%
mean (days)	64,09	35,36	37,36	31,85	40,19	1,21	3,20	31,74	3,17	24,17	24,25	5,21	8,37	6,38	8,00	40,22	24,20
standart dev.	7,54	6,19	2,92	3,64	4,39	0,40	0,40	3,55	0,38	2,38	2,44	0,41	0,78	0,79	0,09	4,42	2,40
mean / stdev	12%	17%	8%	11%	11%	34%	12%	11%	12%	10%	10%	8%	9%	12%	1%	11%	10%

Experimental Design Result for 111th experiment is showed inTable 16.

Table 16: Result of the Experimental Design for 111th experiment

243 Experiments' Phase Result for 111th experiment			
design	ship	install	commission
Joint	joint	joint	Joint
Total Cost: 131,963$ Makespan:154 days			

Data of Experiment 111 is depicted in Table 17.

Table 17: Experiment 111's Factor Levels

	Cp	durincfac	ext.fac	cost.dec	prob.extr
integ	1500	-	1,3	-	0,2
joint	1500	1,3	1,3	0,4	0,2
cust	1500	1,4	1,3	0,4	0,2

In Monte-Carlo simulation study for Experiment 132 average cost is 119,393$ and average duration is 209 days. Table18 shows the results of the simulation study for experiment 132.

Table 18: Results of the simulation study for Exp.132 (‰ of all runs)

			Design				Ship						Install				commission	
	Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Resoruce	integ	1000	812	133	0	0	0	0	1000	1000	0	0	0	0	0	0	0	0
	Joint	0	0	707	0	0	806	0	0	0	0	0	0	0	0	0	0	0
	Cust	0	188	160	1000	1000	194	1000	0	0	1000	1000	1000	1000	1000	1000	1000	1000

Criticality index and standard deviation of each activity for 132nd experiment in simulation study is shown in Table19.

Table 19: Criticality of each activity in simulation study for Exp.132(% of all runs)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
ACTIVITY	Design system	Order components	Order tooling/spares/consumables	Write / translate manuals	Analyze system design	Package equipment	Prepare customs documentation	International shipping	Local shipping	Ensure local regulations / permits	Prepare the site	Obtain additional parts	Locate equipment	Clean & Checkout components	Integrate components	Acceptance Testing	Train customer staff
number	1000	119	0	175	825	1000	0	1000	1000	128	0	0	1000	1000	1000	1000	0
% of tot	100%	12%	0%	18%	83%	100%	0%	100%	100%	13%	0%	0%	100%	100%	100%	100%	0%
mean (days)	63,91	36,15	40,26	34,27	42,62	1,19	3,20	31,76	3,19	25,37	25,39	5,21	8,39	6,40	8,42	42,58	25,44
standart dev.	7,42	7,45	3,71	4,19	4,95	0,40	0,40	3,57	0,39	2,77	2,79	0,40	0,79	0,80	0,82	4,93	2,83
mean / stdev	12%	21%	9%	12%	12%	33%	13%	11%	12%	11%	11%	8%	9%	13%	10%	12%	11%

Experimental Design Result for 132nd experiment is shown in Table20.

Table 20: Result of the Experimental Design for 132nd experiment

243 Experiments' Phase Result for 132nd experiment			
design	ship	install	commission
Cust	joint	cust	İnteg
Total Cost: 177,511$ Makespan: 156 days			

Data of Experiment 132 is depicted in Table21.

Table 21: Experiment 132's Factor Levels

	Cp	durincfac	ext.fac	cost.dec	prob.extr
integ	1500	-	1,7	-	0,2
joint	1500	1,3	1,7	0,6	0,2
cust	1500	1,5	1,7	0,4	0,2

In Monte-Carlo simulation study for Experiment 51 average cost is 73,946$ and average duration is 224 days. Table22 shows the results of the simulation study for experiment 51.

Table 22: Results of the simulation study for Exp.51 (‰ of all runs)

			Design				Ship						İnstall				commission	
	Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Resoruce	integ	1000	610	162	0	0	0	0	1000	845	0	0	0	0	0	0	0	0
	Joint	0	108	431	108	0	745	0	0	30	158	0	0	0	0	0	0	0
	Cust	0	282	407	892	1000	255	1000	0	125	842	1000	1000	1000	1000	1000	1000	1000

Criticality index and standard deviation of each activity for 51st experiment in simulation study is shown in Table23.

Table 23: Criticality of each activity in simulation study for Exp.51 (% of all runs)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
ACTIVITY	Design system	Order components	Order tooling/spares/consumables	Write / translate manuals	Analyze system design	Package equipment	Prepare customs documentation	International shipping	Local shipping	Ensure local regulations / permits	Prepare the site	Obtain additional parts	Locate equipment	Clean & Checkout components	Integrate components	Acceptance Testing	Train customer staff
number	1000	160	101	134	605	868	0	868	923	158	162	150	1000	1000	1000	1000	142
% of tot	100%	16%	10%	13%	61%	87%	0%	87%	92%	16%	16%	15%	100%	100%	100%	100%	14%
mean (days)	69,11	40,93	40,98	33,51	43,12	1,43	3,39	33,63	3,72	25,05	26,08	5,58	9,15	6,77	9,05	43,10	25,85
standart dev.	17,31	8,95	5,36	7,12	10,34	0,58	0,79	7,94	1,08	4,31	6,06	1,19	2,10	1,58	2,04	10,32	5,88
mean / stdev	25%	22%	13%	21%	24%	41%	23%	24%	29%	17%	23%	21%	23%	23%	23%	24%	23%

Experimental Design Result for 51st experiment is shown in Table 24.

Table 24: Result of the Experimental Design for 51st experiment

243 Experiments' Phase Result for 51st experiment			
design	ship	install	commission
Cust	cust	Cust	joint
Total Cost: 146,182$ Makespan: 172 days			

Data of Experiment 51 is depicted in Table 25.

Table 25: Experiment 51's Factor Levels

	Cp	durincfac	ext.fac	cost.dec	prob.extr
integ	1000	-	1,7	-	0,2
joint	1000	1,3	1,7	0,6	0,2
cust	1000	1,5	1,7	0,4	0,2

In Monte-Carlo simulation study for Experiment 114 average cost is 157,017$ and average duration is 204 days. Table 26 shows the results of the simulation study for experiment 114.

Table 26: Results of the simulation study for Exp.114 (‰ of all runs)

			Design				Ship						Install				commission	
	Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Resoruce	integ	1000	838	161	0	0	203	0	1000	1000	0	0	0	0	0	0	0	0
	Joint	0	0	679	0	0	797	0	0	0	0	0	0	0	0	219	0	0
	Cust	0	162	160	1000	1000	0	1000	0	0	1000	1000	1000	1000	1000	781	1000	1000

Criticality index and standard deviation of each activity for 114th experiment in simulation study is shown in Table27.

Table 27: Criticality of each activity in simulation study for Exp.114 (% of all runs)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
ACTIVITY	Design system	Order components	Order tooling/spares/consumables	Write / translate manuals	Analyze system design	Package equipment	Prepare customs documentation	International shipping	Local shipping	Ensure local regulations / permits	Prepare the site	Obtain additional parts	Locate equipment	Clean & Checkout components	Integrate components	Acceptance Testing	Train customer staff
number	1000	214	162	112	512	842	0	842	873	158	127	150	1000	1000	1000	1000	142
% of tot	100%	21%	16%	11%	51%	84%	0%	84%	87%	16%	13%	15%	100%	100%	100%	100%	14%
mean (days)	69,11	38,33	40,38	34,26	43,12	1,17	3,39	33,63	3,41	25,84	26,08	5,58	9,15	6,77	8,79	43,10	25,85
standart dev.	17,31	11,44	10,83	8,45	10,34	0,38	0,79	7,94	0,81	5,87	6,06	1,19	2,10	1,58	2,02	10,32	5,88
mean / stdev	25%	30%	27%	25%	24%	32%	23%	24%	24%	23%	23%	21%	23%	23%	23%	24%	23%

Experimental Design Result for 114th experiment is shown in Table 28.

Table 28: Result of the Experimental Design for 114th experiment

243 Experiments' Phase Result for 114th experiment			
design	ship	install	commission
Cust	cust	cust	integ
Total Cost: 160,299$ Makespan: 152			

Data of Experiment 114 is depicted in Table 29.

Table 29: Experiment 114's Factor Levels

	Cp	durincfac	ext.fac	cost.dec	prob.extr
integ	1000	-	1,3	-	0,2
joint	1000	1,3	1,3	0,6	0,2
cust	1000	1,5	1,3	0,4	0,2

The mode decision of each activity is overestimated by using the phase decision in Experimental Design. The activities that have never become critical are also performed by the one performer of the phase. This overestimation resulted with higher total costs in Experimental Design. If the non-critical activities are performed by less costly modes, then the total cost is calculated as closer to the simulation result.

For example in Experiment 132, if the 3rd, 7th, 10th, 11th, 12th and 17th activities-which are all non-critical are to be performed by the less costly decision customer, then the phase generalization result 177,511$ drops to 151,695$. If the 209 – 156 = 53 days penalty cost is added to this cost, then it drops to 98,011$.

Results of the simulation study indicate mainly that activities with high cost and accordingly long duration has a determining effect in mode selection. To give an example, 5th, 11th and 16th activities make for the 60% of total cost and are always performed by the customer in all four experiments.

We can verify from the mean and the variance of the durations in simulation study that the effects of near-critical paths are insignificant and the expected project completion times will not be affected.

For proper decision of modes performing each activity, simulation study should be conducted first, and then the non-critical activities should be assigned to the lowest costly mode. That is to say, the criticality results obtained from the simulation study might be used to modify the experimental design like a close-loop.

CHAPTER 6

CONCLUSION

Project scheduling under uncertainty and risk have drawn the attention of many researchers. Among project scheduling areas, systems integration projects gain importance in the era of globalization and higher export rates in the field of machinery and equipment. While realizing these projects, the design is generally performed by the seller (integrator) and for the rest of the activities including the commissioning of the system, there is not a generally accepted performer of the activity. The selection of the performer (mode) of each activity is the most significant decision affecting the cost and the completion time of the project. Implementation problems lead to project delays, increased costs, and decreased performance, leading to customer dissatisfaction with the systems integrator.

In this study, activities could be performed in one of three ways: by the integrator, by the customer, or jointly between the integrator and customer. The major contribution of this study was to select the performer (mode) of each activity constructing the project network while taking into consideration of varying cost, duration and extreme event probability of each activity among different modes-integrator, joint work and customer.

Generally, integrator work has a higher cost and lower risk, while customer work has lower cost and higher risk. The customer ultimately defines the scope of work, but since costs and risks are generally shared in the contract, it is in the interest of both parties to identify the single best scope of work.

A proper division of responsibilities will reduce implementation risks and customer dissatisfaction.

A case study was presented which was performed to the data based on a project where a Japanese systems integrator working with a Turkish distributor providing an integrated system to a large Turkish vehicle manufacturer. In this study, four different international integration scenarios, and expected costs and durations of each activity were taken into consideration. These scenarios varied by the location of the customer (first-world or developing country) and the option of using a distributor. The results of the study indicate that in the Design phase, all activities are done by the integrator or jointly. The Ship phase contains the most significant expected cost tradeoffs between all three modes. The Install and Commission phases are exclusively done jointly. Critical activities are always given to the mode with the lowest risk (probability of extreme events). Non-critical activities may be given to either low risk or low cost resources.

The effects of the parameters of the problem on the selection of modes had been considered with an Experimental Design and a Monte-Carlo Simulation Study. Five parameters affecting the mode selection were defined in Experimental Design, and 243 alternative combinations of these parameters were listed. In this study, the mode decision was done phase by phase, that is every activity in the same phase is performed by the same mode. Expected costs and durations are used. The results of the Experimental Design showed that the selected parameters (factors) affected the selection of modes, mostly by changing the assignment share between Customer and Joint Work. The mode decision of each activity is overestimated by using the phase decision in Experimental Design. The activities that have never become critical are also performed by the one performer of the phase. This overestimation resulted with higher total costs in Experimental Design.

In Monte-Carlo simulation study, it has been aimed to see how the exact result of the ISPSP (Integrated Systems Project Scheduling Problem) differs in phase generalization. In this study, either normal figures or extreme figures are selected in the project network, thus, expected values are not used.

For further study, simulation study might be conducted for more experiments from the experimental design. The constraints like budget limits and predefined makespan might be inserted to the mathematical formulation. Logit transformation might be performed to the experimental design results to estimate a model and to conduct ANOVA analysis.

REFERENCES

Alpan, B.N.(1994). *Simulation Method as a Technique in Risk Analysis of Project Evaluation Process*, Unpublished MBA Thesis, METU.

Baker, S., Ponniah, D. and Simith, S., (1998). *Techniques for the analysis of risks in major projects.* Journal of the Operational Research Society 49, 567-572.

Brucker P., Drexl A., Möhring R., Neumann K., Pesch E. (1999)*. Resource-constrained project scheduling: Notation, classification models, and methods.* EJOR 112, 3-41.

Chase, R., Aquilano, N., and Jacobs, F.,(1998). *Production operations management*, 8th ed., Irwin McGraw-Hill, Boston, MA.

Davis, E.W. (1973). *Project Scheduling Under Resource Constraints Historical Review and Categorization of Procedures*, AIIE Transactions 5, 297-313.

Drexl A., (1991). *Scheduling of project networks by job assigment.* Management Science Vol.37, No.12, 1590-1602.

Drexl, A. and Gruenewald, J.(1993). *Nonpreemptive Multi-Mode Resource Constrained Project Scheduling*, IIE Transactions 25, 74-81.

Fabrycky, W.J. and Thuesen, G.J. (1980). *Economic Decision Analysis*, New Jersey: Prentice-Hall Inc., Englewood Cliffs.

Gallagher, C.(1987). *A Note on PERT Assumptions*, Management Science 33, 1360.

Harrison I.W.,(1973). *Capital Investment Appraisal*, McGraw-Hill Comp.

Hartmann S. and Drexl A., (1998). *Project scheduling with multiple modes: a comparison of exact algortihms.* Inc.Networks 32: 283-297.

Herroelen W.S., (1972). *Resource-constrained project scheduling – the state of the art.* Oper. Res. Quart. Vol.23, No.3

İçmeli, O., Erengüç, S.S. and Zappe, J.C. (1993). *Project Scheduling Problems: A Survey*, International J. of Operations and Production Management 13. 249-265.

Integrated Systems and Controls Council, (1992). *Considerations when planning and implementing integrated material handling systems,* Material Handling Industry of America, Charlotte, NC.

Küçümen, B.Ö.(1999). *A Decision Support System for Fuzzy Scheduling of Software Projects*, Unpublished M.Sc Thesis, METU.

Lacksonen, T. and Ertem M.A.(2004), "*Optimal Scope of Work for International Integrated Systems*," Progress in Material Handling Research: 2004, Charlotte, NC: Material Handling Industry of America, 118-138.

Lacksonen, T., (2002) *Global Material Handling Systems Design*, in Progress in Material Handling Research: 2002, Charlotte, NC: Material Handling

Maximum travel per diem allowances for foreign areas, Retrieved 1 May 2005 from United States State Department web site: www.state.gov/m/a/als/prdm/2005/.

McGraw, D., (2003) "My job lies over the ocean," *ASEE Prism,* 13, 4, 24-29.

Mori, M. and Tseng, C.C.(1997). *A Genetic Algorithm for Multi-Mode Resource Constrained Project Scheduling Problem*, European J. of Operational Research 100, 134-141.

Oktay, M.(2000). *Fuzzy Project Scheduling with Motivation Considerations*, Unpublished M.Sc Thesis, METU.

Özdamar L. and Ulusoy G.(1993). *A survey on the Resource-Constrained Project Scheduling Problem.*

Özdamar, L. and Ulusoy, G.(1994). *A local Constraint Based Analysis to Project Scheduling Under General Resource Constraints*, European J. of Operational Research 79, 287-298.

Paul, A. and Gutierrez G. (2000). *Analysis of the effects of uncertainty, risk-pooling, and subcontracting mechanisms on project performance*, Operations Research Vol.48, No.6, 927-938

Pouliquen, L.Y. (1970). *Risk Analysis in Project Appraisal*, World Bank Staff Occasional Papers No.11.

Sarıaslan, H. (1989). *Risk Analysis in Project Evaluation*, A.Ü. Siyasal Bilgiler Fak. Dergisi, Cilt XLIV, Sayı 1-2, Ocak-Haziran 99-118.

Slowinski R. (1998). *Two approaches to problems of resource allocation among project activities: a comparative stud.* J. Oper. Res. Soc. 31. 711-723.

Staff, (2004). "Top twenty systems suppliers," *Modern Materials Handling* 58.

Talbot, F.B.(1982). *Resource-Constrained Project Scheduling with Time-Resource Trade-offs: The Nonpreemptive Case*, Management Science 28, 1197-1210.

Trade, Retrieved 1 May 2005 from World Bank web site: www.worldbank.org/trade.

APPENDIX A

Table 1: 3rd simulation run's data for Exp.111

	ACTIVITY	Design system	Order components	Order tooling/spares/consumables	Write / translate manuals	Analyze system design	Package equipment	Prepare customs documentation	International shipping	Local shipping	Ensure local regulations / permits	Prepare the site	Obtain additional parts	Locate equipment	Clean & Checkout components	Integrate components	Acceptance Testing	Train customer staff
	i j	11	23	24	25	26	67	68	79	9.10	69	6.10	10.11	10.12	12.13	13.14	14.16	14.15
Integrator (1)	Duration	60	31	28	20	25	1	3	30	3	15	15	4	7	4	7	33	15
	Cost	0	2.240	1.680	11.200	42.000	1.120	3.360	3.360	1.120	3.360	44.400	3.800	17.600	11.840	12.160	56.240	22.800
Joint work (2)	Duration	78	40	36	26	33	1	3	39	4	20	20	5	8	5	8	42	21
	Cost	0	896	672	4.480	16.800	448	1.344	1.344	448	1.344	17.760	1.520	7.040	4.736	4.864	22.496	9.120
Customer (3)	Duration	90	47	42	30	38	2	4	46	5	23	23	6	10	6	10	49	23
	Cost	0	448	336	2.240	8.400	224	672	672	224	672	8.880	760	3.520	2.368	2.432	11.248	4.560

i,j = nodes

r = Resource-Mode for r=1 integrator, 2 Joint Work, 3 Customer

$X_{ijr} \in \{0,1\} \qquad \forall ij\ ,\ r = 1,2,3$

Y_i = finish time of node i

$Y_i \geq 0$

Min z = (0X_{111} + X_{231} 2.240 + X_{241} 1.680 + X_{251}11.200 + X_{261} 42.000 + X_{671}1.120 + X_{681} 3.360 + X_{791} 3.360 + $X_{9.10.1}$ 1.120 + X_{691} 3.360 +

$X_{6.10.1}$ 44.400 + $X_{10.11.1}$ 3.800 + $X_{10.12.1}$ 17.600 + $X_{12.13.1}$ 11.840 + $X_{13.14.1}$12.160 + $X_{14.16.1}$ 56.240+
$X_{14.15.1}$ 22.800 +

0X_{112} + X_{232} 896 + X_{242} 672 + X_{252} 4.480 + X_{262} 16.800 + X_{672} 448 + X_{682} 1.344 + X_{792} 1.344 + $X_{9.10.2}$ 448 + X_{692} 1.344 + $X_{6.10.2}$ 17.760 + $X_{10.11.2}$ 1.520 + $X_{10.12.2}$ 7.040 + $X_{12.13.2}$ 4.736 + $X_{13.14.2}$4.864 + $X_{14.16.2}$ 22.496 + $X_{14.15.2}$ 9.120 +

0X_{113} + X_{233} 448 + X_{243} 336 + X_{253} 2.240 + X_{263} 8.400 + X_{673} 224 + X_{683} 672 + X_{793} 672 + $X_{9.10.3}$ 224 + X_{693} 672 + $X_{6.10.3}$ 8.880 + $X_{10.11.3}$ 760 + $X_{10.12.3}$ 3.520 + $X_{12.13.3}$ 2.368 + $X_{13.14.3}$2.432 + $X_{14.16.3}$ 11.248+ $X_{14.15.3}$ 4.560 +

$(Cp)1500^* Y_{16} – 1500^*164(t_{ijmin})$

subject to

Resource-Mode Selection Constraints

$$X_{111} + X_{112} + X_{113} = 1$$
$$X_{231} + X_{232} + X_{233} = 1$$
$$X_{241} + X_{242} + X_{243} = 1$$
$$X_{251} + X_{252} + X_{253} = 1$$
$$X_{261} + X_{262} + X_{263} = 1$$
$$X_{671} + X_{672} + X_{673} = 1$$
$$X_{681} + X_{682} + X_{683} = 1$$
$$X_{791} + X_{792} + X_{793} = 1$$
$$X_{9.10.1} + X_{9.10.2} + X_{9.10.3} = 1$$
$$X_{691} + X_{692} + X_{693} = 1$$
$$X_{6.10.1} + X_{6.10.2} + X_{6.10.3} = 1$$
$$X_{10.11.1} + X_{10.11.2} + X_{10.11.3} = 1$$

$X_{10.12.1} + X_{10.12.2} + X_{10.12.3} = 1$

$X_{12.13.1} + X_{12.13.2} + X_{12.13.3} = 1$

$X_{13.14.1} + X_{13.14.2} + X_{13.14.3} = 1$

$X_{14.16.1} + X_{14.16.2} + X_{14.16.3} = 1$

$X_{14.15.1} + X_{14.15.2} + X_{14.15.3} = 1$

Precedence Constraints for network

$Y_1 = 0$

$Y_1 + 60^* X_{111} - Y_2 \leq 0$

$Y_1 + 78^* X_{112} - Y_2 \leq 0$

$Y_1 + 90^* X_{113} - Y_2 \leq 0$

$Y_2 + 31^* X_{231} - Y_3 \leq 0$

$Y_2 + 40^* X_{232} - Y_3 \leq 0$

$Y_2 + 47^* X_{233} - Y_3 \leq 0$

$Y_2 + 28^* X_{241} - Y_4 \leq 0$

$Y_2 + 36^* X_{242} - Y_4 \leq 0$

$Y_2 + 42^* X_{243} - Y_4 \leq 0$

$Y_2 + 20^* X_{251} - Y_5 \leq 0$

$Y_2 + 26^* X_{252} - Y_5 \leq 0$

$Y_2 + 30^* X_{253} - Y_5 \leq 0$

$Y_2 + 25^* X_{261} - Y_6 \leq 0$

$Y_2 + 33^* X_{262} - Y_6 \leq 0$

$Y_2 + 38^* X_{263} - Y_6 \leq 0$

$Y_3 - Y_6 \leq 0$

$Y_4 - Y_6 \leq 0$

$Y_5 - Y_6 \leq 0$

$Y_6 + 1^* X_{671} - Y_7 \leq 0$

$Y_6 + 1^* X_{672} - Y_7 \leq 0$

$Y_6 + 2^* X_{673} - Y_7 \leq 0$

$Y_6 + 3^* X_{681} - Y_8 \leq 0$

$Y_6 + 3^* X_{682} - Y_8 \leq 0$

$Y_6 + 4^* X_{683} - Y_8 \leq 0$

$Y_7 + 30^* X_{791} - Y_9 \leq 0$

$Y_7 + 39^* X_{792} - Y_9 \leq 0$

$Y_7 + 45^* X_{793} - Y_9 \leq 0$

$Y_9 + 3^* X_{9.10.1} - Y_{10} \leq 0$

$Y_9 + 4^* X_{9.10.2} - Y_{10} \leq 0$

$Y_9 + 5^* X_{9.10.3} - Y_{10} \leq 0$

$Y_6 + 15^* X_{691} - Y_9 \leq 0$

$Y_6 + 20^* X_{692} - Y_9 \leq 0$

$Y_6 + 23^* X_{693} - Y_9 \leq 0$

$Y_6 + 15^* X_{6.10.1} - Y_{10} \leq 0$

$Y_6 + 20^* X_{6.10.2} - Y_{10} \leq 0$

$Y_6 + 23^* X_{6.10.3} - Y_{10} \leq 0$

$Y_8 \qquad - Y_9 \leq 0$

$Y_{10} + 4^* X_{10.11.1} - Y_{11} \leq 0$

$Y_{10} + 5^* X_{10.11.2} - Y_{11} \leq 0$

$Y_{10} + 6^* X_{10.11.3} - Y_{11} \leq 0$

$Y_{10} + 7^* X_{10.12.1} - Y_{12} \leq 0$

$Y_{10} + 8^* X_{10.12.2} - Y_{12} \leq 0$

$Y_{10} + 10^* X_{10.12.3} - Y_{12} \leq 0$

$$Y_{11} - Y_{12} \leq 0$$

$$Y_{12} + 4 * X_{12.13.1} - Y_{13} \leq 0$$
$$Y_{12} + 5 * X_{12.13.2} - Y_{13} \leq 0$$
$$Y_{12} + 6 * X_{12.13.3} - Y_{13} \leq 0$$

$$Y_{13} + 7 * X_{13.14.1} - Y_{14} \leq 0$$
$$Y_{13} + 8 * X_{13.14.2} - Y_{14} \leq 0$$
$$Y_{13} + 10 * X_{13.14.3} - Y_{14} \leq 0$$

$$Y_{14} + 33 * X_{14.16.1} - Y_{16} \leq 0$$
$$Y_{14} + 42 * X_{14.16.2} - Y_{16} \leq 0$$
$$Y_{14} + 49 * X_{14.16.3} - Y_{16} \leq 0$$

$$Y_{14} + 15 * X_{14.15.1} - Y_{15} \leq 0$$
$$Y_{14} + 21 * X_{14.15.2} - Y_{15} \leq 0$$
$$Y_{14} + 23 * X_{14.15.3} - Y_{15} \leq 0$$
$$Y_{15} - Y_{16} \leq 0$$

APPENDIX B

	FACTORS IN 243 EXPERIMENTS							COST	MODES IN PHASE DECISION			
				Joint		Customer						
exp.no	Cp	ext.fac	prob.extr	durincfac	cost.dec	durincfac	cost.dec	total	design	ship	install	commission
1	1000	1.3	0.05	1.2	0.4	1.4	0.2	77,247	cust	cust	cust	joint
2	1000	1.3	0.1	1.2	0.4	1.4	0.3	93,444	joint	joint	cust	joint
3	1000	1.3	0.2	1.2	0.4	1.4	0.4	101,283	joint	joint	joint	joint
4	1000	1.3	0.05	1.2	0.4	1.5	0.2	85,266	cust	cust	cust	joint
5	1000	1.3	0.1	1.2	0.4	1.5	0.3	94,018	joint	joint	joint	joint
6	1000	1.3	0.2	1.2	0.4	1.5	0.4	101,283	joint	joint	joint	joint
7	1000	1.3	0.05	1.2	0.4	1.6	0.2	89,339	joint	joint	cust	joint
8	1000	1.3	0.1	1.2	0.4	1.6	0.3	94,018	joint	joint	joint	joint
9	1000	1.3	0.2	1.2	0.4	1.6	0.4	101,283	joint	joint	joint	joint
10	1000	1.5	0.05	1.2	0.5	1.4	0.2	79,096	cust	cust	cust	cust
11	1000	1.5	0.1	1.2	0.5	1.4	0.3	100,538	cust	cust	cust	joint
12	1000	1.5	0.2	1.2	0.5	1.4	0.4	123,960	joint	joint	cust	joint
13	1000	1.5	0.05	1.2	0.5	1.5	0.2	89,091	cust	cust	cust	joint
14	1000	1.5	0.1	1.2	0.5	1.5	0.3	108,833	cust	cust	cust	joint
15	1000	1.5	0.2	1.2	0.5	1.5	0.4	124,524	joint	joint	joint	joint
16	1000	1.5	0.05	1.2	0.5	1.6	0.2	97,189	cust	cust	cust	joint
17	1000	1.5	0.1	1.2	0.5	1.6	0.3	112,846	joint	joint	cust	joint
18	1000	1.5	0.2	1.2	0.5	1.6	0.4	124,524	joint	joint	joint	joint
19	1000	1.7	0.05	1.2	0.6	1.4	0.2	80,552	cust	cust	cust	cust
20	1000	1.7	0.1	1.2	0.6	1.4	0.3	103,897	cust	cust	cust	cust
21	1000	1.7	0.2	1.2	0.6	1.4	0.4	134,326	cust	cust	cust	joint
22	1000	1.7	0.05	1.2	0.6	1.5	0.2	91,316	cust	cust	cust	cust
23	1000	1.7	0.1	1.2	0.6	1.5	0.3	114,205	cust	cust	cust	joint
24	1000	1.7	0.2	1.2	0.6	1.5	0.4	143,323	cust	joint	cust	joint
25	1000	1.7	0.05	1.2	0.6	1.6	0.2	101,094	cust	cust	cust	joint
26	1000	1.7	0.1	1.2	0.6	1.6	0.3	122,658	cust	cust	cust	joint
27	1000	1.7	0.2	1.2	0.6	1.6	0.4	146,861	joint	joint	cust	joint
28	1000	1.3	0.05	1.3	0.4	1.4	0.2	77,640	cust	cust	cust	cust
29	1000	1.3	0.1	1.3	0.4	1.4	0.3	97,900	cust	cust	cust	joint
30	1000	1.3	0.2	1.3	0.4	1.4	0.4	112,307	joint	joint	joint	joint
31	1000	1.3	0.05	1.3	0.4	1.5	0.2	87,803	cust	cust	cust	joint
32	1000	1.3	0.1	1.3	0.4	1.5	0.3	104,156	joint	joint	cust	joint
33	1000	1.3	0.2	1.3	0.4	1.5	0.4	112,307	joint	joint	joint	joint
34	1000	1.3	0.05	1.3	0.4	1.6	0.2	95,822	cust	cust	cust	joint
35	1000	1.3	0.1	1.3	0.4	1.6	0.3	104,730	joint	joint	joint	joint
36	1000	1.3	0.2	1.3	0.4	1.6	0.4	112,307	joint	joint	joint	joint

Experimental Design Results

APPENDIX B

37	1000	1.5	0.05	1.3	0.5	1.4	0.2	79,096	cust	cust	cust	cust
38	1000	1.5	0.1	1.3	0.5	1.4	0.3	100,985	cust	cust	cust	cust
39	1000	1.5	0.2	1.3	0.5	1.4	0.4	128,928	cust	cust	cust	joint
40	1000	1.5	0.05	1.3	0.5	1.5	0.2	89,756	cust	cust	cust	cust
41	1000	1.5	0.1	1.3	0.5	1.5	0.3	111,458	cust	cust	cust	joint
42	1000	1.5	0.2	1.3	0.5	1.5	0.4	135,400	joint	joint	cust	joint
43	1000	1.5	0.05	1.3	0.5	1.6	0.2	99,751	cust	cust	cust	joint
44	1000	1.5	0.1	1.3	0.5	1.6	0.3	119,753	cust	cust	cust	joint
45	1000	1.5	0.2	1.3	0.5	1.6	0.4	135,964	joint	joint	joint	joint
46	1000	1.7	0.05	1.3	0.6	1.4	0.2	80,552	cust	cust	cust	cust
47	1000	1.7	0.1	1.3	0.6	1.4	0.3	103,897	cust	cust	cust	cust
48	1000	1.7	0.2	1.3	0.6	1.4	0.4	134,979	cust	cust	cust	cust
49	1000	1.7	0.05	1.3	0.6	1.5	0.2	91,316	cust	cust	cust	cust
50	1000	1.7	0.1	1.3	0.6	1.5	0.3	115,025	cust	cust	cust	cust
51	1000	1.7	0.2	1.3	0.6	1.5	0.4	146,182	cust	cust	cust	joint
52	1000	1.7	0.05	1.3	0.6	1.6	0.2	102,080	cust	cust	cust	cust
53	1000	1.7	0.1	1.3	0.6	1.6	0.3	125,333	cust	cust	cust	joint
54	1000	1.7	0.2	1.3	0.6	1.6	0.4	155,179	cust	joint	cust	joint
55	1000	1.3	0.05	1.4	0.4	1.4	0.2	77,640	cust	cust	cust	cust
56	1000	1.3	0.1	1.4	0.4	1.4	0.3	98,073	cust	cust	cust	cust
57	1000	1.3	0.2	1.4	0.4	1.4	0.4	123,331	cust	cust	cust	cust
58	1000	1.3	0.05	1.4	0.4	1.5	0.2	88,196	cust	cust	cust	cust
59	1000	1.3	0.1	1.4	0.4	1.5	0.3	108,612	cust	cust	cust	joint
60	1000	1.3	0.2	1.4	0.4	1.5	0.4	123,331	joint	joint	joint	joint
61	1000	1.3	0.05	1.4	0.4	1.6	0.2	98,359	cust	cust	cust	joint
62	1000	1.3	0.1	1.4	0.4	1.6	0.3	114,868	joint	joint	cust	joint
63	1000	1.3	0.2	1.4	0.4	1.6	0.4	123,331	joint	joint	joint	joint
64	1000	1.5	0.05	1.4	0.5	1.4	0.2	79,096	cust	cust	cust	cust
65	1000	1.5	0.1	1.4	0.5	1.4	0.3	100,985	cust	cust	cust	cust
66	1000	1.5	0.2	1.4	0.5	1.4	0.4	129,155	cust	cust	cust	cust
67	1000	1.5	0.05	1.4	0.5	1.5	0.2	89,756	cust	cust	cust	cust
68	1000	1.5	0.1	1.4	0.5	1.5	0.3	111,905	cust	cust	cust	cust
69	1000	1.5	0.2	1.4	0.5	1.5	0.4	140,368	cust	cust	cust	joint
70	1000	1.5	0.05	1.4	0.5	1.6	0.2	100,416	cust	cust	cust	cust
71	1000	1.5	0.1	1.4	0.5	1.6	0.3	122,378	cust	cust	cust	joint
72	1000	1.5	0.2	1.4	0.5	1.6	0.4	146,840	joint	joint	cust	joint
73	1000	1.7	0.05	1.4	0.6	1.4	0.2	80,552	cust	cust	cust	cust
74	1000	1.7	0.1	1.4	0.6	1.4	0.3	103,897	cust	cust	cust	cust
75	1000	1.7	0.2	1.4	0.6	1.4	0.4	134,979	cust	cust	cust	cust

Experimental Design Results

APPENDIX B

76	1000	1.7	0.05	1.4	0.6	1.5	0.2	91,316	cust	cust	cust	cust
77	1000	1.7	0.1	1.4	0.6	1.5	0.3	115,025	cust	cust	cust	cust
78	1000	1.7	0.2	1.4	0.6	1.5	0.4	146,835	cust	cust	cust	cust
79	1000	1.7	0.05	1.4	0.6	1.6	0.2	102,080	cust	cust	cust	cust
80	1000	1.7	0.1	1.4	0.6	1.6	0.3	126,153	cust	cust	cust	cust
81	1000	1.7	0.2	1.4	0.6	1.6	0.4	156,730	cust	cust	cust	integ
82	1500	1.3	0.05	1.2	0.4	1.4	0.2	96,602	cust	cust	cust	joint
83	1500	1.3	0.1	1.2	0.4	1.4	0.3	106,290	joint	joint	joint	joint
84	1500	1.3	0.2	1.2	0.4	1.4	0.4	115,427	joint	joint	joint	joint
85	1500	1.3	0.05	1.2	0.4	1.5	0.2	101,385	joint	joint	cust	joint
86	1500	1.3	0.1	1.2	0.4	1.5	0.3	106,290	joint	joint	joint	joint
87	1500	1.3	0.2	1.2	0.4	1.5	0.4	115,427	joint	joint	joint	joint
88	1500	1.3	0.05	1.2	0.4	1.6	0.2	101,721	joint	joint	joint	joint
89	1500	1.3	0.1	1.2	0.4	1.6	0.3	106,290	joint	joint	joint	joint
90	1500	1.3	0.2	1.2	0.4	1.6	0.4	115,427	joint	joint	joint	joint
91	1500	1.5	0.05	1.2	0.5	1.4	0.2	101,051	cust	cust	cust	joint
92	1500	1.5	0.1	1.2	0.5	1.4	0.3	122,353	cust	cust	cust	joint
93	1500	1.5	0.2	1.2	0.5	1.4	0.4	141,164	joint	joint	joint	joint
94	1500	1.5	0.05	1.2	0.5	1.5	0.2	113,198	cust	cust	cust	joint
95	1500	1.5	0.1	1.2	0.5	1.5	0.3	127,101	joint	joint	cust	joint
96	1500	1.5	0.2	1.2	0.5	1.5	0.4	141,164	joint	joint	joint	joint
97	1500	1.5	0.05	1.2	0.5	1.6	0.2	119,036	joint	joint	cust	joint
98	1500	1.5	0.1	1.2	0.5	1.6	0.3	127,402	joint	joint	joint	joint
99	1500	1.5	0.2	1.2	0.5	1.6	0.4	141,164	joint	joint	joint	joint
100	1500	1.7	0.05	1.2	0.6	1.4	0.2	103,900	cust	cust	cust	cust
101	1500	1.7	0.1	1.2	0.6	1.4	0.3	128,973	cust	cust	cust	joint
102	1500	1.7	0.2	1.2	0.6	1.4	0.4	162,459	cust	joint	cust	joint
103	1500	1.7	0.05	1.2	0.6	1.5	0.2	117,766	cust	cust	cust	joint
104	1500	1.7	0.1	1.2	0.6	1.5	0.3	141,653	cust	cust	cust	joint
105	1500	1.7	0.2	1.2	0.6	1.5	0.4	166,795	joint	joint	cust	joint
106	1500	1.7	0.05	1.2	0.6	1.6	0.2	130,031	cust	cust	cust	joint
107	1500	1.7	0.1	1.2	0.6	1.6	0.3	147,128	joint	joint	cust	joint
108	1500	1.7	0.2	1.2	0.6	1.6	0.4	166,901	joint	joint	joint	joint
109	1500	1.3	0.05	1.3	0.4	1.4	0.2	99,532	cust	cust	cust	cust
110	1500	1.3	0.1	1.3	0.4	1.4	0.3	119,596	cust	cust	cust	joint
111	1500	1.3	0.2	1.3	0.4	1.4	0.4	131,963	joint	joint	joint	joint
112	1500	1.3	0.05	1.3	0.4	1.5	0.2	112,436	cust	cust	cust	joint
113	1500	1.3	0.1	1.3	0.4	1.5	0.3	122,358	joint	joint	joint	joint
114	1500	1.3	0.2	1.3	0.4	1.5	0.4	131,963	joint	joint	joint	joint

Experimental Design Results

APPENDIX B

115	1500	1.3	0.05	1.3	0.4	1.6	0.2	117,219	joint	joint	cust	joint
116	1500	1.3	0.1	1.3	0.4	1.6	0.3	122,358	joint	joint	joint	joint
117	1500	1.3	0.2	1.3	0.4	1.6	0.4	131,963	joint	joint	joint	joint
118	1500	1.5	0.05	1.3	0.5	1.4	0.2	101,716	cust	cust	cust	cust
119	1500	1.5	0.1	1.3	0.5	1.4	0.3	125,425	cust	cust	cust	cust
120	1500	1.5	0.2	1.3	0.5	1.4	0.4	155,633	cust	cust	cust	joint
121	1500	1.5	0.05	1.3	0.5	1.5	0.2	117,041	cust	cust	cust	joint
122	1500	1.5	0.1	1.3	0.5	1.5	0.3	138,733	cust	cust	cust	joint
123	1500	1.5	0.2	1.3	0.5	1.5	0.4	158,324	joint	joint	joint	joint
124	1500	1.5	0.05	1.3	0.5	1.6	0.2	129,188	cust	cust	cust	joint
125	1500	1.5	0.1	1.3	0.5	1.6	0.3	143,481	joint	joint	cust	joint
126	1500	1.5	0.2	1.3	0.5	1.6	0.4	158,324	joint	joint	joint	joint
127	1500	1.7	0.05	1.3	0.6	1.4	0.2	103,900	cust	cust	cust	cust
128	1500	1.7	0.1	1.3	0.6	1.4	0.3	129,793	cust	cust	cust	cust
129	1500	1.7	0.2	1.3	0.6	1.4	0.4	164,010	cust	cust	cust	integ
130	1500	1.7	0.05	1.3	0.6	1.5	0.2	119,367	cust	cust	cust	integ
131	1500	1.7	0.1	1.3	0.6	1.5	0.3	143,234	cust	cust	cust	integ
132	1500	1.7	0.2	1.3	0.6	1.5	0.4	177,511	cust	joint	cust	integ
133	1500	1.7	0.05	1.3	0.6	1.6	0.2	131,631	cust	cust	cust	integ
134	1500	1.7	0.1	1.3	0.6	1.6	0.3	155,913	cust	cust	cust	integ
135	1500	1.7	0.2	1.3	0.6	1.6	0.4	181,847	joint	joint	cust	integ
136	1500	1.3	0.05	1.4	0.4	1.4	0.2	99,532	cust	cust	cust	cust
137	1500	1.3	0.1	1.4	0.4	1.4	0.3	121,057	cust	cust	cust	cust
138	1500	1.3	0.2	1.4	0.4	1.4	0.4	147,738	cust	cust	cust	integ
139	1500	1.3	0.05	1.4	0.4	1.5	0.2	115,062	cust	cust	cust	integ
140	1500	1.3	0.1	1.4	0.4	1.5	0.3	134,624	cust	cust	cust	integ
141	1500	1.3	0.2	1.4	0.4	1.5	0.4	147,738	joint	joint	joint	integ
142	1500	1.3	0.05	1.4	0.4	1.6	0.2	127,089	cust	cust	cust	integ
143	1500	1.3	0.1	1.4	0.4	1.6	0.3	137,385	joint	joint	joint	integ
144	1500	1.3	0.2	1.4	0.4	1.6	0.4	147,738	joint	joint	joint	integ
145	1500	1.5	0.05	1.4	0.5	1.4	0.2	101,716	cust	cust	cust	cust
146	1500	1.5	0.1	1.4	0.5	1.4	0.3	125,425	cust	cust	cust	cust
147	1500	1.5	0.2	1.4	0.5	1.4	0.4	155,874	cust	cust	cust	integ
148	1500	1.5	0.05	1.4	0.5	1.5	0.2	117,214	cust	cust	cust	integ
149	1500	1.5	0.1	1.4	0.5	1.5	0.3	138,929	cust	cust	cust	integ
150	1500	1.5	0.2	1.4	0.5	1.5	0.4	168,909	cust	cust	cust	integ
151	1500	1.5	0.05	1.4	0.5	1.6	0.2	129,360	cust	cust	cust	integ
152	1500	1.5	0.1	1.4	0.5	1.6	0.3	151,371	cust	cust	cust	integ
153	1500	1.5	0.2	1.4	0.5	1.6	0.4	171,600	joint	joint	joint	integ

Experimental Design Results

APPENDIX B

154	1500	1.7	0.05	1.4	0.6	1.4	0.2	103,900	cust	cust	cust	cust
155	1500	1.7	0.1	1.4	0.6	1.4	0.3	129,793	cust	cust	cust	cust
156	1500	1.7	0.2	1.4	0.6	1.4	0.4	164,010	cust	cust	cust	integ
157	1500	1.7	0.05	1.4	0.6	1.5	0.2	119,367	cust	cust	cust	integ
158	1500	1.7	0.1	1.4	0.6	1.5	0.3	143,234	cust	cust	cust	integ
159	1500	1.7	0.2	1.4	0.6	1.5	0.4	177,519	cust	cust	cust	integ
160	1500	1.7	0.05	1.4	0.6	1.6	0.2	131,631	cust	cust	cust	integ
161	1500	1.7	0.1	1.4	0.6	1.6	0.3	155,913	cust	cust	cust	integ
162	1500	1.7	0.2	1.4	0.6	1.6	0.4	191,020	cust	joint	cust	integ
163	2000	1.3	0.05	1.2	0.4	1.4	0.2	112,011	joint	joint	cust	joint
164	2000	1.3	0.1	1.2	0.4	1.4	0.3	118,562	joint	joint	joint	joint
165	2000	1.3	0.2	1.2	0.4	1.4	0.4	129,571	joint	joint	joint	joint
166	2000	1.3	0.05	1.2	0.4	1.5	0.2	113,057	joint	joint	joint	joint
167	2000	1.3	0.1	1.2	0.4	1.5	0.3	118,562	joint	joint	joint	joint
168	2000	1.3	0.2	1.2	0.4	1.5	0.4	129,571	joint	joint	joint	joint
169	2000	1.3	0.05	1.2	0.4	1.6	0.2	113,057	joint	joint	joint	joint
170	2000	1.3	0.1	1.2	0.4	1.6	0.3	118,562	joint	joint	joint	joint
171	2000	1.3	0.2	1.2	0.4	1.6	0.4	129,571	joint	joint	joint	joint
172	2000	1.5	0.05	1.2	0.5	1.4	0.2	121,109	cust	cust	cust	joint
173	2000	1.5	0.1	1.2	0.5	1.4	0.3	139,886	joint	joint	cust	joint
174	2000	1.5	0.2	1.2	0.5	1.4	0.4	157,804	joint	joint	joint	joint
175	2000	1.5	0.05	1.2	0.5	1.5	0.2	130,996	joint	joint	cust	joint
176	2000	1.5	0.1	1.2	0.5	1.5	0.3	140,922	joint	joint	joint	joint
177	2000	1.5	0.2	1.2	0.5	1.5	0.4	157,804	joint	joint	joint	joint
178	2000	1.5	0.05	1.2	0.5	1.6	0.2	132,481	joint	joint	joint	joint
179	2000	1.5	0.1	1.2	0.5	1.6	0.3	140,922	joint	joint	joint	joint
180	2000	1.5	0.2	1.2	0.5	1.6	0.4	157,804	joint	joint	joint	joint
181	2000	1.7	0.05	1.2	0.6	1.4	0.2	125,275	cust	cust	cust	integ
182	2000	1.7	0.1	1.2	0.6	1.4	0.3	151,100	cust	cust	cust	integ
183	2000	1.7	0.2	1.2	0.6	1.4	0.4	183,826	joint	joint	cust	integ
184	2000	1.7	0.05	1.2	0.6	1.5	0.2	141,628	cust	cust	cust	integ
185	2000	1.7	0.1	1.2	0.6	1.5	0.3	160,803	joint	joint	cust	integ
186	2000	1.7	0.2	1.2	0.6	1.5	0.4	184,730	joint	joint	joint	integ
187	2000	1.7	0.05	1.2	0.6	1.6	0.2	149,050	joint	joint	cust	integ
188	2000	1.7	0.1	1.2	0.6	1.6	0.3	162,189	joint	joint	joint	integ
189	2000	1.7	0.2	1.2	0.6	1.6	0.4	184,730	joint	joint	joint	integ
190	2000	1.3	0.05	1.3	0.4	1.4	0.2	119,851	cust	cust	cust	integ
191	2000	1.3	0.1	1.3	0.4	1.4	0.3	138,371	joint	joint	cust	integ
192	2000	1.3	0.2	1.3	0.4	1.4	0.4	150,858	joint	joint	joint	integ

Experimental Design Results

APPENDIX B

193	2000	1.3	0.05	1.3	0.4	1.5	0.2	131,943	joint	joint	cust	integ
194	2000	1.3	0.1	1.3	0.4	1.5	0.3	138,945	joint	joint	joint	integ
195	2000	1.3	0.2	1.3	0.4	1.5	0.4	150,858	joint	joint	joint	integ
196	2000	1.3	0.05	1.3	0.4	1.6	0.2	132,989	joint	joint	joint	integ
197	2000	1.3	0.1	1.3	0.4	1.6	0.3	138,945	joint	joint	joint	integ
198	2000	1.3	0.2	1.3	0.4	1.6	0.4	150,858	joint	joint	joint	integ
199	2000	1.5	0.05	1.3	0.5	1.4	0.2	122,563	cust	cust	cust	integ
200	2000	1.5	0.1	1.3	0.5	1.4	0.3	145,676	cust	cust	cust	integ
201	2000	1.5	0.2	1.3	0.5	1.4	0.4	176,236	joint	joint	cust	integ
202	2000	1.5	0.05	1.3	0.5	1.5	0.2	138,758	cust	cust	cust	integ
203	2000	1.5	0.1	1.3	0.5	1.5	0.3	157,984	joint	joint	cust	integ
204	2000	1.5	0.2	1.3	0.5	1.5	0.4	176,800	joint	joint	joint	integ
205	2000	1.5	0.05	1.3	0.5	1.6	0.2	148,645	joint	joint	cust	integ
206	2000	1.5	0.1	1.3	0.5	1.6	0.3	159,020	joint	joint	joint	integ
207	2000	1.5	0.2	1.3	0.5	1.6	0.4	176,800	joint	joint	joint	integ
208	2000	1.7	0.05	1.3	0.6	1.4	0.2	125,275	cust	cust	cust	integ
209	2000	1.7	0.1	1.3	0.6	1.4	0.3	151,100	cust	cust	cust	integ
210	2000	1.7	0.2	1.3	0.6	1.4	0.4	189,302	cust	cust	cust	integ
211	2000	1.7	0.05	1.3	0.6	1.5	0.2	141,628	cust	cust	cust	integ
212	2000	1.7	0.1	1.3	0.6	1.5	0.3	168,006	cust	cust	cust	integ
213	2000	1.7	0.2	1.3	0.6	1.5	0.4	201,838	joint	joint	cust	integ
214	2000	1.7	0.05	1.3	0.6	1.6	0.2	157,981	cust	cust	cust	integ
215	2000	1.7	0.1	1.3	0.6	1.6	0.3	177,709	joint	joint	cust	integ
216	2000	1.7	0.2	1.3	0.6	1.6	0.4	202,742	joint	joint	joint	integ
217	2000	1.3	0.05	1.4	0.4	1.4	0.2	119,851	cust	cust	cust	integ
218	2000	1.3	0.1	1.4	0.4	1.4	0.3	140,252	cust	cust	cust	integ
219	2000	1.3	0.2	1.4	0.4	1.4	0.4	167,606	cust	cust	cust	integ
220	2000	1.3	0.05	1.4	0.4	1.5	0.2	135,888	cust	cust	cust	integ
221	2000	1.3	0.1	1.4	0.4	1.5	0.3	154,645	joint	joint	cust	integ
222	2000	1.3	0.2	1.4	0.4	1.5	0.4	167,606	joint	joint	joint	integ
223	2000	1.3	0.05	1.4	0.4	1.6	0.2	147,980	joint	joint	cust	integ
224	2000	1.3	0.1	1.4	0.4	1.6	0.3	155,219	joint	joint	joint	integ
225	2000	1.3	0.2	1.4	0.4	1.6	0.4	167,606	joint	joint	joint	integ
226	2000	1.5	0.05	1.4	0.5	1.4	0.2	122,563	cust	cust	cust	integ
227	2000	1.5	0.1	1.4	0.5	1.4	0.3	145,676	cust	cust	cust	integ
228	2000	1.5	0.2	1.4	0.5	1.4	0.4	178,454	cust	cust	cust	integ
229	2000	1.5	0.05	1.4	0.5	1.5	0.2	138,758	cust	cust	cust	integ
230	2000	1.5	0.1	1.4	0.5	1.5	0.3	162,266	cust	cust	cust	integ
231	2000	1.5	0.2	1.4	0.5	1.5	0.4	193,616	joint	joint	cust	integ

Experimental Design Results

232	2000	1.5	0.05	1.4	0.5	1.6	0.2	154,953	cust	cust	cust	integ
233	2000	1.5	0.1	1.4	0.5	1.6	0.3	174,574	joint	joint	cust	integ
234	2000	1.5	0.2	1.4	0.5	1.6	0.4	194,180	joint	joint	joint	integ
235	2000	1.7	0.05	1.4	0.6	1.4	0.2	125,275	cust	cust	cust	integ
236	2000	1.7	0.1	1.4	0.6	1.4	0.3	151,100	cust	cust	cust	integ
237	2000	1.7	0.2	1.4	0.6	1.4	0.4	189,302	cust	cust	cust	integ
238	2000	1.7	0.05	1.4	0.6	1.5	0.2	141,628	cust	cust	cust	integ
239	2000	1.7	0.1	1.4	0.6	1.5	0.3	168,006	cust	cust	cust	integ
240	2000	1.7	0.2	1.4	0.6	1.5	0.4	207,220	cust	integ	cust	integ
241	2000	1.7	0.05	1.4	0.6	1.6	0.2	157,981	cust	cust	cust	integ
242	2000	1.7	0.1	1.4	0.6	1.6	0.3	183,458	cust	integ	cust	integ
243	2000	1.7	0.2	1.4	0.6	1.6	0.4	212,704	integ	integ	cust	integ

Experimental Design Results

APPENDIX C

```
Sub Solver()

    Dim i As Integer

    For i = 1 To 1000
    Sheets(i).Activate
    SolverReset
    SolverAdd cellRef:="$C$12:$S$14", relation:=5, Comment:="", Report:=True
    SolverAdd cellRef:="$C$15:$S$15", relation:=2, formulaText:="1", Comment:="", _
        Report:=True
    SolverAdd cellRef:="$C$20", relation:=2, formulaText:="0", Comment:="", Report _
        :=True
    SolverAdd cellRef:="$C$20:$R$20", relation:=3, formulaText:="0", Comment:="", _
        Report:=True
    SolverAdd cellRef:="$C$21:$C$43", relation:=1, formulaText:="$E$21:$E$43", _
        Comment:="", Report:=True
    SolverAdd cellRef:="$H$21:$H$43", relation:=1, formulaText:="$J$21:$J$43", _
        Comment:="", Report:=True
    SolverAdd cellRef:="$M$21:$M$43", relation:=1, formulaText:="$O$21:$O$43", _
        Comment:="", Report:=True
    SolverOk SetCell:="$Q$23", MaxMinVal:=2, ValueOf:=0, ByChange:= _
        "$C$12:$S$14;$C$20:$R$20", Engine:=2, EngineDesc:="Standard LP/Quadratic"
    SolverModel CheckFor:=1, ShowTransformations:=False, SolveTransformed:=False, _
        ShowExceptions:=False, DesiredModel:=5, SolveWith:=1, Engines:=1, ReqSmooth:= _
        False, FastSetup:=False, Sparse:=False, ActiveOnly:=False
    SolverOk SetCell:="$Q$23", MaxMinVal:=2, ValueOf:=0, ByChange:= _
        "$C$12:$S$14;$C$20:$R$20", Engine:=2, EngineDesc:="Standard LP/Quadratic"
    SolverLPOptions MaxTime:=500000000, Iterations:=5000000000#, Precision:= _
        0.00000001, PivotTol:=0.000001, ReducedTol:=0.000001, StepThru:=False, Scaling _
        :=False, AssumeNonneg:=False, BypassReports:=False, Derivatives:=1
    SolverIntOptions MaxSubProblems:=5000000000#, MaxIntegerSols:=5000000000#, _
        IntTolerance:=0.05, SolveWithout:=False, UseDual:=True, ProbingFeasibility:= _
```

```
        False, BoundsImprovement:=False, OptimalityFixing:=False, UsePrimalHeuristic:= _
        False
    SolverIntOptions MaxGomoryCuts:=20, GomoryPasses:=1, MaxKnapsackCuts:=20, _
        KnapsackPasses:=1
    SolverOk SetCell:="$Q$23", MaxMinVal:=2, ValueOf:=0, ByChange:= _
        "$C$12:$S$14;$C$20:$R$20", Engine:=2, EngineDesc:="Standard LP/Quadratic"
    SolverSolve UserFinish:=True
    SolverFinishDialog keepFinal:=1
    Next i
End Sub
Sub kopyalama()
Dim i As Integer
For i = 1 To 1000
    Windows("instances.xls").Activate
    Sheets("IntDur").Select
    Range(Cells(i + 101, 20), Cells(i + 101, 36)).Select
    Selection.Copy
    Windows("30 nolu deney 1000 instances.xls").Activate
    Sheets(i + 198).Activate
    Range("C3").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Windows("instances.xls").Activate
    Sheets("JointDur").Select
    Range(Cells(i + 101, 20), Cells(i + 101, 36)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Windows("30 nolu deney 1000 instances.xls").Activate
    Range("C6").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Windows("instances.xls").Activate
    Sheets("CustDur").Select
    Range(Cells(i + 101, 20), Cells(i + 101, 36)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Windows("30 nolu deney 1000 instances.xls").Activate
```

```
    Range("C9").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Windows("instances.xls").Activate
    Sheets("IntCost").Select
    Range(Cells(i + 101, 2), Cells(i + 101, 18)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Windows("30 nolu deney 1000 instances.xls").Activate
    Range("C4").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Windows("instances.xls").Activate
    Sheets("JointCost").Select
    Range(Cells(i + 101, 2), Cells(i + 101, 18)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Windows("30 nolu deney 1000 instances.xls").Activate
    Range("C7").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Windows("instances.xls").Activate
    Sheets("CustCost").Select
    Range(Cells(i + 101, 2), Cells(i + 101, 18)).Select
    Application.CutCopyMode = False
    Selection.Copy
    Windows("30 nolu deney 1000 instances.xls").Activate
    Range("C10").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Range("I8").Select
    Application.CutCopyMode = False

Next i
End Sub
```