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Application of the Resource-Constrained Project Scheduling and Planning Problems in the Production of Seismic Isolators Using Mathematical Programming Approach

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Buca/IZMIR

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Abdul Waris SHAFIQUE

APPLICATION OF THE RESOURCE-CONSTRAINED PROJECT SCHEDULING AND PLANNING PROBLEMS IN THE PRODUCTION OF SEISMIC ISOLATORS USING MATHEMATICAL PROGRAMMING APPROACH

ABSTRACT

The manufacturing system of seismic isolators has a project-based production process and therefore, it is generally required to prepare a project plan or schedule for their production under restricted resources such as machinery and manpower. Based on this motivation, a well-known project scheduling problem in the literature, which is named a single-mode resource-constrained project scheduling (RCPS) problem is investigated in this term project for the production project of the seismic isolators. First, a deterministic optimization model which is formulated as an integer program is presented to solve the examined problem under certain environments. The deterministic optimization results are provided by solving the integer programming model of the classical RCPSP problem using LINGO 17.0 optimization software. Then, the uncertainties in the activity durations and the resource capacities or availabilities are also considered by making use of hybridizing the fuzzy mathematical programming and scenario-based stochastic programming (i.e., pessimistic, most likely, and optimistic scenarios) approaches. In addition to these uncertain project parameters/inputs, the project schedules (or completion times of the activities) are also considered as uncertain variables and represented by triangular fuzzy numbers. First, the previously mentioned deterministic optimization model (i.e., integer programming model) is solved separately for each scenario and then, its optimization results are also compared to the results of the constraint programming model which is coded in IBM ILOG CPLEX optimization studio. It is proven that both the integer programming and constraint programming models have generated the same optimization results within reasonable computing times. Afterward, to obtain fuzzy project schedules for different probability values of the pessimistic, optimistic, and most likely scenarios, a fuzzy-

stochastic optimization model that integrates all of these scenarios (i.e., pessimistic, most likely, and optimistic cases) is formulated and also converted into its crisp equivalent form to minimize the expected value of the total project duration (i.e., makespan). The fuzzy-stochastic optimization results/project schedules are produced via LINGO optimization software again. In other words, fuzzy completion times of the project activities are generated for the pessimistic, most likely, and optimistic cases to provide managerial insights to the production project managers of a seismic isolator manufacturing company.

Keywords: Project scheduling, Optimization, Resource constraints, RCPSP

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CHAPTER 1
INTRODUCTION

1.1 Background

In a project-based production process, efficient and optimal project management strategies result in the project's successful execution, decrease expenditures, improve revenues, and lower the risk of profit loss. A key factor in assuring project success is effective project scheduling which may be obtained by setting realistic deadlines for projects, allocating resources wisely, and controlling the quality to reduce product faults. Therefore, project scheduling is one of the key responsibilities of project management, although it can be challenging due to resource limitations together with activities precedence relationship. Researchers consider the project scheduling problem as one of the most prevalent and fundamental problems, and several methods for its development have been discussed using various aspects (Vanhoucke, 2013). In fact, the major issue with project scheduling is that it is difficult to estimate how long it will take to conduct a project's operation to accomplish a particular goal. In initial studies on project schedules, it was assumed that a project's activities could only be presented through the implementation of time duration. However, resources may be constrained or delayed in real life for several reasons. Furthermore, project activities typically include a great deal of uncertainty, which could cause delays in the project's duration. Such uncertainties may occur for a variety of reasons, for instance: activities may take longer or shorter duration than initial estimation, resources may become unavailable, activities may be dropped due to changes in project scope, materials may arrive late, estimation errors may occur in activity duration, weather conditions may have an impact, activity due date may change, and natural hazards may occur. Any project schedule that is disrupted or delayed results in higher expenses because of waste of resources, missing unnoticed deadlines, and enhanced system inefficiencies because of constant rescheduling. To overcome such delays, the traditional and static deterministic project planning and scheduling methods are typically insufficient to be implemented in real-world projects without any consideration of variability

(Chakrabortty & Sarker, 1993). To lessen the impact of such disruptions managers consequently, require rescheduling. In fact, by considering the precedence relationships among project activities, planning and scheduling methods like program evaluation and review technique and the critical path method are suggested. But also, it is proposed to apply some limitations and evaluate their impacts. Resource restrictions are one of the main limitations of project planning and scheduling, which is regarded as a basic problem for project scheduling and is known as the resource-constrained project scheduling problem (RCPSP) (Barzinpour & Sadjadi, 2018). RCPSP which is a resource-constrained optimization scheduling problem recently received significant attention. The reason is that it extends traditional project scheduling by considering the resource restriction which is necessary to complete the project activities. In RCPSP, activities are assigned to available resources to meet predefined objectives. The major goal of resource-constrained project scheduling problems is minimizing the project's total duration or makespan, and by minimizing the project duration, finding the optimal schedule while satisfying the project resource constraints. It is always desirable to obtain a high-quality solution and a quick rate of convergence from an optimization algorithm. Moreover, projects must be completed on schedule, within the authorized budget, and in line with the predetermined specifications when resources are limited (Hosseinian, 2018).

1.2 Project Aims

This term project aims to investigate the single-mode resource-constrained project-scheduling problem (RCPSP) for a seismic isolators production project. Since the manufacturing process for seismic isolators is project-based, it is necessary to create an optimized project schedule for their production when labor and other resources such as machinery are limited. Therefore, the term project's objective is to reduce the overall project time for a seismic isolator production project, which has finite resources, such as manpower and machine resources. Briefly, in the term project, the resource-constrained project scheduling problem for the seismic isolator production project is addressed using mathematical programming approaches such as the integer programming model, constraint programming model, and fuzzy-stochastic

optimization model. Later, since most of the real-life project scheduling problems may involve uncertainties in the activity durations and resource availabilities, a fuzzy-stochastic optimization model is also proposed to deal with these uncertainties or dynamic conditions under various scenarios, such as optimistic, most likely, and pessimistic cases. Furthermore, by utilizing mathematical programming techniques for different cases, the overall project duration is minimized under constrained resource capacities and compare results are presented to production managers. Hence, this project will enable project managers to decide how to schedule the tasks for a seismic isolator production resource-constrained project for execution and minimize the project completion duration even if resources are insufficient. As in real life, it is always compulsory to finalize the project in the estimated time, otherwise, delays may cause the failure of a project.

CHAPTER 2
LITERATURE REVIEW

In this term project, a project scheduling problem is defined by using various problem characteristics and approaches. With some exceptions, such as: lowering cost, maximizing quality elements, or a mix of both, the main goal of a project scheduling problem is to minimize the makespan (Chakrabortt & Sarker, 2018). Usually, large-scale projects especially construction projects are typically carried out by a few subcontractors who have access to a variety of resources, including budget, manpower, materials, and other resources (Moradi, Hafezalkotob, & Ghezavati, 2018). Managing the resources during a project-based production has key importance as it can either make a project successful or fail. Total project makespan may be impacted due to several factors such as delays in supplies or shipping, incorrect equipment installation, rescheduling workers for other tasks, etc. (Nicał, 2017). Therefore, project managers must carefully plan the projects' schedules and utilize the resources if they want to arrange and complete them in a timely, high-quality, and reasonable manner.

During a construction project, there are various resource problems that may occur. Such resource problems that could arise during a project schedule are classified into three groups such as time/cost trade-off, resource levelling, and resource allocation (Adamu, Abass, & Okafor, 2007).

2.1 Time/cost trade-off problems

When there are no restrictions on the resources' availability, such problems could occur. The main challenge is to shorten the time it takes to complete a project by allocating more resources to some tasks so that they may be completed more quickly. When this is the case, there are a variety of approaches to choosing an activity's duration so that the resulting schedules' project completion times are all equal. Each timeline, however, can produce a different estimate of the project's overall direct costs. Therefore, it would be ideal to have a mechanism for figuring out the least expensive

timetable for every given project duration. Such techniques have been developed, each of which is predicated on a distinct set of assumptions on the structure of the activity-direct cost relationship (Csordas, 2017). This term project is not intended to address such problems.

2.2 Resource-levelling problems

It is a method of project scheduling which involves resolving scheduling challenges to guarantee that a project can be completed with the resources available. The materials, time, or tools needed to complete a project are referred to as resources in resource-leveling approaches. Resource leveling is to make the most of available resources while maintaining within the project's schedule, financial, and scope constraints. Because leveling resources requires balancing the needs of several projects on the same set of resources, project managers may find it challenging. Here are some possible outcomes based on a team's requirements: first, in order to keep the current project deadline, additional resources might need to be made available. Second, if the goal is to complete the project with the already available resources, the project's deadline might be extended (Basset & Atef, 2021).

Given a level completion date for the project, the project aim may be to gradually increase the number of diverse resources needed such as to keep the constant rate of resource utilization (Asana, 2021). Thus, this makes the resource-levelling problem outside the scope of this term project.

2.3 Resource-constrained problems/Resource allocation

When the resources needed for the project's activities are insufficient, such kind of project scheduling problems occur. Early attempts of solving the classical project scheduling problems for which numerous optimization procedures are available not sufficient to describe all aspects of a real-world problem. In order to solve management issues in sectors like construction, CPM and PERT have been extensively implemented. CPM/PERT, on the other hand, is predicated on the idea that there is

always a limitless supply of resources available for a project (Lixing, Wang, & Lee, 2008). However, in the real-life project may have restricted resources. Therefore, it is suggested to impose some resource and precedence restrictions to achieve the project optimization objectives and to overcome such problems, numerous optimization techniques have been introduced throughout time and RCPSPs are one of them (Wauters, Kinable, & Smet, 2014).

RCPSP which is also known as resource-constrained project scheduling problem is a subclass of the scheduling problem that addresses situations in which the workforce used to do the tasks which are constrained and each job has an arrival time, a due date, and a penalty for late completion (Cavalcante, 2013). RCPSP approaches have been considered one of the most difficult combinatorial optimization scheduling problems (Moradi, Hafezalkotob, & Ghezavati, 2019). Moreover, RCPSP problem is well-known in scientific literature and classified as NP-hard (Rosłon & Kulejewski, 2008). In RCPSPs directed arcs use to describe precedence relations and nodes to represent activities. In addition, precedence restrictions prevent activity from the beginning until all its predecessors have finished. Each activity in the resource-constrained project scheduling problem needs a certain number of resources to be processed, including equipment, raw materials, machinery, information, money, natural resources such as oil, coal, and water etc., and people and their skills. It is mentioned that in RCPSPs, both renewable and non-renewable resources are typically utilized in project activities. The scheduling method may also ensure the allowing resource-sharing possibility of renewable resources during a project. Contrary, it is also known that money may be interpreted as a non-renewable resource (Chakrabortty & Sarker, 2018). Indeed, the goal of project scheduling is accomplished by effectively utilizing the resources such as equipment, labor, and other tangible items that aid in the project's execution. The major aim of RCPSPs is to maintain the finish-start precedence constraints and renewable resource restrictions while minimizing the project makespan (Tannady & Maimury, 2018). In order to achieve the objective of lowering the overall makespan, RCPSP may assign these resources to each activity in the project and determine the actual start time of each activity, subject to satisfying the activity duration and certain logical limitations (Yuan, Lin, & Gen, 2021).

In this term project, the focus will be on resource-constrained project scheduling problem. By considering the characteristics of the seismic isolator production project, resource-constrained project scheduling problem (RCPSP) will be discussed with single-mode extension as seismic isolator production involves sharing of various kind of finite resources. Briefly, the single-mode resource-constrained project scheduling problem (SMRCPSP), is a scheduling problem where each of the project's operations must be carried out in accordance with a prescribed manner or mode while utilizing a specific quantity of the available resources. In addition, as seismic isolator production projects which is dominated by project-based production may involve uncertainties in the activity durations and resource availabilities, therefore mathematical programming approaches such as fuzzy-stochastic optimization model is also proposed to deal with these uncertainties or dynamic conditions under various scenarios in later steps of this term project.

CHAPTER 3
PROBLEM DESCRIPTION & MATHEMATICAL MODEL FORMULATION

The RCPSP is one of the most challenging combinatorial optimization problems in the literature, which has also NP-hard nature. In this term project, for the single-mode resource-constrained project scheduling problem, the following assumptions have been considered:

- First before beginning a project activity, the dependence activities(predecessors) will be completed.
- The project's activities mainly have known and predetermined durations.
- Unless there is an interruption, activities will not be interrupted.
- The activities cannot begin prior to their scheduled start times.
- Finally, the major aim is to finish the project as quickly as possible.

In this term project, the project's activities are represented by the set {j=1……., J} where 1 represents the dummy node that stands as a source and is placed at the start of the project and J represents as sink and placed at the end, respectively. The non-preemptable duration of the project activities is mentioned by d_j. In addition, the activities are topologically arranged for ease of notation, meaning that each predecessor of the project activity j has a lower number than j. As discussed before, the project activities are connected by precedence and resource constraints. Therefore, it is mentioned that an activity cannot begin until all its predecessors have finished due to the precedence restriction. The set of activity j's immediate predecessors is defined by P_j (Chakrabortty & Sarker, 2018).

Resource constraints occur because activity j needs kk_{jr} units of resources of type r ε R to be processed for each period of its length. Activities might not start at the earliest (precedence-feasible) moment since resource r is only available with the constant period availability of Kr units for each period. Instead, they might start later.

Furthermore, the objective is to decrease the project's lead time by organizing the activities so that precedence and resource limits are respected (Schwarze, 1979).

The time horizon T, which is denoted as the upper bound, is discretized in the formulation for SMRCPSPs. By having a repeated forward and backward recursion with LFTj = T as, for example, a time set [EFTj, LFTj] can be established which contains the earliest and latest finish durations for each project activity j. For SMRCPSP, the Decision variables are defined in the following 0-1 programming model (Pritsker, Waiters, & Wolfe, 1969).

It is described that if the binary decision variable is x_{jt} =1, it means project activity j is successfully completed at the period (t) ending. If x_{jt} =0, the statement will be false. The mathematical model of the single-mode, single-objective resource-constrained project scheduling problem (RCPSP) is formulated as follows:

Objective Function

$$Minimize\ \varphi = \sum_{j=J} \sum_{t=EFTj}^{LFTj} t \,.\, x_{jt} \qquad (3.1)$$

The objective function given in Eq. (3.1) aims to minimize the project makespan (or the completion time of the last or ending activity).

List of Constraints

According to constraint set in Eq. (3.2), each activity should be completed at only single time period within its earliest and latest finishing time interval.

$$\sum_{t=EFTj}^{LFTj} x_{jt} = 1 \qquad j = 1, \ldots, J \qquad (3.2)$$

The constraint set in Eq. (3.3) ensures that the precedence relations between the project activities should be satisfied.

$$\sum_{t=EFTi}^{LFTi} t \,.\, x_{it} \leq \sum_{t=EFTj}^{LFTj} (t - d_j) \,.\, x_{jt} \qquad (i, j) \in P_j \qquad (3.3)$$

The constraint set in Eq. (3.4) corresponds to the capacity limitations of the renewable project resources.

$$\sum_{j=2}^{J} kk_{jr} \,.\, \sum_{s=t}^{t+dj-1} \,.\, x_{js} \leq K_r \qquad r \in R,\ t = 1,..,\ T \quad (3.4)$$

Definition of the binary decision variables:

$$x_{jt} \in \{0,1\} \quad j = 1,..,\ J\ , \quad t = EFT_j,..,\ LFT_j \quad (3.5)$$

Formulation of construction or project-based steel building production projects as a RCPSP

The following steps may need to consider while formulating the project-based production projects as RCPSP.

- The main objective function is to reduce the activities completion time and, as a result, the minimizing the project's duration.
- Second, the activity constraint function ensures that each activity is given a specific end time that fits inside its time limit.
- Third, precedence constraint ensures relationships among each pair of activities (i, j), also i comes right away j.
- Lastly, resource constraint restricts the usage of the total resource for each period to the amount that is available.

In present days, steel construction or building fabrication projects face a lot of challenges such as delays happen due to the lack of resources, late arrival of materials, and estimation errors that may affect the project's progress. Whatever the reasons happen, the project manager needs to estimate them during the scheduling and planning phase of a project. There are various methods or algorithms that are discussed in the literature to minimize such effects. This study's aim is to identify the resource problem that companies such as especially construction companies working on building, bridge construction, highways projects, and steel fabrication projects encounter during the project phase and formulate them as SMRCPSP. When one of the effective, currently used algorithms such as the SMRCPSPs algorithm is applied to the problem which has finite resources, the outcome will assist the engineers in deciding how to schedule the tasks for project execution, ensuring that total durations are kept to a minimum even when the available resources are limited in excess. Thus, such algorithms outcomes may make it less common for construction companies or enterprises to give up on their projects and will help to finish their projects before deadlines (Adamu, Abass, & Okafor, 2007).

CHAPTER 4
A REAL-LIFE APPLICATION IN THE SEISMIC ISOLATOR PRODUCTION PROJECT

4.1 Background

Installing the isolation devices under a structure can protect it from large-scale earthquakes using the seismic isolation technique. Usually, most earthquakes happen due to tectonic plates colliding with each other. The effects of ground motion caused by the interaction of tectonic plates are terrible and devastating. For instance, on March 11, 2011, the Great East Japan Earthquake occurred. Northeastern Japan was hit by a magnitude 9.0 earthquake and a fierce tsunami that left extensive devastation in its wake. It is mentioned that more than 15,000 people lost their lives during Great East Japan Earthquake (Nakamura & Okada, 2019). Therefore, the priority in every earthquake is to preserve people's lives. Moreover, the protection of people's assets, properties, and other public and private infrastructures is also mandatory to maintain economic activities. In fact, People's daily lives become challenging if economic activities are interrupted or collapse as a result of an earthquake, which would also disturb post-disaster rehabilitation. Therefore, proper seismic isolation is required in structures especially that lie in an earthquake zone.

In structural engineering, seismic isolation is a technique used to protect against the effects of earthquakes on structures, hospitals, and highly risky buildings such as nuclear plants and LNG tanks. Furthermore, it is also called a passive control technique that reduces the force of seismic activity by using flexible bearings. Seismic isolators are one of the most important isolation systems. In addition, seismic isolators have been used all over the world for the past 30 years to enhance the capacity of buildings, nonstructural elements, and components from the destructive effects of seismic forces (Polat, 2017). There are various types of seismic isolators depending on the structure's needs. This study examines the use of lead core elastomeric seismic isolators in a building project which is one of the famous types of seismic isolators.

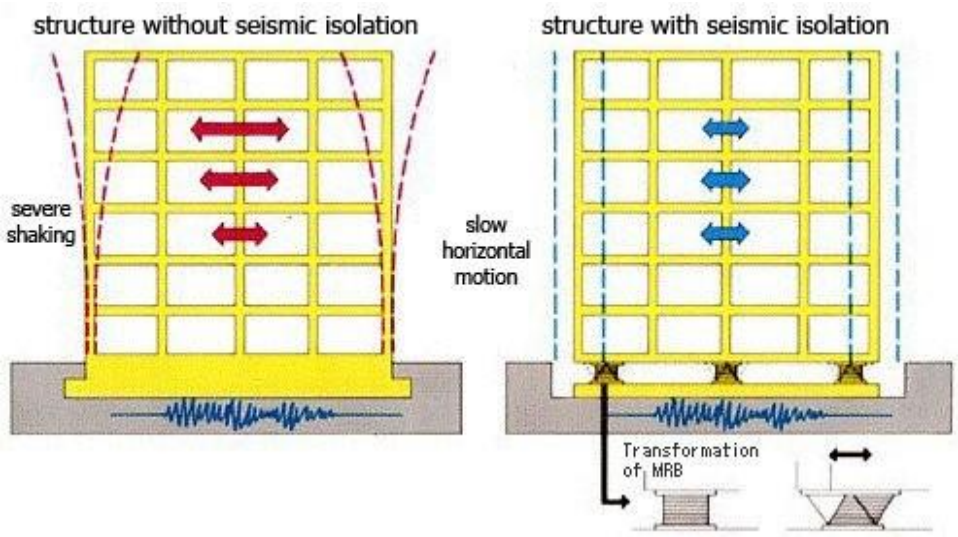


Figure 4.1 The building with and without seismic isolators (Polat, 2017)

4.2 Lead core elastomeric seismic isolators

Lead core elastomeric seismic isolators have three major components: laminated steel plates, a lead core, and elastomer (i.e., rubber). The inner laminated plates enhance the vertical stiffness of the isolator to overcome the structural loads. The elastomer allows deformation and flexibility to handle the structure rotations, and axial and shear deformations. The lead core acts as a absorber component which provides damping by deformation during a seismic shock and it is arranged in the center of the isolator (Warn, 2012). Indeed, the elastomeric isolator which only has more than one layer of thin rubber sheets and inner plates has a very low horizontal stiffness. It can considerably minimize the shaking of the structure. The seismic isolation approach is now practical because of the development of lead-core elastomeric isolators. In such isolators, due to energy-absorbing components, higher horizontal stiffness can be achieved and are more effective for decreasing the accelerations in the buildings during an earthquake (Nakamura, & Okada, 2019).

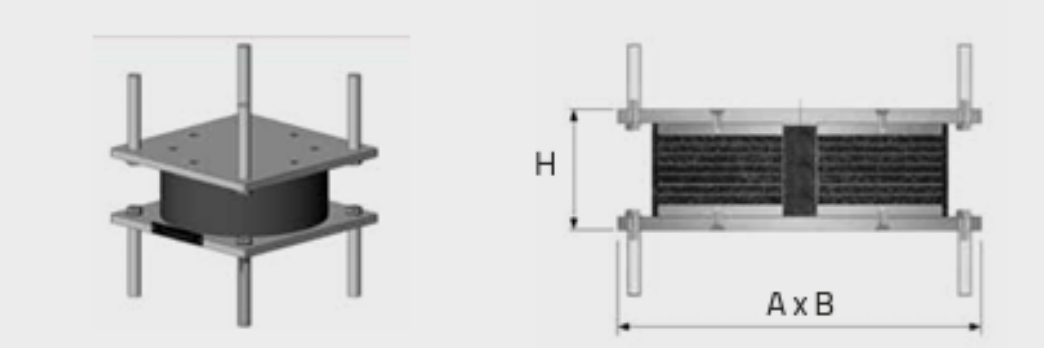


Figure 4.2 The lead core seismic isolator (Maurer, 2018)

4.3 Project details

In this term project, application of resource-constrained project scheduling and planning in a real-life seismic isolator production project will be represented by using a mathematical programming approach. The lead core elastomeric seismic isolators will be used in a hospital project in Greece to enhance the building capacity against seismic forces. A total of 130 isolators will be delivered. Isolators will be manufactured by Maurer which is already experienced in the production of seismic isolators. Moreover, the company also manufactures various kinds of bridge joints, structural bearings, restraint systems, bridge dampers, vibration absorbers, and isolation devices. The company was founded in 1876 in Germany and more than 1000 employees are working in various locations of the world including China, Russia, Germany, and Turkey (Maurer, 2022).

In the manufacturing of lead core elastomeric isolators, various production activities are involved. To perform these activities machinery and manpower such as CNC for milling, tapping machines for drilling and lathing, plasma cutters for cutting steel plates, coating equipment for coating, and welding machines for welding steel components are the major sources. Furthermore, manpower is defined as the number of workers and machinery requirements as hours. The required data for the activities including durations and hours have been taken from the manufacturing company. All-necessary activity details such as activity descriptions, required durations, and resources are mentioned in table. In Figure 4.4, precedence relationship among

activities is represented by using AON network technique. To get optimized results, optimization software called LINGO 17.0 is used on Dell inter-core i5 computer.

Table 4.1 The project data (i.e., project activities, their durations, precedence relations and resource requirements) for the production process of the seismic isolators

Production Plan of the Seismic Isolators											
Acitivity	Activity Description	Durations (Days)			Machinery Req. (Hours)			Manpower Req.			Dependence (Immediate predecessors)
		Optimistic	Pessimistic	Most likely	Optimistic	Pessimistic	Most likely	Optimistic	Pessimistic	Most likely	
1	Dummy Activity (Start)	0	0	0	0	0	0	0	0	0	-
2	Plasma arc cutting of steel plates and other production required components	4	5	4	24	30	27	2	4	3	1
3	Lead core cutting & lathing	1	2	2	7	12	10	1	2	2	1
4	Production parts milling at CNC milling machine	2	4	3	16	20	18	2	3	3	2
5	Sandblasting	1	2	2	6	9	8	1	2	2	4
6	Drilling in steel outer plates & in other steel components	2	3	2	15	20	18	1	3	2	5
7	First assembly (outer steel plates fabrication)	3	4	4	20	25	23	3	5	4	6
8	Coating of laminated reinforcement steel plates	2	4	3	18	27	23	2	4	3	5
9	Tapped holes drilling in outer reinforcement plates	1	2	2	12	15	14	1	3	2	8
10	First assembly coating (outer steel plates fabrication)	3	4	3	35	40	38	2	3	3	7
11	Rubber Processing and shaping at fabricator	5	8	7	40	50	45	4	5	5	1
12	Cutting of rubber layers	3	6	4	18	22	20	4	6	5	11
13	Second assembly (Bearing fabrication)	2	3	2	9	11	10	3	4	4	3,9,12
14	Bearing Vulcanization	6	8	7	55	65	60	5	6	6	13
15	Static & dynamic testing	3	7	5	38	50	44	2	3	3	14
16	Final Assembly	3	5	4	10	12	11	3	5	4	10,15
17	Quality control	2	3	2	6	7	7	2	3	3	16
18	Packing	1	2	2	4	5	5	1	2	2	17
19	Dummy Activity (End)	0	0	0	0	0	0	0	0	0	18

Table 4.2 The earliest and latest finishing times of the project activities under pessimistic, most likely and optimistic scenarios

Early Finish and Late Finish Durations of Project Activities									
Activities	Optimistic			Pessimistic			Most likely		
	Durations (Days)	Early Finish Time (EFT)	Latest Finish Time(LFT)	Durations (Days)	Early Finish Time (EFT)	Latest Finish Time(LFT)	Durations (Days)	Early Finish Time (EFT)	Latest Finish Time(LFT)
1	0	0	16	0	0	26	0	0	21
2	4	4	27	5	5	45	4	4	36
3	1	1	24	2	2	40	2	2	32
4	2	6	29	4	9	49	3	7	39
5	1	7	30	2	11	51	2	9	41
6	2	9	32	3	14	54	2	11	43
7	3	12	35	4	18	58	4	15	47
8	2	9	29	4	15	49	3	12	39
9	1	10	27	2	17	45	2	14	36
10	3	15	38	4	22	62	3	18	50
11	5	5	21	8	8	34	7	7	28
12	3	8	24	6	14	40	4	11	32
13	2	12	26	3	20	43	2	16	34
14	6	18	35	8	28	55	7	23	45
15	3	21	38	7	35	62	5	28	50
16	3	24	41	5	40	67	4	32	54
17	2	26	43	3	43	70	2	34	56
18	1	27	44	2	45	72	2	36	58
19	0	27	44	0	45	72	0	36	58

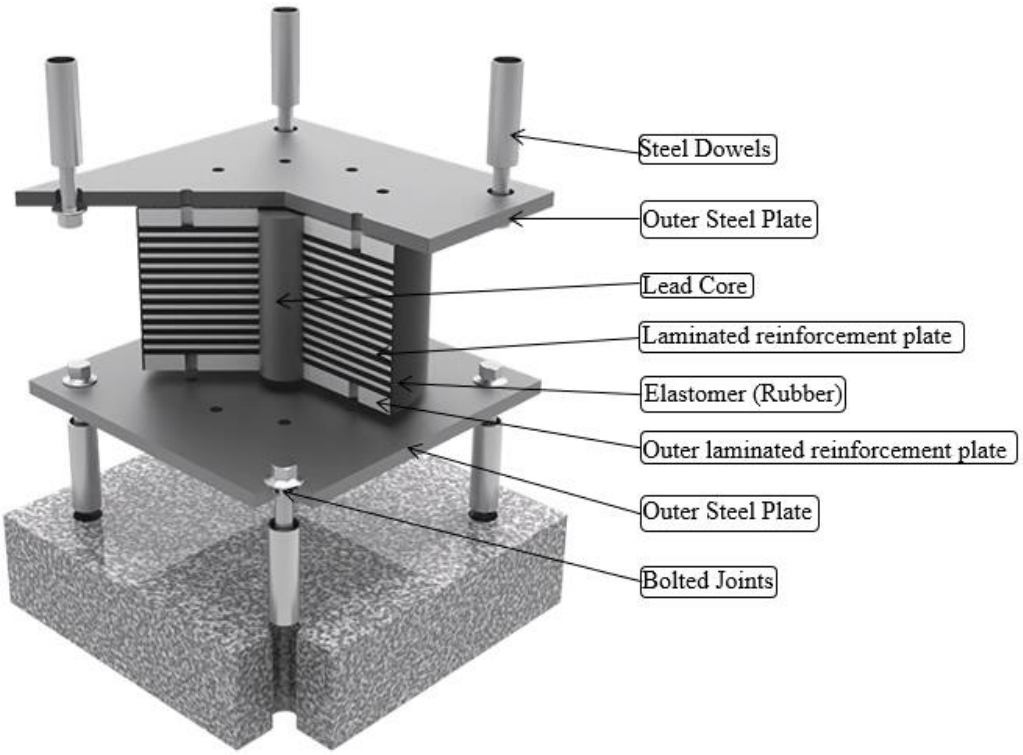


Figure 4.3 A detailed view of the lead core seismic isolator (Losanno, 2019)

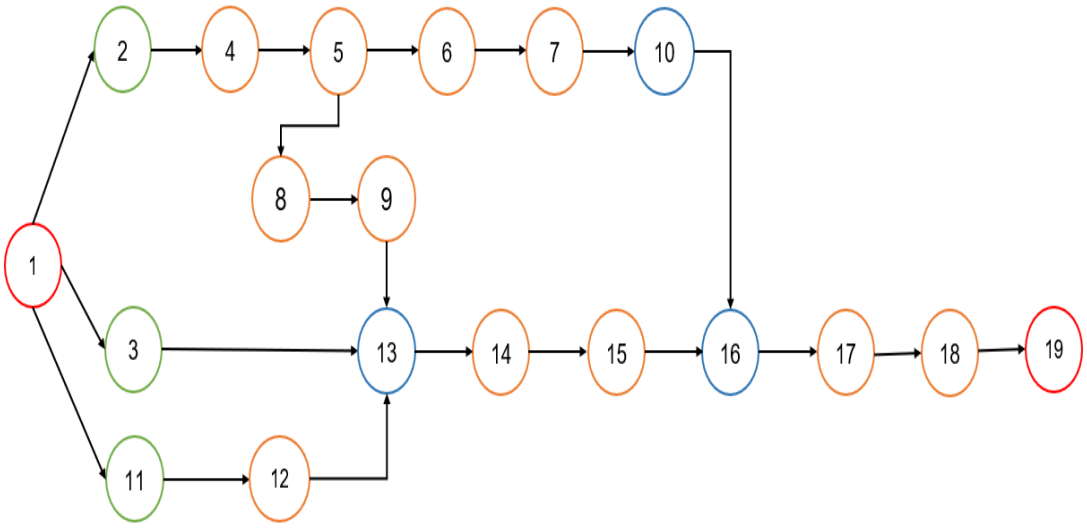


Figure 4.4 The AON project network diagram for the precedence relations among the project activities or production operations of the seismic isolators

CHAPTER 5
OPTIMIZATION RESULTS AND DISCUSSIONS

As discussed before in this term project, we consider the crisp and fuzzy single-mode resource-constrained project scheduling problem. The objective is to minimize the project completion time. Initially, the project activities are determined by using three cases: optimistic, Most Likely, and Pessimistic. Manpower and machinery requirements for each case are mentioned in Table 4.1. Moreover, durations, early finish times, and late finish times for each case activity are mentioned in Table 4.2. Later, each case is formulated separately on the Lingo optimization program, and the results are evaluated. In the below descriptions, the detailed results and evaluations for each case have been discussed.

5.1 Deterministic project scheduling via integer programming approach by considering crisp completion times:

5.1.1 Optimistic scenario

For the optimistic case, the resource constraints are mentioned in the below table:

Table 5.1. The list of resource limitations for the optimistic scenario.

Resource Constraints		
Resource	Capacity	Units
R1 (Machinery)	90	hours
R2 (Manpower)	12	man required

Table 5.2 The deterministic optimization results provided by LINGO optimization software for the optimistic scenario.

Activity	Completion Time	Activity	Completion Time
1	0	11	5
2	4	12	8
3	2	13	12
4	6	14	18
5	7	15	21
6	9	16	24
7	13	17	26
8	9	18	27
9	10	19	27
10	16		

5.1.1.1 Resource profiles and Gantt charts for the optimistic case

The optimal project schedule of the optimistic case are represented in below Gantt charts for the machinery and manpower resources:

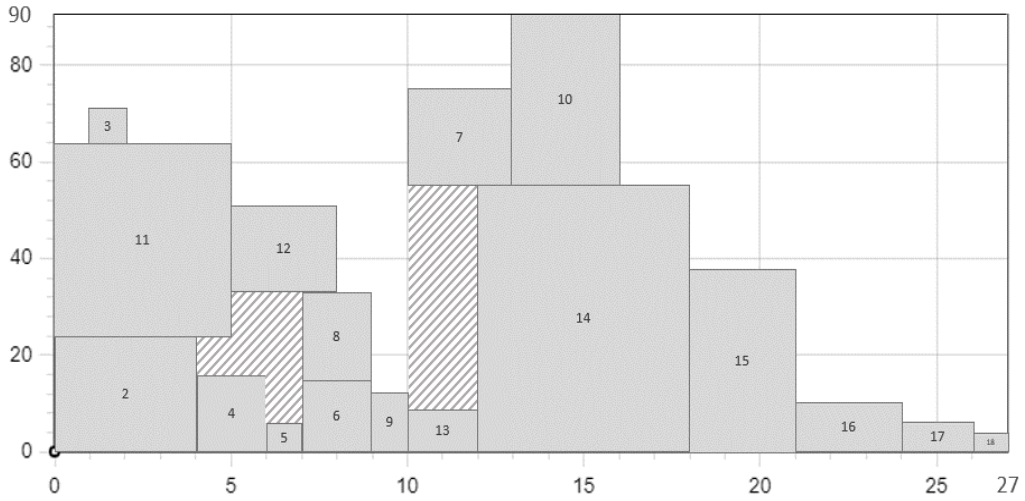


Figure 5.1 Machinery resource profile for the optimal schedule of the optimistic case

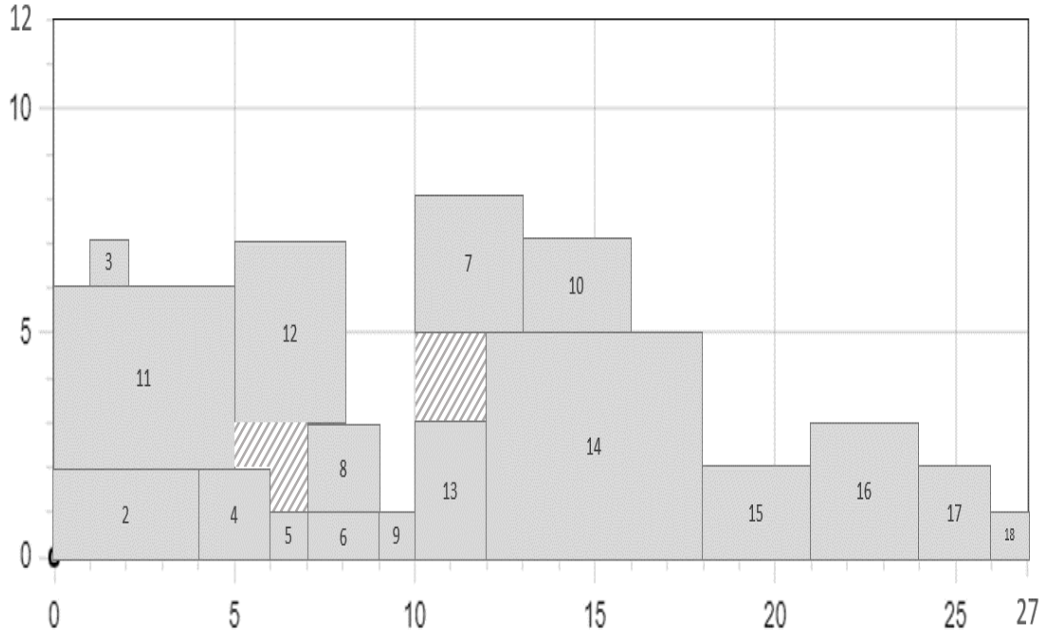


Figure 5.2 Manpower resource profile for the optimal schedule of the optimistic case

5.1.2 Most likely scenario

For the most likely case, the resource constraints are mentioned in the below given table:

Table 5.3 The list of resource limitations for the most likely scenario

Resource Constraints		
Resource	Capacity	Units
R1 (Machinery)	82	hours
R2 (Manpower)	11	man required

Table 5.4 The deterministic optimization results provided by LINGO optimization software for the most likely scenario

Activity	Completion Time	Activity	Completion Time
1	0	11	7
2	4	12	11
3	4	13	16
4	7	14	23
5	9	15	28
6	11	16	32
7	15	17	34
8	12	18	36
9	14	19	36
10	26		

5.1.2.1 Resource profiles and Gantt charts for the most likely case

The optimal project schedule of the most likely case are represented in the below Gantt charts for the machinery and manpower resources:

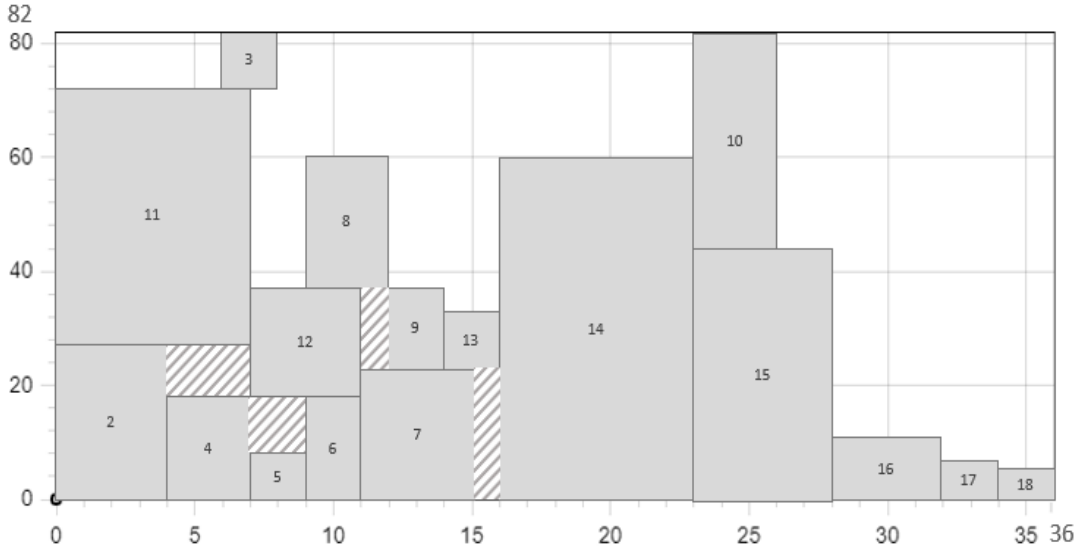


Figure 5.3 Machinery resource profile for the optimal schedule of the most likely case.

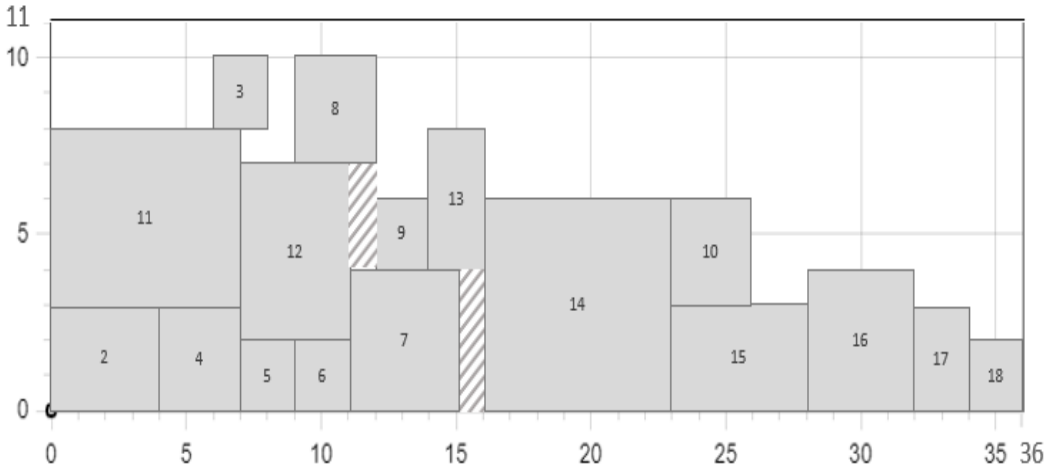


Figure 5.4 Manpower resource profile for the optimal schedule of the most likely case

5.1.3 Pessimistic scenario

For the pessimistic case, the resource constraints are mentioned in the below given table:

Table 5.5 The list of resource limitations for the pessimistic scenario

Resource Constraints		
Resource	Capacity	Units
R1 (Machinery)	75	hours
R2 (Manpower)	10	man required

Table 5.6 The deterministic optimization results provided by LINGO optimization software for the pessimistic scenario

Activity	Completion Time	Activity	Completion Time
1	0	11	13
2	5	12	19
3	4	13	22
4	9	14	30
5	11	15	37
6	33	16	46
7	37	17	49
8	17	18	51
9	19	19	51
10	41		

5.1.3.1 Resource profiles and Gantt charts for the pessimistic case:

The optimal project schedule of the pessimistic case are represented in the below Gantt graphs for the machinery and manpower resources:

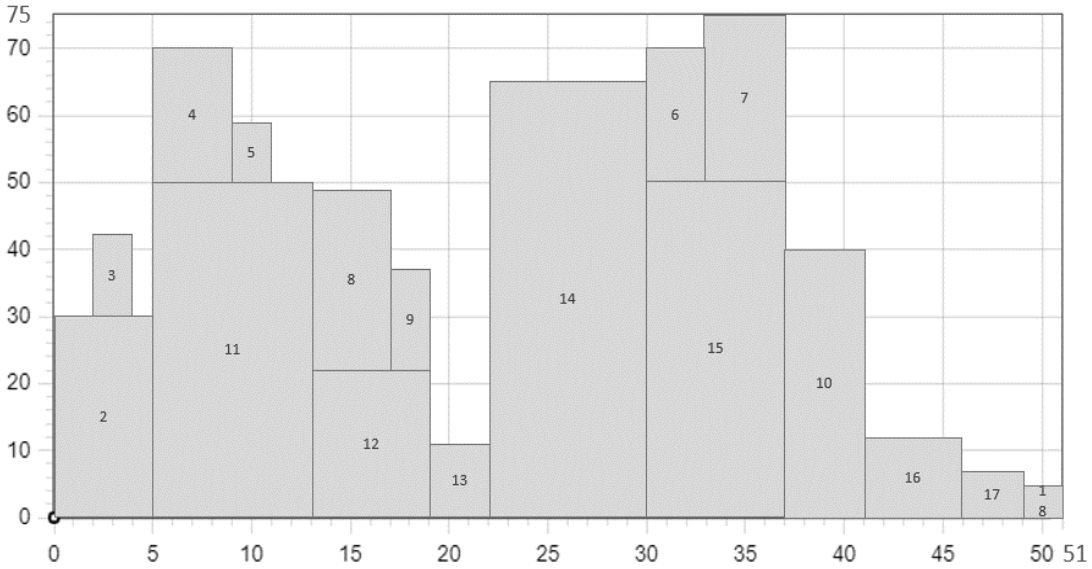


Figure 5.5 Machinery resource profile for the optimal schedule of the pessimistic case

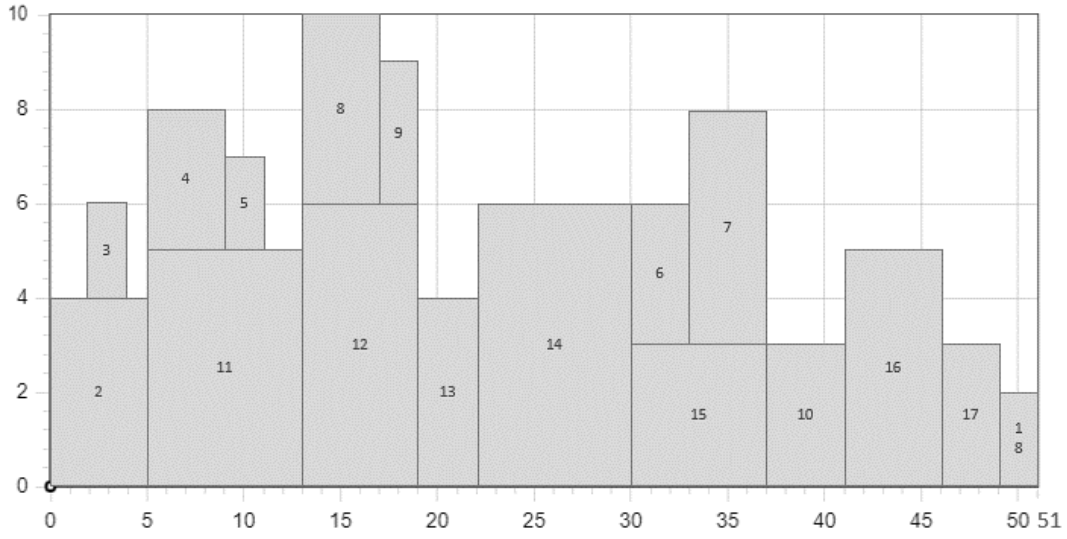


Figure 5.6 Manpower resource profile for the optimal schedule of the pessimistic case

5.2 Deterministic project scheduling via constraint programming approach by considering crisp completion times

In addition to the previously mentioned integer programming model of the examined RCPSP, we also used the constraint programming method as an alternative solution approach to provide further comparisons. To do this, the optimistic, most likely, and pessimistic cases are also solved separately by using constraint programming (CP) model which is coded in IBM ILOG CPLEX optimization studio. The same optimization results are provided via the constraint programming model as presented in Table 5.8 and Figures 5.7, 5.8, 5.9.

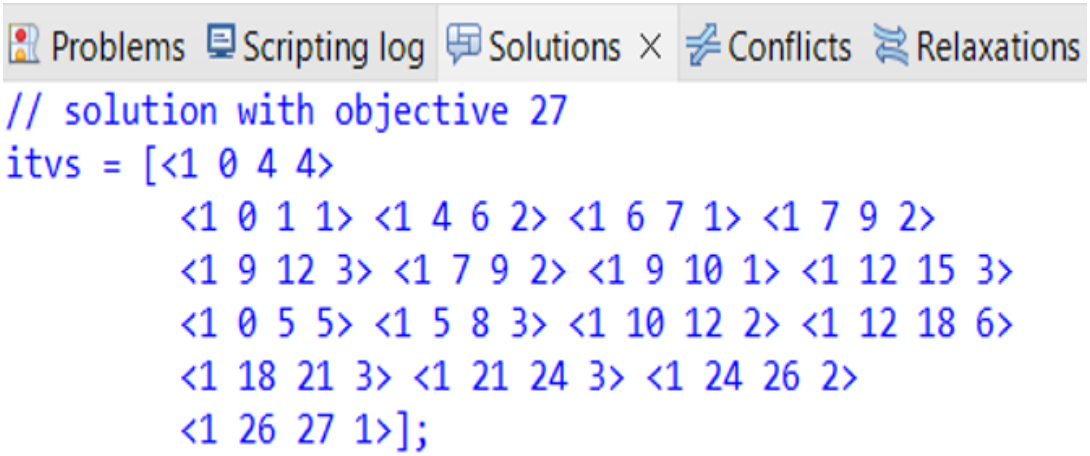


Figure 5.7 ILOG CPLEX optimization studio project scheduling results of the optimistic case

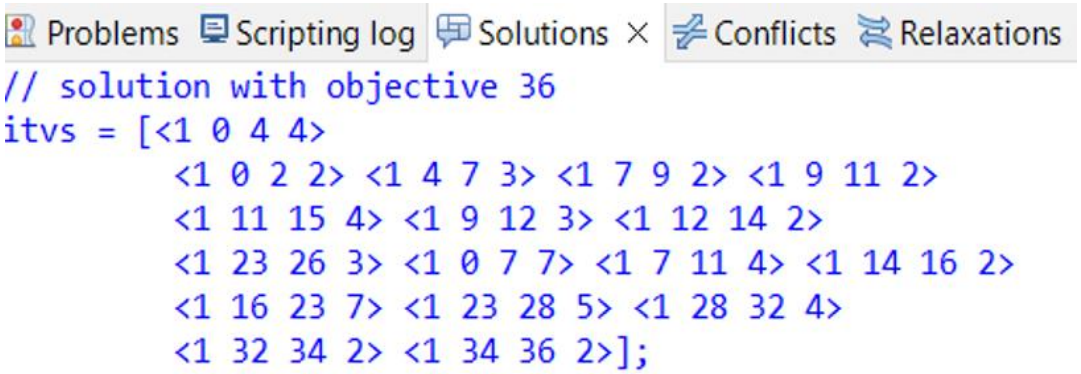


Figure 5.8 ILOG CPLEX optimization studio project scheduling results of most likely case

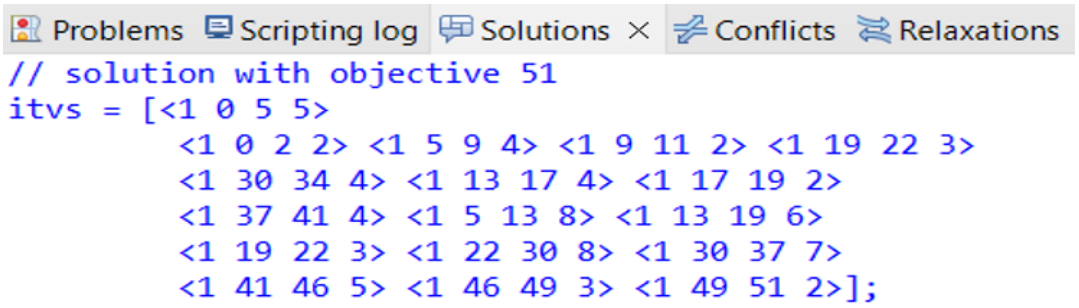


Figure 5.9 ILOG CPLEX optimization studio project scheduling results of pessimistic case

Table 5.7 The project schedules under different scenarios provided by the constraint programming model coded in IBM ILOG CPLEX Optimization studio

Activities	**Optimistic Case**	**Most Likely Case**	**Pessimistic Case**
1(dummy)	-	-	-
2	4	4	5
3	1	2	2
4	6	7	9
5	7	9	11
6	9	11	22
7	12	15	34
8	9	12	17
9	10	14	19
10	15	26	41
11	5	7	13
12	8	11	19
13	12	16	22
14	18	23	30
15	21	28	37
16	24	32	46
17	26	34	49
18	27	36	51
19(dummy)	-	-	-

5.3 Project scheduling by considering fuzzy completion times of the activities under different scenarios

In this part of the term project, the previously formulated deterministic optimization model is modified by taking into account different probabilistic scenarios for the uncertain project parameters as well as the fuzzy completion times of the project activities. The proposed fuzzy-stochastic optimization model is formulated in the following Eqs. (5.1) – (5.8).

Objective Function

$$Minimize\ z = \sum_{j=J} . \sum_{t=EFTjf}^{LFTjf} . \sum_{f=1}^{3} t.\, x_{jtf} \,.\, prb_f \qquad (5.1)$$

The objective function given in Eq. (5.1) aims to minimize the total expected project duration (or makespan) by considering occurrence probabilities of different scenarios.

List of Constraints

$$\sum_{t=EFTjf}^{LFTjf} x_{jtf} = 1 \qquad j = 1, \ldots, J,\ f \varepsilon F \qquad (5.2)$$

According to the constraint set in Eq. (5.2), each project activity should be completed at an uncertain time interval which is stated as a triangular fuzzy number. In other words, the left right and midpoints of a triangular fuzzy number correspond to the completion times of that project activity under optimistic, pessimistic and most likely scenarios.

$$\sum_{t\,=EFTif}^{LFTif} t \,.\, x_{itf} \leq \sum_{t\,=EFTjf}^{LFTjf} (t - d_{jf}) \,.\, x_{jtf} \qquad (5.3)$$

In Eq. (5.3) $(i, j) \in P_j$ and $f \varepsilon F$. Constraint set in Eq. (5.3) maintains that precedence relations among the project activities have to be satisfied under each scenario. In this constraint, uncertain activity durations are also taken into consideration as probabilistic model parameters.

$$\sum_{j=2}^{J} kk_{jrf} \cdot \sum_{s=t}^{t+djf-1} x_{jsf} \leq K_{rf} \tag{5.4}$$

In Eq. (5.4) $r \in R,\ t = 1,..,\ T$ and $f \varepsilon F$. Constraint set in Eq. (5.4) ensures that capacity limitations of the renewable project resources cannot be exceeded in each scenario. In this constraint, uncertain resource capacities are also stated as probabilistic project parameters similar to the activity durations.

$$\sum_{f=2} \cdot \sum_{t=EFTjf}^{LFTjf} t.\, x_{jtf} \leq \sum_{f=3} \cdot \sum_{t=EFTjf}^{LFTjf} t.\, x_{jtf} \qquad j = 1,\ \ldots,\ J \tag{5.5}$$

$$\sum_{f=1} \cdot \sum_{t=EFTjf}^{LFTjf} t.\, x_{jtf} \leq \sum_{f=2} \cdot \sum_{t=EFTjf}^{LFTjf} t.\, x_{jtf} \qquad j = 1,\ \ldots,\ J \tag{5.6}$$

Constraint sets in Eqs. (5.5) – (5.6) are formulated as logical inequalities for the fuzzy completion times of the project activities. According to constraint set in Eq. (5.5), the midpoint of a triangular fuzzy completion time of any activity should be less than or equal to its right point. In other words, the completion time of any activity under most likely scenario cannot exceed its completion time under pessimistic scenario. Similarly, according to the constraint set in Eq. (5.6), the left point of a triangular fuzzy completion time of any activity should be less than or equal to its midpoint. In other words, the completion time of any activity under optimistic scenario should be less than or equal to its completion time under most likely scenario.

Definition of the binary decision variables:

$$x_{jtf} \in \{0,1\} \quad j = 1,..,\ J,\ \ t = EFT_j,..,\ LFT_j,\ f \varepsilon F \tag{5.7}$$

$$x_{jtf} = 0 \qquad j = 1,\ \ldots,\ J,\ \ f \varepsilon F,\ t \varepsilon T \tag{5.8}$$

In Eq. (5.7), project activities fuzzy completion times are represented as binary integer variables. According to the constraint set in Eq. (5.7), fuzzy completion time of an activity should be within the interval of its earliest and latest finishing times. On the other hand, according to the constraint set in Eq. (5.8), its value must be equal to it doesn't take place in the interval of these earliest and latest finishing times.

5.3.1 The produced optimization results by considering fuzzy activity durations

Table 5.8 Project schedule provided by the solution of the proposed fuzzy-stochastic optimization model through LINGO optimization software

Activities	Completion Time		
	Optimistic Case	Most likely Case	Pessimistic Case
1	0	0	0
2	4	4	5
3	3	8	12
4	6	7	9
5	7	9	11
6	9	11	22
7	12	15	34
8	9	12	17
9	10	14	19
10	16	26	41
11	5	7	13
12	8	11	19
13	12	16	22
14	18	23	30
15	21	28	37
16	24	32	46
17	26	34	49
18	27	36	51
19	27	36	51

When the previously formulated fuzzy-stochastic optimization model is solved by using the LINGO 17.0 optimization software, the above-mentioned fuzzy completion times results are obtained for each project activity under each scenario.

5.3.2 Resource profiles and Gantt charts for only the optimistic case when the fuzzy completion times are considered

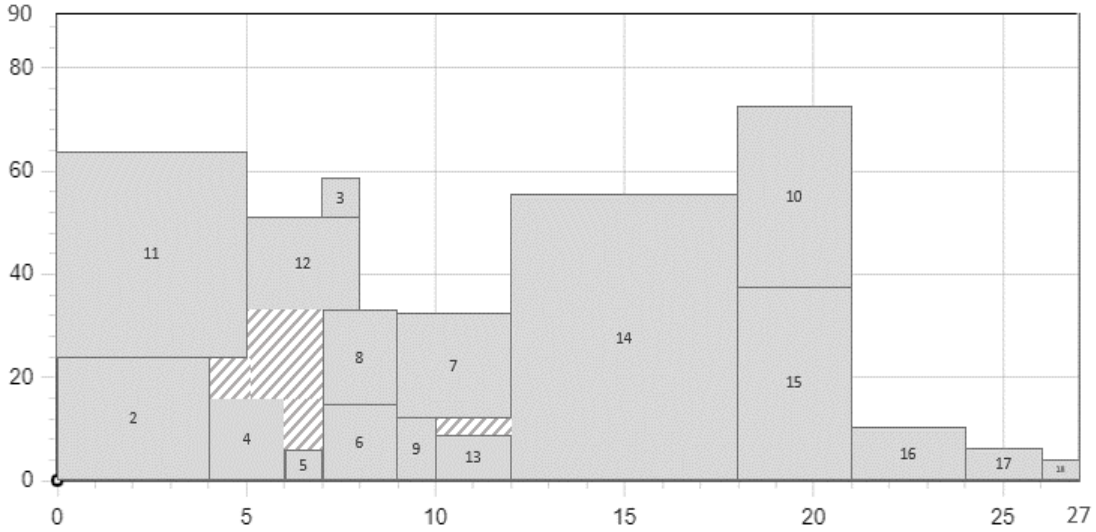


Figure 5.10 Machinery resource profile for the optimal schedule of the optimistic case when the fuzzy completion times are considered

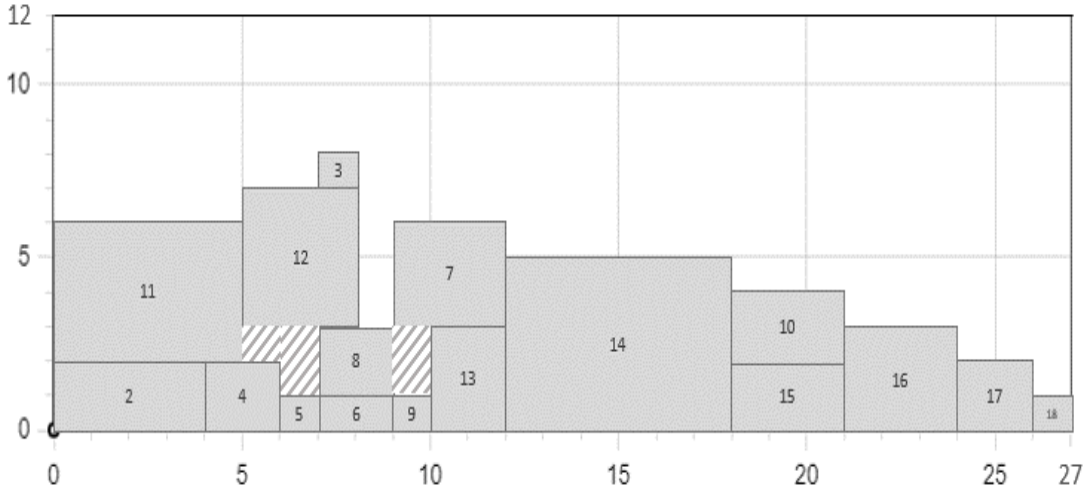


Figure 5.11 Manpower resource profile for the optimal schedule of the optimistic case when the fuzzy completion times are considered

5.3.3 Resource profiles and Gantt charts for only the most likely case when the fuzzy completion times are considered

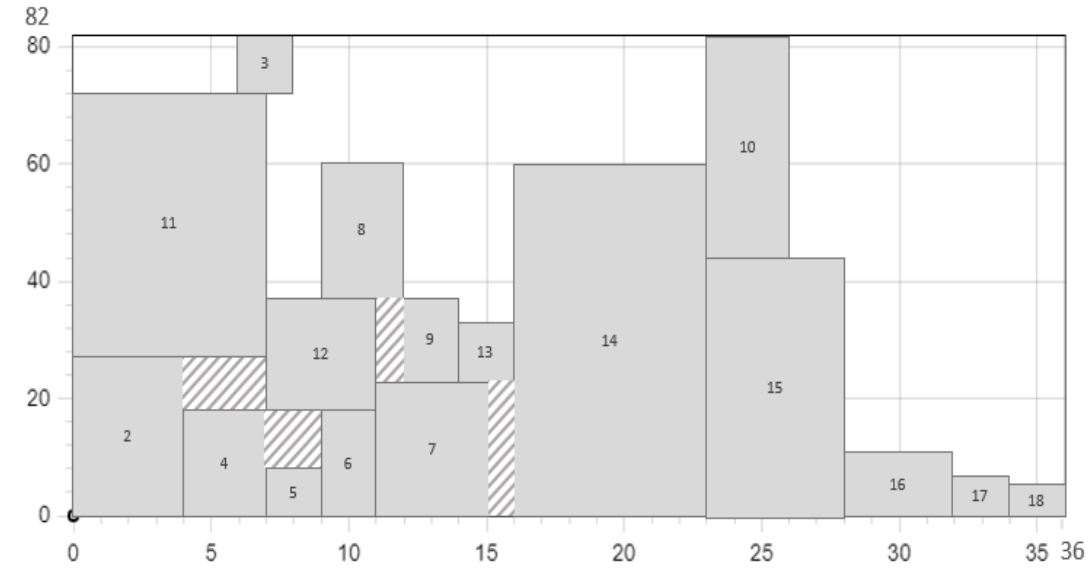


Figure 5.12 Machinery resource profile for the optimal schedule of the most likely case when the fuzzy completion times are considered

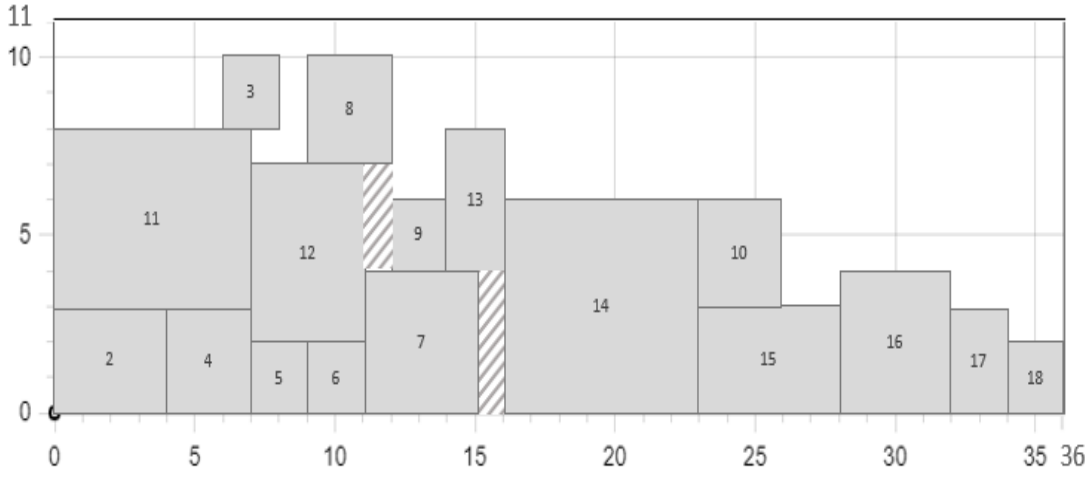


Figure 5.13 Manpower resource profile for the optimal schedule of the most likely case when the fuzzy completion times are considered.

5.3.4 Resource profiles and Gantt charts for only the pessimistic case when the fuzzy completion times are considered:

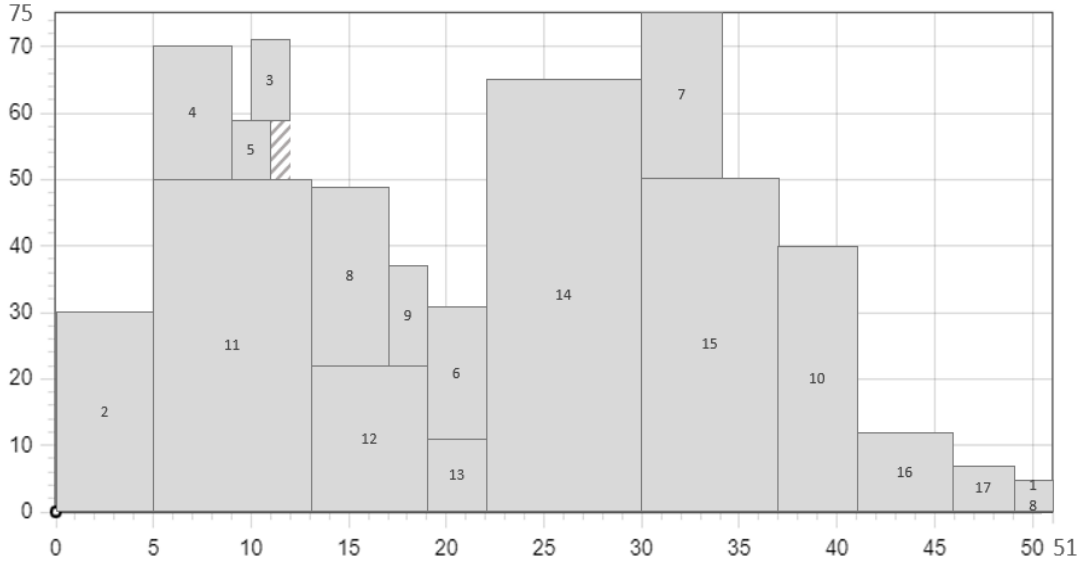


Figure 5.14 Machinery resource profile for the optimal schedule of the pessimistic case when the fuzzy completion times are considered.

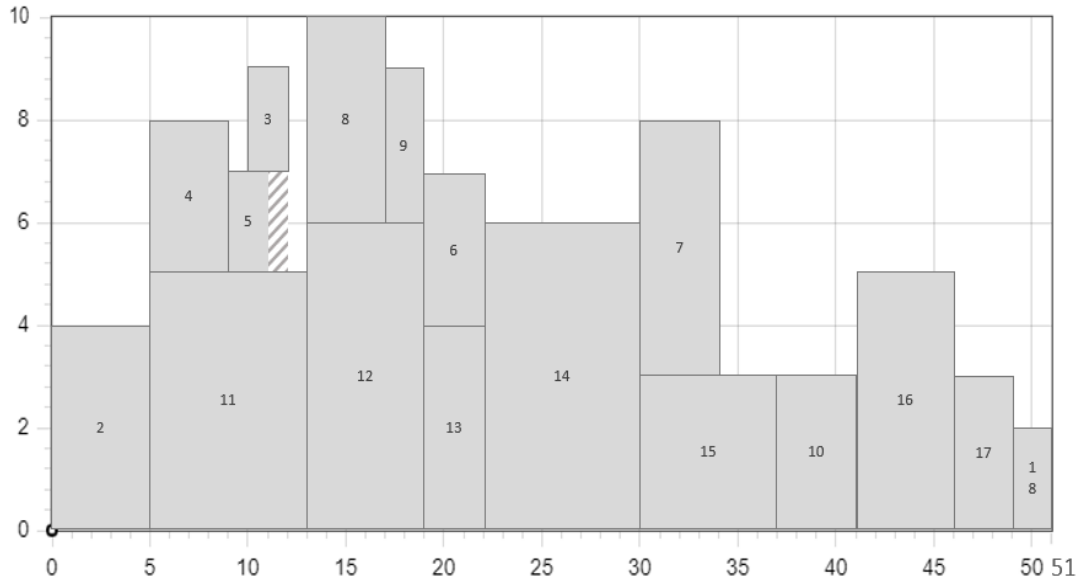


Figure 5.15 Manpower resource profile for the optimal schedule of the pessimistic case when the fuzzy completion times are considered.

5.3.5 Comparison of the optimization results (i.e., project schedules) by considering crisp & fuzzy completion times of the project activities:

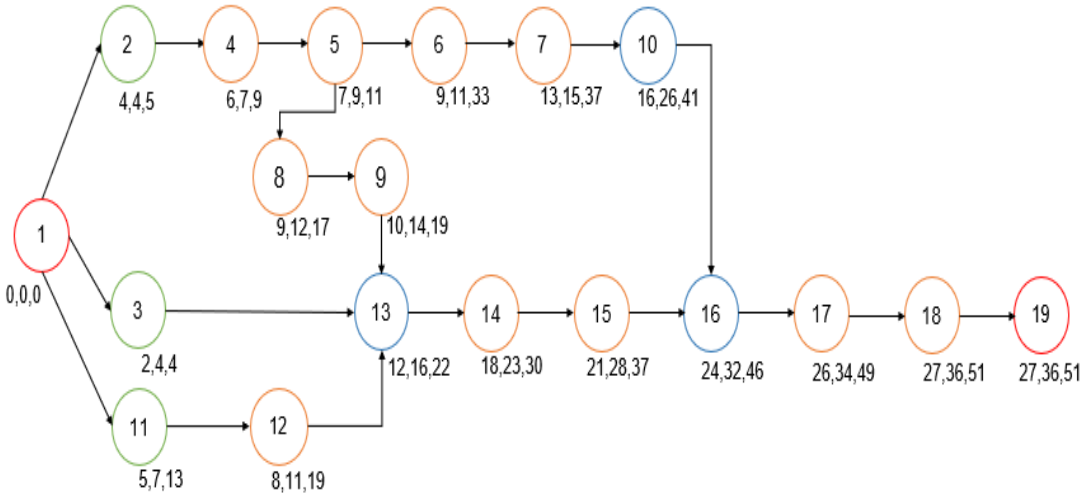


Figure 5.16 Optimization results of the seismic isolator production project scheduling by considering crisp completion times separately under different scenarios

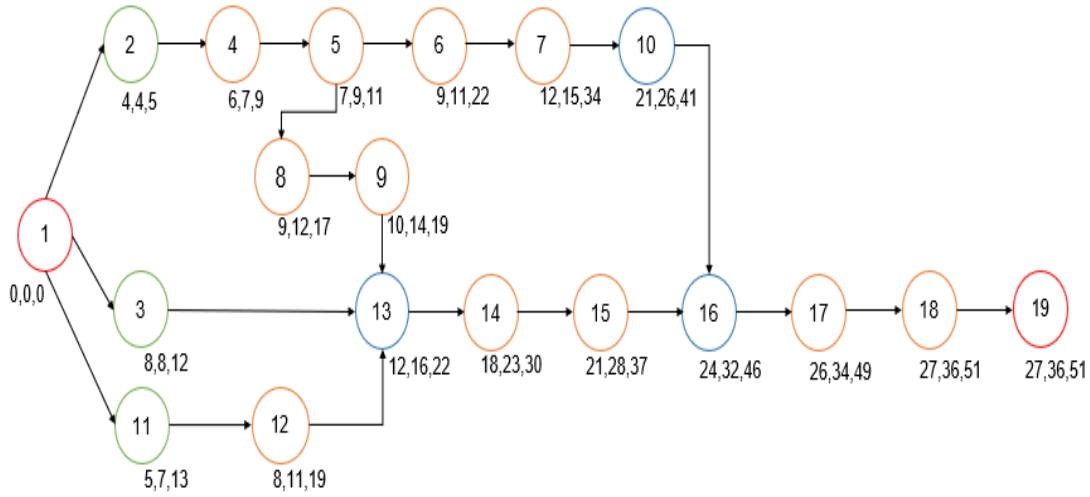


Figure 5.17 Optimization results of the seismic isolator production project scheduling by considering fuzzy completion times in an integrated way (or integration of different scenarios in a single optimization model)

5.3.6 Scenario analysis by having different probabilities

Scenario 1

Table 5.9 Scenario 1 probability values for optimistic, most likely, and pessimistic cases

Optimistic Case Probability	Most likely Case Probability	Pessimistic Case Probability
0.4	0.4	0.2

Table 5.10 completion times for project scheduling by scenario 1 probability values

Activities	Completion Time		
	Optimistic Case	Most likely Case	Pessimistic Case
1	0	0	0
2	4	4	5
3	4	13	13
4	6	7	9
5	7	9	11
6	9	11	22
7	12	15	35
8	9	12	17
9	10	14	19
10	21	26	41
11	5	7	13
12	8	11	19
13	12	16	22
14	18	23	30
15	21	28	37
16	24	32	46
17	26	34	49
18	27	36	51
19	27	36	51

Scenario 2

Table 5.11 Scenario 2 probability values for optimistic, most likely, and pessimistic cases

Optimistic Case Probability	Most likely Case Probability	Pessimistic Case Probability
0.2	0.4	0.4

Table 5.12 completion times for project scheduling by having scenario 2 probability values

Activities	Completion Time		
	Optimistic Case	Most likely Case	Pessimistic Case
1	0	0	0
2	4	4	5
3	1	2	12
4	6	7	9
5	7	9	11
6	9	11	22
7	12	15	34
8	9	12	17
9	10	14	19
10	18	26	41
11	5	7	13
12	8	11	19
13	12	16	22
14	18	23	30
15	21	28	37
16	24	32	46
17	26	34	49
18	27	36	51
19	27	36	51

Scenario 3

Table 5.13 Scenario 3 probability values for optimistic, most likely, and pessimistic cases

Optimistic Case Probability	Most likely Case Probability	Pessimistic Case Probability
0.2	0.5	0.3

Table 5.14 completion times for project scheduling by having scenario 3 probability values

Activities	Completion Time		
	Optimistic Case	Most likely Case	Pessimistic Case
1	0	0	0
2	4	4	5
3	1	2	7
4	6	7	9
5	7	9	11
6	9	11	22
7	12	15	35
8	9	12	17
9	10	14	19
10	21	26	41
11	5	7	13
12	8	11	19
13	12	16	22
14	18	23	30
15	21	28	37
16	24	32	46
17	26	34	49
18	27	36	51
19	27	36	51

Scenario 4

Table 5.15 Scenario 4 probability values for optimistic, most likely, and pessimistic cases

Optimistic Case Probability	Most likely Case Probability	Pessimistic Case Probability
0.3	0.4	0.3

Table 5.16 completion times for project scheduling by having scenario 4 probability values

Activities	Completion Time		
	Optimistic Case	Most likely Case	Pessimistic Case
1	0	0	0
2	4	4	5
3	4	5	5
4	6	7	9
5	7	9	11
6	9	11	22
7	12	16	34
8	9	12	17
9	10	14	19
10	15	26	41
11	5	7	13
12	8	11	19
13	12	16	22
14	18	23	30
15	21	28	37
16	24	32	46
17	26	34	49
18	27	36	51
19	27	36	51

Scenario 5

Table 5.17 Scenario 5 probability values for optimistic, most likely, and pessimistic cases.

Optimistic Case Probability	Most likely Case Probability	Pessimistic Case Probability
0.3	0.3	0.4

Table 5.18 completion times for project scheduling by having scenario 5 probability values

Activities	Completion Time		
	Optimistic Case	Most likely Case	Pessimistic Case
1	0	0	0
2	4	4	5
3	1	2	12
4	6	7	9
5	7	9	11
6	9	11	22
7	12	15	36
8	9	12	17
9	10	14	19
10	17	28	41
11	5	7	13
12	8	11	19
13	12	16	22
14	18	23	30
15	21	28	37
16	24	32	46
17	26	34	49
18	27	36	51
19	27	36	51

In scenario analysis, optimistic, most likely, and pessimistic cases were also examined by having different probabilities on Lingo optimization software. For this purpose, the different scenarios are developed depending on different probabilities and their results are discussed in the above-mentioned tables. It is observed that in all scenarios, the total project durations for all cases were remained same. However, the change in optimized durations at different activities were observed from optimization results.

CHAPTER 6
CONCLUSIONS AND FUTURE WORKS

To summarize, a resource-constrained project scheduling problem (RCPSP) has been discussed in this term project. The objective of this term project is to minimize the total project duration of a seismic isolator production project which has limited resources such as manpower and machinery. For this purpose, the mathematical programming approaches (i.e., integer programming model, constraint programming model, and fuzzy-stochastic optimization model) are used to deal with a real-life resource-constrained project scheduling problem. Thereafter, since most of the real-life project scheduling problems may involve uncertainties in the activity durations and resource availabilities, we also proposed a fuzzy-stochastic optimization model to cope with these uncertainties or dynamic conditions under different scenarios, i.e., optimistic, most likely, and pessimistic cases. Under different scenarios, by applying the aforementioned mathematical programming approaches, the total project duration or makespan is minimized while having limited resource capacities. The optimization results which are provided by making use of LINGO and IBM ILOG OPL CPLEX optimization studio are also compared and presented to the project managers of the seismic isolator manufacturing company to give a deep managerial insight.

As mentioned previously, the constraint programming model of the examined problem is only solved for different scenarios in a separate way. In the future, the constraint programming model of the stated problem can also be developed for the fuzzy-stochastic RCPSP problem by considering these scenarios in an integrated way. Moreover, several variants of the RCPSP such as multi-mode RCPSP, and multi-project scheduling problems can also be formulated by considering uncertain project parameters/data as well as the uncertain project schedules (i.e., fuzzy, stochastic, or fuzzy-random completion times of the project activities) (Ipsilandis, 2007). Future works may also include developing multi-objective mathematical models for more than only one project objective rather than project makespan (i.e., maximizing the utilization rate of the resources, etc.).

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APPENDICES

Appendix A. LINGO Code of the deterministic optimization model (Integer programming) of the RCPSP

```
Sets:
activity/1..19/:d,eft,lft;
period/1..44/;
resource/1..2/:K;
derived1(activity,period):x;
derived2(activity,resource):kk;
precedence(activity,activity)/1 2, 1 3, 1 11, 2 4, 3 13, 4 5, 5 6, 5
8, 6 7, 7 10, 8 9, 9 13, 10 16, 11 12, 12 13, 13 14, 14 15, 15 16, 16
17, 17 18, 18 19/;
endsets
data:
d=0,4,1,2,1,2,3,2,1,3,5,3,2,6,3,3,2,1,0;
kk=0,0,24,2,7,1,16,2,6,1,15,1,20,3,18,2,12,1,35,2,40,4,18,4,9,3,55,5
,38,2,10,3,6,2,4,1,0,0;
K=90,12;
eft=0,4,1,6,7,9,12,9,10,15,5,8,12,18,21,24,26,27,27;
lft=16,27,24,29,30,32,35,29,27,38,21,24,26,35,38,41,43,44,44;
enddata

!(1);Min=@sum(activity(j)|j#eq#19:@sum(period(t)|t#ge#eft(j)#and#t#l
e#lft(j):t*x(j,t)));
!Subject to;
!(2);@for(activity(j):@sum(period(t)|t#ge#eft(j)#and#t#le#lft(j):x(j
,t))=1);
!(3);@for(precedence(i,j):@sum(period(t)|t#ge#eft(i)#and#t#le#lft(i)
:t*x(i,t))<=@sum(period(t)|t#ge#eft(j)#and#t#le#lft(j):(t-
d(j))*x(j,t)));
!(4);@for(resource(r):@for(period(t):@sum(activity(j)|j#ge#2#and#j#l
t#19:kk(j,r)*@sum(period(s)|s#ge#t#and#s#le#(t+d(j)-
1):x(j,s)))<=K(r)));
!(5);@for(activity(j):@for(period(t)|t#ge#eft(j)#and#t#le#lft(j):@bi
n(x(j,t))));
```

Appendix B. IBM ILOG CPLEX Optimization Studio code of the constraint programming model of the deterministic RCPSP

```
NbTasks=17;

NbRsrcs=2;

Capacity=[90 12];

Tasks={<1,4,[24,2],{3,4,5,6,9,7,8,12,13,14,15,16,17}>,

<2,1,[7,1],{12,13,14,15,16,17}>,

<3,2,[16,2],{4,5,6,9,7,8,12,13,14,15,16,17}>,

<4,1,[6,1],{5,6,9,7,8,12,13,14,15,16,17}>,

<5,2,[15,1],{6,9,15,16,17}>,

<6,3,[20,3],{9,15,16,17}>,

<7,2,[18,2],{8,12,13,14,15,16,17}>,

<8,1,[12,1],{12,13,14,15,16,17}>,

<9,3,[35,2],{15,16,17}>,

<10,5,[40,4],{11,12,13,14,15,16,17}>,

<11,3,[18,4],{12,13,14,15,16,17}>,

<12,2,[9,3],{13,14,15,16,17}>,

<13,6,[55,5],{14,15,16,17}>,

<14,3,[38,2],{15,16,17}>,

<15,3,[10,3],{16,17}>,

<16,2,[6,2],{17}>,

<17,1,[4,1],{}>};
```

```
using CP;

int NbTasks = ...;

int NbRsrcs = ...;

range RsrcIds = 1..NbRsrcs;

int Capacity[RsrcIds] = ...;

tuple Task {

   key int id;

   int pt;

   int dmds[RsrcIds];

   {int} succs;

}

{Task} Tasks = ...;

dvar interval itvs[t in Tasks] size t.pt;

minimize max(t in Tasks) endOf(itvs[t]);

subject to {

 forall(r in RsrcIds)

       sum  (t in Tasks: t.dmds[r]>0) pulse(itvs[t], t.dmds[r]) <=
Capacity[r];

 forall(t1 in Tasks, t2id in t1.succs)

       endBeforeStart(itvs[t1],itvs[<t2id>]);

}
```

Appendix C. LINGO code of the fuzzy-stochastic optimization model (Integer programming model) of the RCPSP under uncertainty

```
Sets:
activity/1..19/;
period/1..58/;
resource/1..2/;
fuzzy/1..3/:prb;
set1(activity,fuzzy):d,eft,lft;
set2(resource,fuzzy):K;
derived1(activity,period,fuzzy):x;
derived2(activity,resource,fuzzy):kk;
precedence(activity,activity)/1 2, 1 3, 1 11, 2 4, 3 13, 4 5, 5 6,
5 8, 6 7, 7 10, 8 9, 9 13, 10 16, 11 12, 12 13, 13 14, 14 15, 15 16,
16 17, 17 18, 18 19/;
endsets
data:
d=0,0,0,4,4,5,1,2,2,2,3,4,1,2,2,2,2,3,3,4,4,2,3,4,1,2,2,3,3,4,5,7,
8,3,4,6,2,2,3,6,7,8,3,5,7,3,4,5,2,2,3,1,2,2,0,0,0;
kk=0,0,0,0,0,0,24,27,30,2,3,4,7,10,12,1,2,2,16,18,20,2,3,3,6,8,9,1
,2,2,15,18,20,1,2,3,20,23,25,3,4,5,18,23,27,2,3,4,12,14,15,1,2,3,35,
38,40,2,3,3,40,45,50,4,5,5,18,20,22,4,5,6,9,10,11,3,
4,4,55,60,65,5,6,6,38,44,50,2,3,3,10,11,12,3,4,5,6,7,7,2,3,3,4,5,5
,1,2,2,0,0,0,0,0,0;
K=90,80,75,12,11,10;
eft=0,0,0,4,4,5,1,2,2,6,7,9,7,9,11,9,11,14,12,15,18,9,12,15,10,14,
17,15,18,22,5,7,8,8,11,14,12,16,20,18,23,28,21,28,35,24,32,40,26,34,
43,27,36,45,27,36,45;
lft=16,21,26,27,36,45,24,32,40,29,39,49,30,41,51,32,43,54,35,47,58
,29,39,49,27,36,45,38,50,62,21,28,34,24,32,40,26,34,43,35,45,55,38,5
0,62,41,54,67,43,56,70,44,58,72,44,58,72;
prb=0.3,0.5,0.2;
enddata

!(1);Min=@sum(activity(j)|j#eq#19:@sum(fuzzy(f):@sum(period(t)|t#g
e#eft(j,f)#and#t#le#lft(j,f):(t*x(j,t,f)*prb(f)))));
!Subject to;
!(2);@for(activity(j):@for(fuzzy(f):@sum(period(t)|t#ge#eft(j,f)#a
nd#t#le#lft(j,f):x(j,t,f))=1));
```

```
!(3);@for(precedence(i,j):@for(fuzzy(f):@sum(period(t)|t#ge#eft(i,
f)#and#t#le#lft(i,f):t*x(i,t,f))<=@sum(period(t)|t#ge#eft(j,f)#and#t
#le#lft(j,f):(t-d(j,f))*x(j,t,f))));
!(4);@for(resource(r):@for(period(t):@for(fuzzy(f):@sum(activity(j
)|j#ge#2#and#j#lt#19:kk(j,r,f)*@sum(period(s)|s#ge#t#and#s#le#(t+d(j
,f)-1):x(j,s,f)))<=K(r,f))));
!(5);@for(activity(j):@for(fuzzy(f):@for(period(t):@bin(x(j,t,f)))
));
!(6);@for(activity(j):@for(fuzzy(f):@for(period(t)|t#lt#eft(j,f)#a
nd#t#gt#lft(j,f):x(j,t,f)=0)));

!(7);@for(activity(j):@sum(fuzzy(f)|f#eq#2:@sum(period(t)|t#ge#eft
(j,f)#and#t#le#lft(j,f):t*x(j,t,f)))<=@sum(fuzzy(f)|f#eq#3:@sum(peri
od(t)|t#ge#eft(j,f)#and#t#le#lft(j,f):t*x(j,t,f))));
!(8);@for(activity(j):@sum(fuzzy(f)|f#eq#1:@sum(period(t)|t#ge#eft
(j,f)#and#t#le#lft(j,f):t*x(j,t,f)))<=@sum(fuzzy(f)|f#eq#2:@sum(peri
od(t)|t#ge#eft(j,f)#and#t#le#lft(j,f):t*x(j,t,f))));
```