ABSTRACT

Title of Document: A DECISION SUPPORT SYSTEM FOR DYNAMIC
INTEGRATED PROJECT SCHEDULING AND
EQUIPMENT OPERATION PLANNING

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Common practice in scheduling under limited resource availability is to first schedule activities with the assumption of unlimited resources, and then assign required resources to activities until available resources are exhausted. The process of matching a feasible resource plan with a feasible schedule is called resource allocation. Then, to avoid sharp fluctuations in the resource profile, further adjustments are applied to both schedule and resource allocation plan within the limits of feasibility constraints. This process is referred to as resource leveling in the literature. Combination of these three stages constitutes the standard approach of top-down scheduling.

In contrast, when scarce and/or expensive resource is to be scheduled, first a feasible and economical resource usage plan is established and then activities are scheduled accordingly. This practice is referred to as bottom-up scheduling in the literature. Several algorithms are developed and implemented in various commercial scheduling software packages to schedule based on either of these approaches.

However, in reality resource loaded scheduling problems are somewhere in between these two ends of the spectrum. Additionally, application of either of these conventional approaches results in just a feasible resource loaded schedule which is not necessarily the cost optimal solution. In order to find the cost optimal solution, activity scheduling and resource allocation problems should be considered jointly. In other words, these two individual problems should be formulated and solved as an integrated optimization problem.

In this research, a novel integrated optimization model is proposed for solving the resource loaded scheduling problems with concentration on construction heavy equipment being the targeted resource type. Assumptions regarding this particular type of resource along with other practical assumptions are provided for the model through inputs and constraints. The objective function is to minimize the fraction of the execution cost of resource loaded schedule which varies based on the selected solution and thus, considered to be the model's decision making criterion. This fraction of cost which hereafter is referred to as operation cost, encompasses four components namely schedule delay cost, shipping, rental and ownership costs for equipment.

Keywords: Resource loaded schedule, Resource Constrained Project Scheduling Problem, Resource allocation, Optimization model

A DECISION SUPPORT SYSTEM FOR DYNAMIC INTEGRATED PROJECT SCHEDULING AND EQUIPMENT OPERATION PLANNING

By

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Dedication

I dedicate this dissertation to my lovely family for their unconditional love and support throughout all stages of my life.

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I express my appreciation to FICO$^{\text{TM}}$ for generously providing the Civil and Environmental Engineering Department of the University of Maryland at College Park with Xpress optimization suite 7.0. User friendly modeling language along with the fast, efficient and precise solver provided within this package contributed a great deal to the overall success of this effort.

At the end, I would like to thank the CEO of EV-YOL Construction Co. who provided the real world data which was used in this study. Performing numerical analysis based on this data has significantly increased the quality of this research.

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List of Abbreviations

AOA	Activity On Arrow
AC	Actual Cost
ACWP	Actual Cost of Work Performed
AD	Actual Damage
BB	Branch and Bound
BCWP	Budgeted Cost of Work Performed
BCWS	Budgeted Cost of Work scheduled
CBS	Constraint Based Scheduling
CI	Complexity Index
CP	Constraint Programming
CPI	Cost Performance Index
CPM	Critical Path Method
CR	Critical Ratio
CV	Cost Variance
D	Activity Duration
DP	Dynamic Programming
DSS	Decision Support System
EE	Explicit Enumeration
EF	Earliest Finish
ES	Earned Schedule
ES	Earliest Start
EV	Earned Value
EVM	Earned Value Management
FF	Free Float

FIFO	First In First Out
FILO	First In Last Out
GA	Genetic Algorithm
GERT	Graphical Evaluation and Review Technique
IE	Implicit Enumeration
IP	Integer Programming
LD	Liquidated Damages
LF	Latest Finish
LOB	Line Of Balance
LP	Linear Programming
LS	Latest Start
MDTSP	Multi Dimensional Travelling Salesman Problem
MDVRP	Multi Dimensional Vehicle Routing Problem
MEVM	Modified Earned Value Management
MIP	Mixed Integer Programming
NCP	Nonlinear Constraint Programming
NLP	Non Linear Programming
NP Hard	Nondeterministic Polynomial time Hard
NPV	Net Present Value
OBCWP	Optimal Budgeted Cost of Work Performed
OBCWS	Optimal Budgeted Cost of Work scheduled
OCPI	Optimal Cost Performance Index
OCR	Optimal Critical Ratio
OCV	Optimal Cost Variance
OEV	Optimal Earned Value
OPV	Optimal Planned Value

OSPI	Optimal Schedule Performance Index
PERT	Performance Evaluation Review Technique
PH	Planning Horizon
PV	Planned Value
QP	Quadratic Programming
RACPM	Resource Activity Critical Path Method
RCSP	Resource Constrained Scheduling Problem
RCPSP	Resource Constrained Project Scheduling Problem
SD	Schedule Deviance
SPI	Schedule Performance Index
SV	Schedule Variance
TF	Total Float
TSP	Travelling Salesman Problem
TSPTW	Travelling Salesman Problem Time Window
VRP	Vehicle Routing Problem

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Chapter 1: Introduction

In this chapter, the majority of subjects that are relevant to the topic of this research are covered. At the same time, these subjects are not in the core of the discussion, so, there is no need to deal with them in a detailed manner. While this chapter provides the reader with sufficient insight about these subjects, other chapters of the document provide detailed discussion on a selected subset of these topics. This chapter starts with the definition of the term *schedule* in both classic and modern contexts. In the next section, a brief history of scheduling is presented followed by a discussion on the common scheduling techniques and their industry of origin. A relatively detailed discussion on the Resource Constrained Scheduling Problem (RCSP) which is the corner stone of this study forms another section of this chapter. Motivating factors behind this research, its contributions and ultimately the organization of the dissertation constitute the remaining three sections of the chapter.

1.1. Definition

Each individual comes across the concept of schedule in one way or another every day. In the mind of a commuter the term schedule translates into the transportation vehicle schedule (i.e. train schedule), for a student it typically means a course plan and for a contractor it represents a time line of activities that should be performed in order to complete a task. As different as the external instances of this word seem to be, they represent the very same core concept.

In the Latin literature the root of the word schedule means a small leaf of paper. A later French root of this word means scroll, note or bill. In a 1936 dictionary schedule is defined as:

“Schedule: A list, as of property; a catalogue; an inventory; a rail road timetable; a classification”

It can be seen that the time element was of less importance in defining the term schedule in 1936. However, in more recent definitions of this term the essential element of time has been embedded. A 1958 dictionary definition of the term schedule endorses this pattern clearly (O'Brien, 1969).

“Schedule: A list of the time certain things are to happen; time table; a time plan for a project”

The term schedule to which we refer in the context of this study is close to the latter definition with slight modifications. The simplest meaning of the term schedule as it is used in this study is:

“A time base plan for accomplishment of a designated set of activities”

More specifically, for the purpose of this study the set of activities are construction/mining projects’ activities.

1.2. Historical background

The evolution of scheduling is historically tied to the evolution of mankind and cannot be separated from human beings’ daily planning and thinking processes. From a historical point of view, wars and military activities are the main contributors to the evolution of scheduling as they are for many other scientific and engineering fields. Wars even in their ancient style, involve scheduling problems such as troop movements and logistics which renders making scheduling-related decisions an inherent part of a commanders’ chore.

Specifically speaking about the subject of the current study, the foot prints of scheduling can also be found in ancient construction projects. Construction of the pyramids in Egypt and the Morro Castle in Puerto Rico are two historical landmarks in which evidences of implementation of primary scheduling rules and techniques are traceable. However, these scheduling techniques are more a series of task sequencing techniques in order to prevent conflicts in the construction process rather than time based scheduling. This can be attributed to the fact that in ancient times labor, material, equipment and construction techniques were major bottlenecks and time was almost of no priority in the construction process. This justifies why the construction of the Morro Castle which with today’s equipment would takes roughly 5 years took 300 years (O'Brien, 1969)!

This historic illustration also supports the fact that modern scheduling in its core consists of two major components which are activity sequencing and timing. If the later added timing element is taken away from this process, the remainder will be reduced to a sequence of tasks without any time linkage which is simply nothing more than the ancient scheduling practice that provides no control over the timeline of projects. This emphasizes the fact that sequencing and timing should work in tandem to form a meaningful schedule with its modern definition.

Reviewing the recent literature shows that more emphasis is put on time component of the schedule. In modern scheduling, time is both a resource to allocate and to build the schedule upon while in sequencing, it is just a component of the allocation process. In other words, the time component of the schedule is in the core of the process in comparison to sequencing.

Scheduling with its modern definition did not exist before the early 1900s. Prior to that, informal scheduling techniques were applied based on the nature of the job, schedulers' organizational capabilities, their academic background and work experience. At the time, this typically intuitive process was not a separate part of projects or production processes.

In the early 1900s engineers became the pioneer advocates of scientific management and among them Taylor, Gantt and the Gilbreths developed the pillars of this field. These basic concepts were converted into the bar chart or Gantt chart by Henry L. Gantt during the World War I which later became the standard scheduling tool (O'Brien, 1969).

During the World War II era, the operation research approaches found their ways into various scientific fields including management science and scheduling. The Gilbreths and Gantt made major contributions to this line of research as well (O'Brien, 1969). In the 1950s the advent of computers became the turning point in efforts for advancing management science and scheduling fields. The nature of computers pushed the structure of the scheduling techniques more toward logic-based programming approaches. Milestone developments of this era are Critical Path Method (CPM) and Performance Evaluation and Review Technique (PERT) which were developed in 1957 and are still widely used although with application of some modifications.

Formal efforts for development of CPM were initiated by an engineering division called Integrated Engineering Control (IEC) within du Pont de Nemours Company in 1956. These efforts specifically targeted the problem of improving the planning and scheduling of construction projects. The end result of these efforts was the successful testing of the developed method on a $ 10 million chemical plant construction project in Louisville, Kentucky in 1958. However, there exists historical evidence which supports the claim that roughly the same method was introduced in the work of Boyan's (target commitment scheduling) at M.I.T. in 1946 (O'Brien, 1969).

The major innovation in CPM is modeling activity scheduling with network structure for which the credit goes to J.E. Kelley. However, Kelley himself has asserted that the application of the network diagrams to describe interrelationships had been a well-established, classical technique among mathematicians for many years by the time he accomplished his work. The significance of Kelly's work is developing a clear cut network framework for modeling an activity schedule upon which linear programming-based optimization models were later mounted. These models typically provide the user with minimum time, minimum cost or optimum time-cost schedules. An extension to this line of research which was introduced roughly about the same time is PERT. This method is the stochastic version of the CPM that emerged in the Navy Polaris program. PERT success became the reason for further incorporation of this system in scheduling the industrial and especially aerospace projects while CPM remained the dominant method for scheduling construction projects due to its successful introduction to this field (O'Brien, 1969).

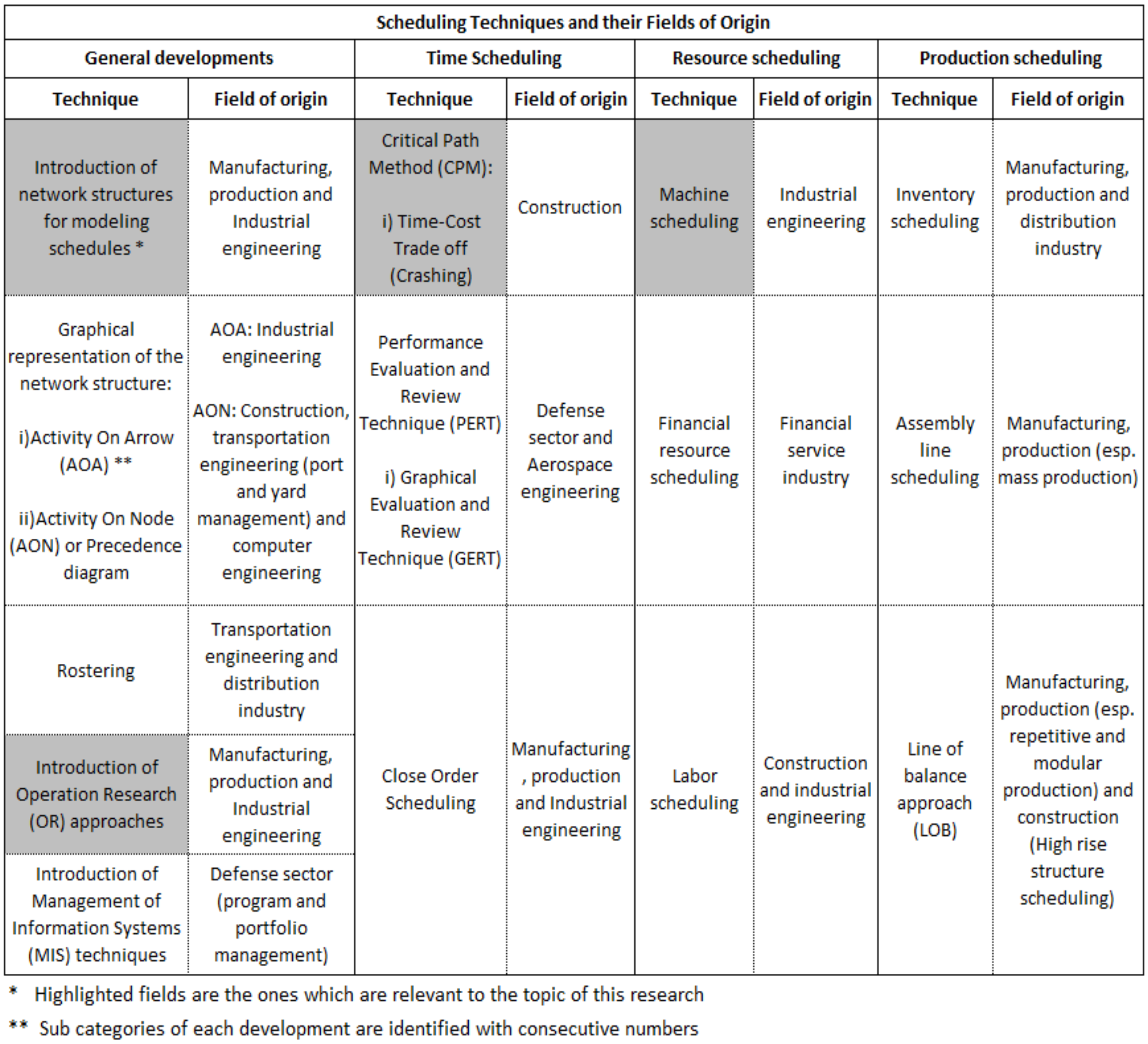
This concludes a brief history of scheduling and scientific management until the late 1950s and early 1960s. Later studies and developments in this field which are relevant to the subject of the current research are discussed in more detail in chapter 2.

1.3. Common scheduling techniques and their industry of origin

Major developments in scheduling techniques and approaches are classified under four categories.

- General development category consists of basic, fundamental and mostly mathematical contributions to the scheduling body of knowledge.
- The second category, being time scheduling techniques, includes general scheduling techniques which are common among different industries and most other techniques are built upon them (i.e. CPM).
- Resource scheduling methods constitute the third category which mainly consists of various resource allocation modules in addition to the main activity scheduling frame-work.
- The fourth category consists of scheduling techniques which are mainly specialized for the production and processing-related industries.

These four categories, approaches developed under each and their fields of origin are shown in Table 1.1 (O'Brien, 1969).



Scheduling Techniques and their Fields of Origin							
General developments		Time Scheduling		Resource scheduling		Production scheduling	
Technique	Field of origin	Technique	Field of origin	Technique	Field of origin	Technique	Field of origin
Introduction of network structures for modeling schedules *	Manufacturing, production and Industrial engineering	Critical Path Method (CPM): i) Time-Cost Trade off (Crashing)	Construction	Machine scheduling	Industrial engineering	Inventory scheduling	Manufacturing, production and distribution industry
Graphical representation of the network structure: i)Activity On Arrow (AOA) ** ii)Activity On Node (AON) or Precedence diagram	AOA: Industrial engineering AON: Construction, transportation engineering (port and yard management) and computer engineering	Performance Evaluation and Review Technique (PERT) i) Graphical Evaluation and Review Technique (GERT)	Defense sector and Aerospace engineering	Financial resource scheduling	Financial service industry	Assembly line scheduling	Manufacturing, production (esp. mass production)
Rostering	Transportation engineering and distribution industry	Close Order Scheduling	Manufacturing , production and Industrial engineering	Labor scheduling	Construction and industrial engineering	Line of balance approach (LOB)	Manufacturing, production (esp. repetitive and modular production) and construction (High rise structure scheduling)
Introduction of Operation Research (OR) approaches	Manufacturing, production and Industrial engineering						
Introduction of Management of Information Systems (MIS) techniques	Defense sector (program and portfolio management)						

* Highlighted fields are the ones which are relevant to the topic of this research

** Sub categories of each development are identified with consecutive numbers

Table 1.1- Scheduling techniques and approaches and their fields of origin

Following is a brief description of each method which is named in the table but is not directly related to this research; therefore, it is not described or even referred to later in this document.

- Rostering: An approach that encompasses various listing methods. Each listing method is applied in a certain circumstances to achieve the appropriate resource allocation strategy. Some examples of these are First In First Out (FIFO) and First In Last Out (FILO) listing methods.
- Management of Information Systems (MIS): A set of data processing methods that are applied to consolidate the data of multiple projects (portfolio of projects) in the structure that is appropriate for feeding an intended scheduling system. Application of MIS is common for program and portfolio management especially in the defense sector.
- Time-Cost trade off (crashing): A technique that is typically used as an extension to CPM or PERT. Its purpose is to decrease the duration of the longest sequence of activities of a given schedule, while considering the cost-duration curve of each activity and keeping track of both incremental and overall changes in the cost of the project.
- Graphical Evaluation and Review Technique (GERT): The Graphical version of the PERT system which is developed to analyze networks with stochastic and logical properties. A typical GERT scheduling network is made up of nodes which represent logically linked milestones and activities (branches) that have probabilities associated with their properties (i.e. duration). As the solution, GERT provides the user with the stochastic completion time of each activity and the overall network.
- Close Order Scheduling: In this approach a task is broken down into stages and at each stage all possible moves are identified. After formation of this network, the

shortest path (the path with the shortest completion time) is recognized as the solution of the scheduling problem.

- Assembly line scheduling: This method is typically applied to manufacturing processes for balancing factors to produce a smooth flow of production both in the level of components and the final product. In other words, this scheduling approach recognizes and provides remedies for bottle necks in the assembly line.
- Line Of Balance scheduling (LOB): A scheduling approach based on cumulative progress control. This approach is very effective for identification of trends, instants of shortcoming and instants of conflicts in the project schedule especially when mass production of repetitive and modular products is the task.

1.4. Resource Constrained Scheduling Problem (RCSP)

A real world scheduling problem consists of a multi-attribute performance measure and various categories of constraints such as logical/technological precedence, time leads or lags, time-varying resource requirements and resource availabilities. Given these properties, almost any real world scheduling problem is subjected to limitations in terms of resource availability therefore, considered to be an instance of RCSP. Moreover, given these characteristics for RCSPs, their solution approaches are typically optimization-based decision support systems (DSS).

RCSPs are classified into the following three major categories based on their properties.

- Disjunctive vs. Cumulative RCSPs: In a disjunctive RCSP each unit of resource performs only one activity in each time unit (i.e. construction equipment). On the contrary, in a cumulative RCSP each unit of resource can perform in a parallel fashion which means it can execute more than one task in each time unit (i.e. computer processors).

- Preemptive vs. Non-preemptive RCSPs: In a preemptive RCSP, activities can be interrupted and resumed anytime between points in time at which they start and finish. In a non- preemptive RCSP when activities are started they cannot be interrupted. In other words, activities cannot be split into stages.
- Elastic vs. Non-elastic RCSPs: In an elastic RCSP the amount of resource assigned to each activity in each time unit can assume any value between zero and the resource capacity, provided that the sum of consumed resource over a certain period of time equals to a given value which is referred to as *energy* in the scheduling literature. In a non-elastic RCSP the amount of resource assigned to each activity in each time unit must only assume a certain value which is the demand for that resource in that particular time unit (Baptiste, Pape, & Nuijten, 2001).

By considering all possible combinations of these properties, eight (2^3) general types of RCSPs can be identified based on the underlying nature of the problem that is being formulated. The problem that is stated in this research is classified as disjunctive, preemptive and non-elastic RCSP. Figure 1.1 illustrates RCSPs system of categorization along with the position of the problem stated in this research within this system.

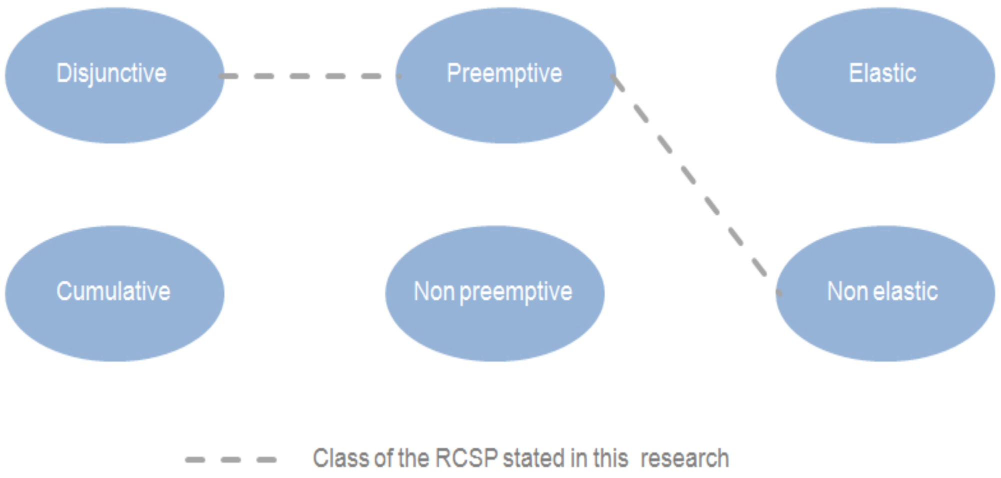


Figure 1.1- RCSP categorization system and class of the problem stated in this research

1.4.1. RCSP breakdown and resulting sub-problems

A typical RCSP in its general format consists of three sub-problems which are as follows.

i. The activity scheduling sub-problem

ii. The resource allocation sub-problem

iii. The resource leveling sub-problem

All these three problems should be solved together to bring about acceptable solutions from practical points of view. These solutions can be found through either integrated or iterative modeling approaches.

Additionally, solutions which are all acceptable for practical purposes might be different from a theoretical perspective and this difference is typically in their level of optimality. These solutions vary over a range of merely feasible solutions to near optimal solutions found through heuristic approaches to exact optimal solutions. Heuristics are approaches that find near optimal solutions in a reasonable time for large and complex problems. These methods are popular because of their capability in tackling real world problems which are typically large and complex and thus, either impossible or extremely difficult to solve.

Generally, research on the resource allocation and leveling sub-problems of RCSPs tend to focus on single-resource scheduling. This is despite the fact that most of the real world projects (i.e. construction projects) utilize multiple resources and the single-resource project is considered an over-simplified version of the real situation. Multiple resource RCSPs have challenged researchers from different communities, such as integer programming (IP) and constraint programming (CP). Due to the fact that this type of RCSP is structurally similar to the problem that is targeted in this research, more detailed discussion on previous studies in this field is provided in the literature review chapter.

1.4.2. Resource types and common decision making (optimality) criteria

Beside the scheduling component which is typically the common element among all RCSPs, other components typically vary from one problem to another. These differences are the underlying cause of each RCSP being unique, hence demanding a unique formulation and/or solution approach.

One component which can potentially alter the nature of an RCSP is type(s) of the resource(s) that are involved in the problem. There are two systems of categorization for resources.

Under the first category, resources are classified into the following three major types.

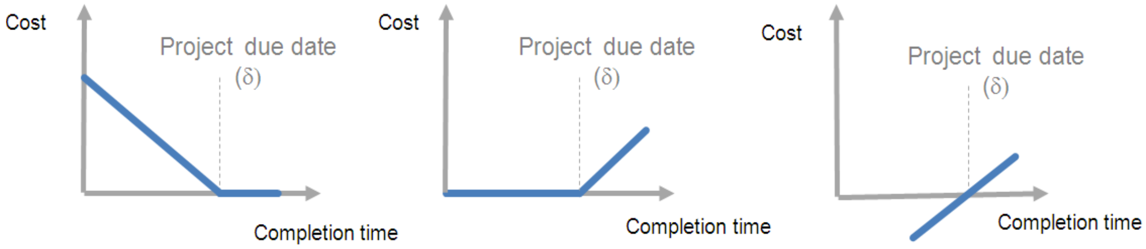
- Renewable resource: Resource is considered renewable, if **only** its availability at any given time unit is constrained (i.e. construction equipment)

- Non-renewable resource: Resource is considered non-renewable if **only** its total consumption (integral availability up to any given point in time) is constrained (i.e. finite quantity of construction material when no delivery constraint exists for each time unit).
- Doubly constrained resource: Resource is considered doubly constrained, if both its incremental and cumulative usage over a given time span is constrained (i.e. finite quantity of construction material which also has a constrained delivery amount for each time unit).

Under the second categorization system, two types of resource are distinguishable from divisibility perspective.

- Discrete resource: Discrete resource is a resource which **only** can be allocated to tasks in discrete amounts (i.e. construction equipment).
- Continuous resources: Continuous resource can be practically allocated in continuous amounts (i.e. electricity).

Another component of RCSP which affects the modeling and solution approach is the class of the decision- making criteria (objective function) selected for the problem. Based on the nature of the problem, more than one of the typical objective functions for RCSP may be combined in a weighted master objective function format. Typical decision-making criteria that are common in the field of RCSP are shown in Figure 1.2. Earliness criterion is used when the objective is just to incentivize early completion, tardiness criterion is used when the objective is just to penalize delay and lateness criteria is an appropriate choice when both incentivizing early completion and penalizing delay is intended (Baptiste, Pape, & Nuijten, 2001).



Earliness criteria **Tardiness criteria** **Lateness criteria**

Figure 1.2- RCSP common decision making (optimality) criteria

1.4.3. Characteristics of the problem targeted in this research

From a theoretical point of view, this problem is a disjunctive, preemptive and non-elastic RCSP which encompasses all three sub-problems of activity scheduling, resource allocation and resource leveling. Also, the resource that is being allocated in this problem is construction heavy equipment which is considered a discrete and doubly constraint type of resource. Moreover, the decision making criteria (master objective function) is minimization of the weighted combination of equipment operation and tardiness costs.

The problem targeted in this research is not only one of the most frequently encountered variations of the resource allocation problem in the construction industry, but also it represents the area of major complications and projects' bottlenecks. The reason for formation of bottle-necks in the equipment allocation process is that heavy equipment is an expensive and very limited type of resource. Moreover, this resource is required per specific sequence which is determined according to the activity schedule on each project's site. Considering these situations, still in its static form and with a small network of projects, the problem is not impossible to solve through application of manual conventional approaches. However, when large network of projects along with dynamic circumstances are involved, the problem becomes computationally cumbersome and thus, either extremely difficult or even impossible to solve.

Following are some major distinctions of the problem targeted in this research and its proposed solution approach with a typical RCSP study found in the literature.

As the result of the specific problem statement, the proposed formulation does not fit in either of the two classic categories of an RCSP problem being fixed duration-flexible resource and flexible duration-fixed resource. It in fact is a combination of both concepts. This issue is discussed in more detail in the literature review chapter.

Additionally, the constraint which governs the availability of the resource in a typical RCSP is a simple cap which is totally different from the network flow conservation constraints which control the availability of the owned pieces of equipment in this formulation.

In the field of manufacturing and industrial engineering, a handful of complex methods have been developed by use of Constraint Based Scheduling (CBS) for solving RCSPs (i.e. edge finding algorithm). However, due to the nature of the problems in that field, the developed methods can handle only a small number of tasks and resources which is a totally different situation from what is the case in the construction industry. Consequently, these methods are not applicable to problems in the context of construction industry.

Problems defined in the field of RCSP are highly specialized for a given situation in the context of a given industry as are the solution approaches provided for them. On the contrary, the problem that has been put forward in this research and the proposed formulation are general purpose within the context of construction/mining industries.

This means that only with slight modifications the problem statement and the solution approach can be customized for any scheduling and resource allocation problem.

Finally, it is worth mentioning that this problem is classified under a sub-category of RCSP which is known as Resource Constrained Project Scheduling Problem (RCPSP) and its solution approach is considered a contribution to the body of knowledge in this field of study.

1.4.4. Discussion on the complexity of RCSPs

The complexity metric introduces a measure for evaluating the difficulty of finding solutions for a given problem through use of numerical algorithms. It is important to consider that both the structure of the problem and the proposed numerical solution algorithm contribute to the problem's complexity and neither of them can be considered individually to determine the order of complexity.

This being said, in the case of an RCSP on the problem description/formulation side, the following factors leverage the level of complexity.

- Size of the feasible region of the problem
- Structure of the activity network which is determined based on a metric referred to as a Complexity Index (CI) in the literature (Elmaghraby S. E., Kamburowski, Michael, & Stallmann, 1993)
- Type of the resource that is being allocated and any mathematical structure that might be added to the scheduling problem as a requirement for the resource allocation process (i.e. addition of network flow constraints, any variation of

traveling salesman problem, any variation of routing problem and assignment problem)

On the solution algorithm side no specific categorization exists and application of each algorithm has its unique effects on the complexity. For instance, in a given RCSP the application of the primal-dual algorithm results in the complexity of O (n^3). The same problem can be solved by use of a constraint propagation algorithm which will result in a lower complexity order being O (n^2) (Baptiste, Pape, & Nuijten, 2001) .

In the context of this study, the action that is taken to reduce the numerical complexity of the problem is to eliminate the vehicle tracking component of the problem. This component is identified as avoidable based on the problem statement in this study. This change results in elimination of unnecessary Multi-Dimensional Travelling Salesman Problem (MDTSP) or Multi-Dimensional Vehicle Routing Problem (MDVRP) from the structure of the formulation and rendering the numerical computations drastically less burdensome.

1.5. Motivation and objective of the research

Integration of activity scheduling and equipment planning while considering all detailed practical issues of the construction/mining industry is an interesting problem which has not been addressed in the literature. Moreover, when it comes to modeling and proposing solution algorithms, this practical problem turns out to be a mathematically challenging problem. So practicality of the problem, its complex mathematical nature and the fact that it has not been previously tackled in the literature are major motivating factors for the author in pursuing it as his dissertation topic.

Moreover, if this problem is solved appropriately and efficiently, implementation of the end product in the construction/mining industry can result in considerable saving. This saving, which is the difference between financial performance of the projects portfolio in optimal and non-optimal (conventionally managed) situations is another driving force for justification of merits of this research.

Additionally, the end product of this research enables management to link future potential projects to a current portfolio and check the possibility of bidding for those projects while respecting equipment availability constraints. The role of this feature in the decision-making process becomes more significant by recognizing the fact that a typical bottle-neck for bidding more projects is shortage of heavy equipment.

Performance capacity of the owned equipment fleet can be gauged by considering the monetary value of the volume of work that is performed using that fleet over a certain period of time as the metric (μ). Comparison of the metric for maximum performance (μ_{max}) with the same metric for the current performance level (μ), reveals the efficiency of the owned fleet ($\varepsilon = \frac{\mu}{\mu\ max}$). The end product of this study enables managers to calculate the optimal performance capacity of the owned equipment fleet while it is utilized to operate in number of projects, in different geographical locations and under projects' schedule constraints ($\mu_{optimal}$). Enabling managers to push μ toward higher values and to easily calculate μ, $\mu_{optimal}$, ε and $\varepsilon_{optimal}$ as major missing factors in managing construction/mining projects, are some other motivating factors of this study.

Ultimately, since none of the commercial scheduling software packages such as Primavera or Microsoft Project (MSP) currently have optimization features, the end product of this research can be used as a supplementary optimization module for them.

1.6. Contributions of the research

In this research, a new IP formulation for integrated scheduling and equipment planning is proposed. Major contributions of this research to the scheduling body of knowledge are as follows.

According to the literature, both the problem statement considering all practical details and the proposed mathematical formulation are totally new and are major contributions to the scheduling body of knowledge. It is worth mentioning that the scheduling module of this problem alone can be modeled using the CBS framework. However, its integration with equipment planning alters the structure of the problem such that CBS alone will not be helpful anymore. In other words, in solving the overall problem two different modeling approaches which are CBS and network frame-works should be combined. Belonging to two separate fields of study is probably one of the underlying reasons for this problem not being tackled before. Figure 1.3 shows the unique stance of this problem within the optimization-related scheduling literature.

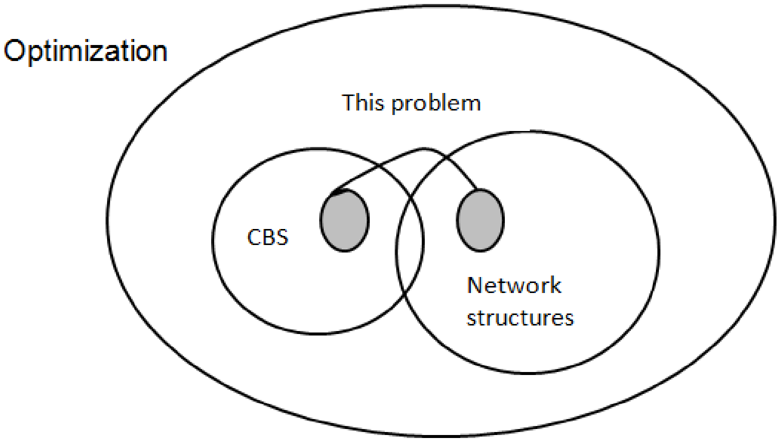


Figure 1.3- Position of this problem within optimization-related scheduling literature

Moreover, in the scheduling module, minimization of the portfolio tardiness has been tied to minimization of a parameter called schedule deviance (SD). SD is a parameter that has been introduced in this study as an addition to already existing parameters in the Earned Value Management (EVM) framework. Addition of SD to EVM and application of relevant adjustments, improve the deficiencies of this system. As a remedy for these deficiencies, the Earned Schedule (ES) concept has been introduced previously. Modification of EVM is another contribution of this research to the scheduling body of knowledge. Also, tying the output of the model to the Modified EVM framework (MEVM) renders the output interpretable and useful for industry decision makers without further processing. Application of this model along with MEVM also enables construction managers to make meaningful comparisons of project performance metrics among different projects.

Additionally, the proposed model can be used for optimal float allocation and provide a scientific and cost optimal solution for the controversial problem of float ownership. This feature is also considered to be a contribution of this research.

Moreover, incorporation of the end result of this study in the project control process establishes a sound system for tracking financial damages or penalties (liquidated and/or actual damages) to the activities that were contributors to delay and thus, identifying exact and fair share of each liable party. This is a valuable mechanism which is currently missing in the industry and can be used as a helpful basis for dispute resolution regarding schedule and delay related claims.

Also, value of the objective function in the proposed model is meaningful and represents the operation cost. It has two elements which are schedule delay cost and overall cost of equipment allocation. The second element itself encompasses equipment shipping, renting and ownership costs. The overall objective function value and the value of its components individually can be used to make managerial decisions.

It is also worth mentioning that, with slight modifications the same platform can be used for allocation of other types of resources such as material and labor. This is another feature that renders this study a unique contribution to the resource constrained scheduling body of knowledge.

Also, since input and output parameters of the proposed model are compatible with the data structure of commercial scheduling software packages (i.e. Primavera and MSP), it can be used as a supplementary optimization module for these packages. Review of literature related to scheduling software packages and direct examination of a variety of them revealed that no optimization function is currently implemented in these packages. Majority of them use prioritization rules as their underlying resource allocation platform and thus, they provide feasible solutions which are generally suboptimal. This increases relevance, necessity and timeliness of this study.

Review of the literature revealed that models introduced in previous studies are either not capable of solving practical size problems or not capable of solving them in a reasonable amount of time. As a result, they are typically replaced with simplified and in several cases over simplified heuristics for solving practical size problems. However, due to specific structures (binary and network structures) which are used in the proposed model, acceptable solutions for practical size problems can be reached within reasonable amount of time.

Another significant deviation of the proposed formulation from what that has been proposed in roughly similar studies is its path independency. This property increases the efficiency of the formulation.

Finally, due to high efficiency and relatively short running time of the proposed model, multiple runs can take place in a reasonable amount of time. As a result, complex project control analyses such as resource exchange, resource-duration exchange (activity crashing) can be easily performed in an optimal fashion through sequential use of this model.

1.7. Organization of the dissertation

The first chapter of this document is dedicated to a general introduction of scheduling and the field of RCSP. The second chapter provides a detailed literature review on the portions of the subject which are directly related to the topic of this research. Overall, these two chapters provide the reader with position of this research in the literature and ensure its novelty, merits and contributions. Hence, the first two chapters mainly focus on previous studies and comparing them with this research.

However, the next five chapters are fully dedicated to the developments accomplished in this research.

Chapter three is dedicated to a detailed problem statement, presentation and justification of the assumptions, description of underlying platforms which are used for modeling and finally detailed description of the proposed mathematical formulation. In the fourth chapter, the validation process of the proposed mathematical model is discussed. Chapter five is fully dedicated to numerical analysis of practical case studies which are designed based on real world data. The sixth chapter covers the discussion on development of the heuristic approach and effects of applying it to real world case studies. Ultimately, chapter seven covers a summary of conclusions and recommendations for future studies.

Chapter 2: Literature Review

This chapter provides an overview of different areas of scheduling body of knowledge which are related to the topic of this study. Additionally, a detailed review has been performed on fields of study which are more directly related to the topic of activity scheduling and equipment planning. Latter review mainly focuses on studies upon which this research has been built.

This being said, since a wide area in the body of knowledge should be reviewed in this chapter, a classification of the literature is performed and is shown in Figure 2.1 as the map of the literature. Breakdown of this chapter roughly follows the pattern shown in this hierarchical chart. This chart also demonstrates where and how the current research fits into the body of knowledge.

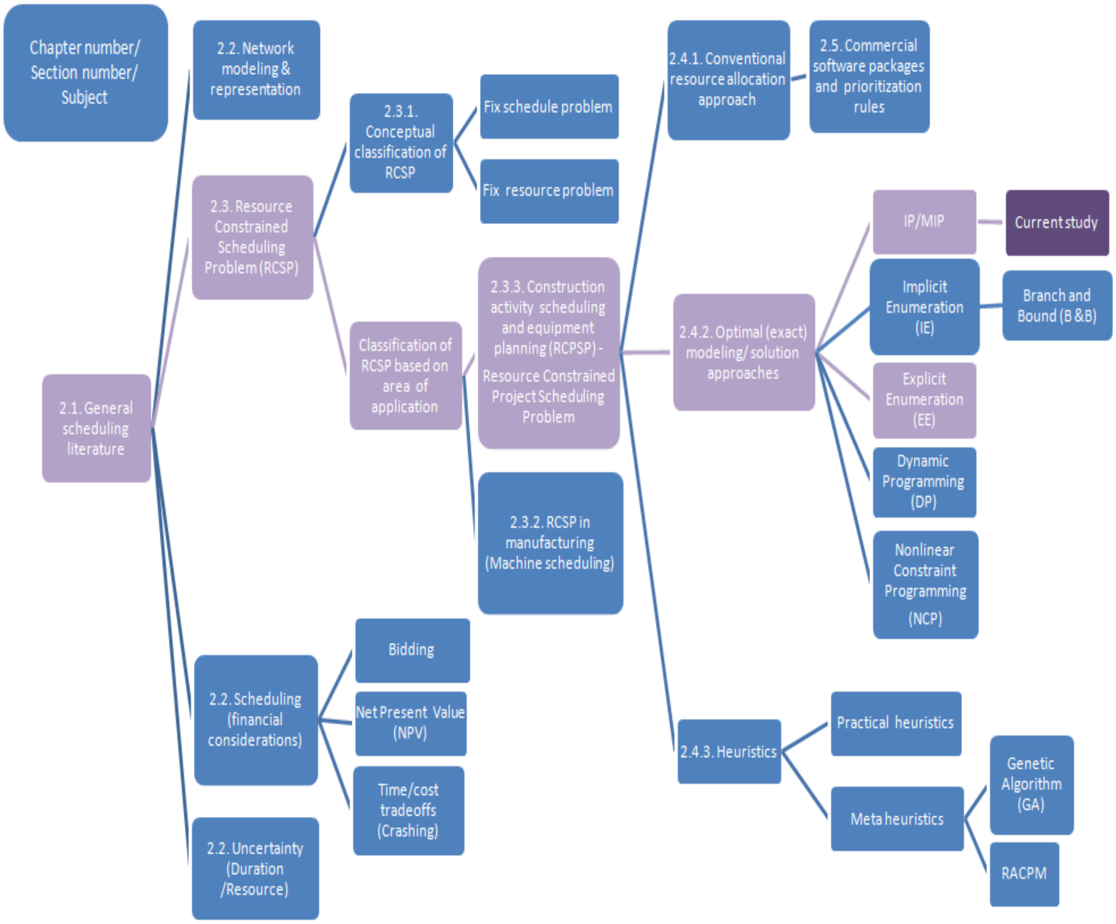


Figure 2.1- Classification of scheduling body of knowledge

2.1. General overview of scheduling literature

Scheduling as it is known today is the developed version of activity network scheduling introduced under CPM and PERT topics. In 1959, the first papers which introduced the concepts of deterministic activity networks as CPM and stochastic activity networks as PERT were published. Only three years later, Bigelow (1962) published his review paper on the subject. It classified all research works which have been done between 1959 and 1961 based on basic theoretical principles and industrial and military applications of both

CPM and PERT. Lerda-Olberg (1966) reviewed the contributions made to the body of knowledge in this area between1962-1965. This paper classified contributions into four main categories of general, theoretical, programming and application-related. Adlakha & Kulkarni (1989) focused on stochastic activity networks and in their paper discussed errors as the result of assumptions in Monte Carlo simulation approaches. This paper also covered previous studies that had been done between1966-1987.

Beside these major milestone papers, several books have summarized major contributions in the activity network and scheduling area. Battersby (1970), Whitehouse (1973), Elmaghraby S. (1977), Kerzner (1979), Moder (1983) and Slowinski & Weglarz (1989) are the significant ones (Elmaghraby S.E. , 1995).

In today's competitive business environment, successful management is equivalent to effective management of resources while satisfying market requirements in the context of any given industry. Since original CPM and PERT assume that resources are unlimited and the project duration is not fixed, which are both unrealistic assumptions, techniques adopted in the real world scheduling practice are modified versions of them. Resource allocation is tying a feasible activity schedule to a feasible resource plan. Resource leveling (resource smoothing) is making adjustments in order to avoid sharp peaks and valleys in the resulting resource plan. Both of these are techniques adopted to modify CPM and PERT for practical purposes (Moslehi, 1993). Although these modifications render CPM and PERT extremely practical, by no means do they guarantee minimization of the project duration (Karshenas & Haber, 1990), (Hegazy, 1999) and (Pantouvakis & Manoliadis, 2006). The concept of project duration minimization or more generally optimization based on other optimality criteria have been the center of focus for studies in this field since 1990. Literature related to this topic is reviewed through the rest of this chapter.

2.2. Review of different aspects of the scheduling problem

Due to the fact that scheduling is a crucial tool for project control, project managers' tastes, demands and expectations have been the major driving force behind developments in this field. However, this demand has been generally responded to by efforts of mathematicians in the field of operations research. This is because of the complex mathematical problems which are encountered in dealing with activity networks.

This being said, in the literature developments in the field of scheduling have been classified into four major practical areas which are (1) representation, modeling and analysis of schedule networks, (2) financial issues, (3) uncertainty modeling and finally (4) scheduling under resource constraint. Literature related to first three areas is briefly reviewed in this section since they are relevant to the topic of this research. However, resource constrained scheduling is the backbone of this study, so the rest of this chapter is devoted to an in-depth discussion and examination of the literature related to this topic.

A major problem that has been addressed in the early times of development of scheduling with its modern definition, was modeling activity schedules with activity networks which have a minimum number of nodes and constructing an Activity On Arrow (AOA) representation of them (Cantor & Dimsdale, 1969), (Sterboul & Wertheimer, 1980) and (Syslo, 1984). Later it was proved that activity network problems are non-deterministic polynomial time hard (NP Hard), and consequently cannot be solved in polynomial time

(Krishnamoorthy & Deo, 1979). Introducing a scale for measuring network complexity (complexity index: CI) was another incremental achievement in this field.

In another line of research, major financial aspects of project management and cost control which are interrelated with activity scheduling have been addressed. Bidding issues that can be related to activity networks have been addressed in the work of Farid & Boyer (1985). Interactions among project accounting elements such as actual costs, payments, cash flow and project's activity network have been discussed by Badger (1974). Integration of a project's Net Present Value (NPV) analyses with activity networks is another financial aspect of project scheduling that has been addressed in the literature by Dayanand & Padman (1993) and Sepil & Kazaz (1994). Also, the concept of time-cost tradeoff (crashing) has been blended into the network structure of activity scheduling problems in studies done by Elmaghraby & Kamburowski (1992) and Dodin & Elimam (2008).

Another practical aspect of scheduling problems that has been addressed by Goldratt (1997) is implementation of activity duration uncertainty, which is mainly the consequence of uncertainty in resource availability, in the activity network. This has been done by addition of appropriate protection time to the duration of each activity in the deterministic version of the schedule to cover uncertain factors. These protection times then accumulate and form project's overall time buffer. This simple modification alters the network of the schedule in many ways. For instance, it transforms the key concept of critical path into a more general concept of critical sequence or chain. Critical chain is defined as the longest chain of logically dependent and/or resource dependent activities in the network of activities.

2.3. Review of the literature related to project scheduling under resource constraints

Resource constrained scheduling targets the problem of producing an activity schedule consistent with resource limitations while accomplishing performance objectives of a project. Reviewing the relevant literature reveals that this problem is NP-Hard which means its optimal solution through mathematical approaches cannot be obtained in polynomial time (Hegazy, 1999).

Moreover, from a mathematical stand point, the real world problem of activity scheduling with resource constraints, with all its managerial and practical details is extremely difficult to state and model regardless of solution approaches (Elmaghraby & Kamburowski, 1992).

By considering many simplifying assumptions, researchers have been successful in developing a number of mathematical models to solve the problem of activity scheduling under resource constraints. Typically, the trend in these studies is to develop a model for solving small to medium size problems (up to 30 activities) to optimality in the first stage. Mathematical models for practical size problems are generally Mixed Integer Program (MIP) or IP models with a large number of constraints and decision variables in the order of thousands. Since typically a practical size problem cannot be solved to optimality, the next essential step is to propose a heuristic to obtain an acceptable near optimal solution within a reasonable amount of time.

Besides the typical structure of these studies, each proposed model considers different criterion for planning scarce resources. Common examples of these criteria are minimization of project duration and minimization of project cost. Following is a chronologically arranged list of milestone studies in this field.

(Patterson & Roth, 1976), (Stinson, Davis, & Khumawala, 1978), (Talbot & Patterson, 1978), (Patterson, Slowsinki, Talbot, & Weglarz, 1989), (Deckro & Hebert, 1992), (Demeulemeester & Herroelen, 1992), (Demeulemeester & Herroelen, 2002) and (Dodin & Elimam, 2008).

Based on the observed trend among studies which are available in the literature, any modeling improvement to consider more realistic and detailed practical assumptions, relaxation of restrictions that exists in previously proposed models and solution algorithm improvement is considered a major contribution to the body of knowledge in this field of study.

2.3.1. Conceptual categorization of RCSP

Resource availability is a core issue in project planning and control. More specifically, resource limitation in project planning often translates into either of the following managerial decision making problems:

i) Resources are limited with no possibility to increase their availability. In this case the decision is to allocate the resources in a way that the project will be completed as early as possible. This situation which is referred to as bottom-up scheduling typically happens when extremely expensive pieces of heavy equipment are involved in the operation.

ii) Resources are limited but extra resources can be acquired through options of buying, renting or leasing. In this problem the decision would be to determine the cost optimal quantities of resources with which activities can be performed as initially scheduled. This situation, which is referred to as top-down scheduling typically happens with hard constraints in terms of contractual and legal commitments are in place.

Review of literature reveals that all previous studies can be classified under either of the above-mentioned classes of problem. In reviewed studies, different criteria such as minimization of project duration, minimization of maximum resource utilization, maximization of resource usage smoothness, minimization of resource utilization costs and maximization of NPV of the project have been considered.

However, the approach that is proposed in this research is a combination of both above-mentioned approaches. In this study, constraints on both resource and activity schedule have been relaxed and both components have been associated with their costs. The objective of the problem is defined as minimization of overall operation cost. In other words, this research proposes an approach which is conceptually a combination of previously developed classic approaches of treating this problem (Flexible schedule-Flexible resource). Figure 2.2, shows a spectrum on which current research is positioned with respect to similar studies. The varying factor on this spectrum is the priority of contractual and legal constraints vs. the priority of resource (equipment) availability constraints.

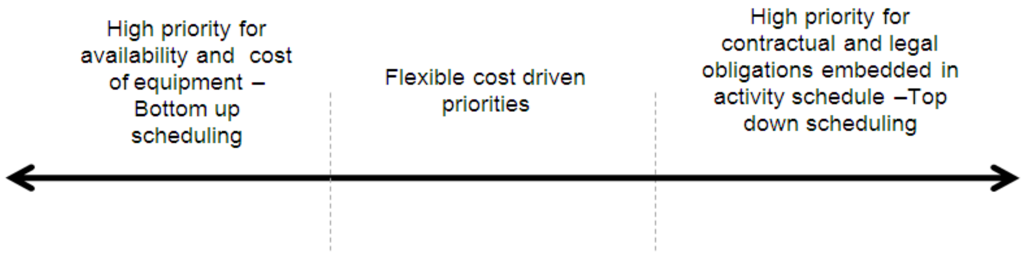


Figure 2.2- Top-down, Bottom-up and cost driven flexible scheduling strategies

2.3.2. Resource Constrained Scheduling Problem (RCSP)

Since the early 1960s, optimization approaches have been applied to synchronize activity schedules with resource utilization plans. The simple version of the problem was initially introduced and discussed in manufacturing and processing literature under the topic of machine assignment problem. As a result of further developments in this field, researchers broadened their area of focus to cover matching of any type of resource pool with a given activity schedule. This well established field is now referred to as resource constrained scheduling problem (RCSP). Since the current research is built upon some of the core concepts developed in this field, relevant RCSP studies are reviewed in this section.

The classic definition of resource in manufacturing literature is a machine that can perform only one task. The problem of finding a feasible or optimal linkage between a machine availability plan and an activity schedule is referred to as a deterministic machine scheduling problem. Original machine scheduling problems have been fully studied in the works of Bellmann & Esogbue (1982), Herroelen (1991) and Blazewicz & Ecker (1993). However, research on this topic is still ongoing due to several simplistic and unrealistic assumptions that were initially put in place for studying the subject.

A significant contribution in this field is the study done by Gargeya & Deane (1996). They relaxed the first assumption of single task machine and replaced it with number of multi task machines. In this modification, each resource is assumed to have limited capacity and each activity can utilize each required resource over several time periods in a piecemeal fashion. This important study is known as the bridge between deterministic machine scheduling problems and RCSPs in the literature. The field of RCPSP studies scheduling of project activities subject to precedence and resource constraints. Even this narrowly defined field of study covers a wide verity of sub problems including integration of activity scheduling and equipment planning which is the subject of the current study (Herroelen, De Reyck, & Demeulemeester, 1998).

2.3.3. Activity scheduling & equipment planning problem

The capability of optimization models in capturing different characteristics of activity scheduling and equipment planning problems, is the major driving force behind their application for solving these problems which are frequently encountered in the construction and mining industries. Using optimization techniques for operation planning of heavy construction and mining equipment was initiated in the late 1960's. However, as a result of the dominant conventional system of management in both of these industries, these techniques were not as accepted as they were in manufacturing practices just until recent years. As a consequent, research in this field was adversely affected and did not improve as much as RCSP in the context of manufacturing and processing.

Since this field of research covers the area of literature which is the most relevant to the topic of this study, greater emphasis has been put on its examination in this chapter.

2.4. Different modeling and solution approaches for activity scheduling and equipment planning problem

Three distinct categories of approaches have been reported in the literature for modeling and solving the activity scheduling and equipment planning problem.

i) The conventional approach in which a feasible activity schedule is matched with a feasible resource utilization plan using practical rules that are common in construction related scheduling practices (Prioritization rules).

ii) Mathematical approaches which result in finding exact optimal solutions for small to medium size problems. Different modeling approaches and solution techniques are used in this area for building optimization models. Some of them are listed below in the order of frequency of usage.

Mixed Integer Programming (MIP), Integer Programming (IP), Dynamic Programming (DP) and Nonlinear Constraint Programming (NCP) are major modeling approaches. On the other hand, Implicit Enumeration techniques (IE) specially Branch and Bound (BB) and Explicit Enumeration techniques (EE) are dominant solution approaches.

iii) Heuristic approaches to solve practical problems with an acceptable optimality gap in a reasonable amount of time.

Each of these three lines of research will be introduced and their relevant literature will be reviewed in detail in the following sections of this chapter.

2.4.1. Conventional solution approaches

As mentioned before, CPM in its original form considers logical/technological precedence among schedule activities while ignoring resource limitations in determination of activities completion date. However, experience has shown that resource limitations are major factors in controlling activities progress and completion. Since the mid 1960's heuristic and practical approaches were adopted to modify the original CPM and its unrealistic assumptions. As a result of these efforts, a two-stage practical technique of building resource loaded schedules was developed.

In this method a project is broken down into two distinct levels. In the upper level activities are scheduled according to the technological constraints and deterministic (CPM) or stochastic (PERT) calculations are performed to form the activity network. In the lower level, practical prioritization rules are used to allocate resources to activities according to the resource availability plan.

Several prioritization rules are reported in the literature. Some of the most common ones are minimum float, maximum resource demand and maximum activity duration. Each rule is applied based on specific circumstances of an individual project and objectives that should be accomplished in that particular setting. In the process of resource loading, activities might be shifted within their float time window in order to find the feasible match between activity schedule and resource plan while minimizing unavoidable extension of project. This is an iterative and extremely time consuming procedure which does not guarantee optimality of the solution (typically produces sub-optimal solution). This approach is applicable only by use of computers when it comes to practical problems(Lu&Li,2003).

2.4.2. Exact optimal modeling and solution approaches

Mathematical models and solution algorithms which have been developed to solve resource loaded scheduling problems to optimality generally have to deal with the issue of combinatorial explosion in these problems (Hegazy, 1999). As the result, they are only applicable to small to medium size problems (schedule networks with maximum of 30 activities). However, development of these models is an essential stepping stone in development of heuristics which are widely used to solve practical problems of industry.

Among conventional optimization approaches, IP has been commonly used to model the resource loaded scheduling problem. Lee & Gatton (1994) presented a complete IP formulation that combined construction activity scheduling with the resource utilization plan. However, as a result of application of prioritization rules in the resource allocation procedure, their proposed solution turned out to be a suboptimal solution of the problem.

Dodin & Elimam (2008) proposed an MIP formulation for integration of activity scheduling and construction equipment planning which minimizes overall cost of the project while considering various time/cost tradeoffs. Examination of RCPSP literature reveals that Dodin & Elimam (2008) work provides the most comprehensive model for integration of project scheduling and equipment planning. In studies prior to this, not only the exact problem of integration of construction equipment planning and scheduling was not addressed, also the proposed models fell short on several practical assumptions. However, since in this model a Traveling Salesman Problem (TSP) is formed for tracking the rout of each equipment, instances of more than one equipment will result in a multi-dimensional TSP (M-TSP) (Laporte, 1992) and (Gavish & Srikanth, 1986). This means that for solving this problem a number of NP Hard problems should be solved simultaneously which renders application of this model impractical for large or even medium size problem. The largest size of the problem that was modeled and solved to optimality by use of this MIP model had 25 activities and reaching an optimal solution took roughly 37,000 seconds. A Pentium III 800 MHz computer system with CPLEX 6.5 optimization solver was used for solving this problem. Therefore, to make this MIP model more computationally tractable, they supplemented it by a heuristic solution algorithm. The major function of this heuristic is to simplify TSPs which are formed to route pieces of equipment among activities. Even application of this heuristic does not increase efficiency of this model to the desired level and it is still considered incompetent in dealing with large problems due to the heavy computational burden. Since the model which is proposed in this study has similarities and shares some basic concepts with Dodin & Elimam (2008) model, special emphasis has been put on review of this work.

On the same line of research, implicit enumeration solution approaches by Davis & Heidorn (1971), more specifically, branch and bound solution approaches by Dorndorf, & Pesch (2000), Herroelen & De Reyck (1998) and dynamic programming approach by Kaplan (1988) provide some state-of-the-art developments.

Younis & Saad (1996) proposed a model for optimal resource allocation and leveling in multi resource projects. In their study, a solution algorithm was proposed based on principles of explicit enumeration. The proposed model consists of three hierarchical levels. The model performs CPM calculations, finds all feasible matches between activity schedules and given resource availability plan by enumeration and finally finds the cost optimal solution by comparing the cost associated with each of the feasible solutions. Obviously, since the model is using explicit enumeration, it will not go far in tackling practical problems and quickly becomes impractical as the size of the problem grows.

Finally, Senouci & Adeli (2001) used nonlinear constraint programming to minimize the total cost of the project while allocating and leveling resources. This model also has shortcomings in dealing with practical problems.

2.4.3. Heuristic approaches and near optimal solutions

As mentioned previously, since optimal resource loading and leveling of activity schedule is an NP Hard Problem, finding acceptable solutions for practical problems within reasonable amount of time is typically possible through application of heuristics (Khattab & Choobineh, 1991). These methods yield near optimal solutions which are accurate enough for practical purposes in a reasonable amount of time. Literature related to heuristic methods and their classification has been reviewed in the following sections.

2.4.3.1. Application of practically developed heuristics

Use of heuristics instead of optimal solution approaches for solving practical resource allocation and scheduling problems goes back to late 1960’s. The majority of these heuristics at their base use a series of activity prioritization rules to rank schedule activities for resource assignment. Then the limited resource will be allocated to highest rank activities and if ties happen during this process, a secondary prioritization rule kicks in. This process continues until the demand is satisfied or pool of available resources is fully exhausted. Application of prioritization rules ensures that logical precedence and duration constraints of the project are not violated. However, there is no guarantee for reaching optimal solution by use of this approach.

In technical terminology of mathematical programming, these practically developed prioritization rules are effective and are practically acceptable cuts that are applied to reduce the size of large feasible region of RCPSP in order to make it solvable in reasonable time. Moreover, these heuristics are simple and inexpensive for incorporation in computer algorithms.

In the study performed by Davis & Patterson (1975) major activity sequencing rules were examined for their efficiency. Examined rules were as follows.

- Minimum Job Slack (MINSLK): Activity with minimum available slack receives resource first.
- Resource Scheduling Method (RSM): Priority of receiving resource is given to an activity that has minimum gap between its earliest finish and latest start (LS) of its successor.

- Minimum Late Finish Time (MINLFT): Priority in receiving resource is given to the activity that has the minimum latest finish time.
- Greatest Resource Demand (GRD): Priority of receiving resource is given to the activity with the greatest demand of resource.
- Greatest Resource Utilization (GRU): Priority of receiving resource is given to the activity that leaves minimum idle time for the resource.
- Shortest Imminent Operation (SIO): Priority of receiving resource is given to the activity that has the earliest possible start time.
- Most Jobs Possible (MJP): Priority of receiving resource is set in a way that the maximum number of jobs (activities) is fed with the available limited resource.
- Select Jobs Randomly (RAN): In this approach activities are selected on a random basis for the purpose of resource allocation.

In the study of Davis & Patterson (1975) project duration as a result of selected prioritization rule has been established as a comparison criterion among heuristics. Also, distribution of project duration which was generated by several runs of the RAN heuristic was used to establish a performance baseline. Considering introduced criterion and baseline, MINSLK, MINLFT and RSM performed the best whereas GRU, GRD, SIO and MJP performed poorly. In other words, the first three were more effective cuts than the latter four. This research also revealed that project and resource properties have considerable effects on performance of resource allocation heuristics.

Also, other heuristics in this category are presented by Harris R. B. (1990) and Kumar & Rajendran (1993). Although emergence of these simple and practical heuristics goes back to a long time ago, this line of research is still active and new prioritization rules are being developed. For instance, Chelaka & Abeyasinghe (2001) introduced the LINRES heuristic which uses conventional CPM and creates an unconventional ancillary network based on which resource will be allocated without ensuring optimality of the solution.

Since from a practical point of view sharp peaks and valleys in a resource allocation plan are not favorable, resource leveling is a necessary step in the allocation process. Optimal resource leveling is an NP Hard optimization problem on its own (Shah, Farid, & Baugh, 1993) which is an inseparable part of the resource allocation problem. Addition of this problem increases the complexity of the originally defined RCPSP. Harris R. (1978) proposed an efficient resource leveling heuristic algorithm which is still being implemented in commercial scheduling and resource allocation software packages. This heuristic which is known as minimum moment approach in the literature, minimizes the overall resource fluctuation over the course of a selected time horizon, by minimizing the first moment of resource histogram around the time axis while keeping the original due date of the project. This heuristic provides good feasible solutions without ensuring optimality.

2.4.3.2. Application of Meta heuristics

Meta heuristics are computational approaches that are used for reaching a near optimal solution in large combinatorial problems. These methods move toward an optimal solution by iteratively improving a candidate solution based on a given performance measure.

Major research in this area has been done by Lu & Li (2003). They developed a heuristic algorithm which is capable of incorporating all other prioritization rules and utilizes different combinations of them (all possible combination of cuts) in a smart fashion in order to obtain an activity schedule that resolves the resource critical issues while satisfying a given measure of performance like project duration. It is shown that use of this heuristic, results in superior solution in comparison to use of each priority rule individually. This algorithm can be tracked in literature under the name of Resource Activity Critical Path Method (RACPM).

Chan & Chua (1996) used a genetic algorithm (GA) to minimize the duration of a resource loaded activity schedule while leveling the resource utilization plan to a certain degree. Leu & Yang (1999) also used GA to optimize multiple objectives of time/cost trade off, resource allocation and resource leveling. In another research later in 1999, the same team of researchers applied fuzzy set theory to incorporate activity duration uncertainty in their previously proposed model (Leu, Chen, & Yang, 1999).

Finally, another state-of-the-art research in utilization of GA based Meta heuristic for finding a solution for resource allocation and leveling problem has been performed by Hegazy (1999). To solve the problem, a multi-objective optimization model was developed by use of GA techniques. As a part of this research, performance of the model was tested and compared against existing heuristics. It was demonstrated that use of this Meta heuristic results in superior solutions in comparison to solutions provided by regular heuristics.

2.5. Commercial scheduling software packages and solution approaches

Review and examination of the literature reveals that commercial scheduling and resource allocation software packages use different prioritization rules for solving resource constrained scheduling problem (Trautmann, Baumann, & Fleischmann, 2008) and (Hegazy, 1999).

Commercial scheduling software packages which are widely used in the industry and are investigated in above-mentioned studies are Primavera (P3, P5 and P6), Microsoft Project (MSP 2007), Project Scheduler (PS8), Crest Software Project Professional (CSPP), Turbo Project Professional (TPP) and Acos Plus (ACO 1).

Review of the related literature also reveals that almost all of these packages share roughly similar platforms for their resource loading and leveling modules. Moreover, they all have both manual and automatic resource allocation options which can be activated upon user discretion. In the automatic mode, the user has the option of selecting different priority rules (i.e. MINSLK and MINFLT) based on unique properties of the problem such as schedule activities, resource type and various managerial policies. Also, all of these software packages have the option of fixing or relaxing a project's duration. Additionally, in all of these software packages the user can manually select activities to which automatic resource allocation and leveling should be applied.

However, the most important conclusion of this section is that none of these software packages utilize optimization approaches. Therefore, solutions provided by them are theoretically inferior in comparison to the solutions that can be obtained by application of optimal approaches or even heuristics that are reported in the literature. It is also worth mentioning that as a result of using different prioritization rules, solutions provided by different software packages for the same problem are not exactly identical.

2.6. Summary

In summary it can be stated that, the research that was found to be the most relevant to the current study is Dodin & Elimam (2008) work on integration of equipment planning and project scheduling. Detailed examination of the literature shows that publications prior to this neither targeted this exact problem, nor did they propose a solution algorithm that can be applied for solving this problem with any type of modification.

As indicated in Ernst (2004) in the field of RCSP, unique characteristics of different industries, organizations and unique circumstances under which each individual problem is defined require development of a unique mathematical formulation and/or even solution algorithm which might be only applicable to one particular problem without possibility of further generalization.

This being said, in the current study, the problem that was targeted in Dodin & Elimam (2008) work has been reconsidered with major modifications. For instance, rental equipment option and resource leveling module have been added to the scope. Also, new optimality criteria have been developed to consider several cost components of projects while tying them to parameters of the Earned Value Management (EVM). Moreover, proposing a new IP formulation to solve practical problems in a reasonable amount of time has been considered as a major part of the research scope. Thus, it can be concluded that application of major extensions and modifications to the statement of the problem proposed and solved by Dodin & Elimam (2008) and development of a totally new model for the proposed problem, makes this study a unique academic effort which is aimed at an intact problem. This renders the content of this study a major contribution to the scheduling body of knowledge.

Ultimately, it can be claimed that the end product of this study provides project and portfolio managers with a state-of-the-art control tool which enables them to easily perform various complicated and time consuming analyses on projects within a given portfolio. In the literature, existence of such system has not been reported.

Chapter 3: Problem Statement and Modeling Approach

This chapter starts with detailed problem statement. In the next step, the modeling/solution approach is discussed. Then mathematical and practical concepts and frameworks that are used to model and solve this problem are discussed. Finally, the practical and the mathematical assumptions used for modeling, the proposed mathematical formulation and a detailed discussion on its components constitute the remainder of this chapter.

3.1. Problem statement

In a high level classification, the problem of activity scheduling and resource (equipment) allocation which is dealt with in this research, is a subcategory of RCSP which is modified for project scheduling and is known as RCPSP in the scheduling literature.

This problem represents a typical situation in construction/mining companies that have a portfolio of large projects at hand simultaneously (i.e. highway construction, energy infrastructure construction, etc.). The conventional approach in dealing with this typical problem is implementation of practically developed allocation strategies which are generally sub-optimal and are proven to be inefficient especially when implemented on large projects with high costs.

Project portfolio of such companies encompasses several thousand activities and each of these activities can be split into several stages. Additionally, for performing each stage, various pieces of heavy equipment might be required in a sequence which is dictated by a specific construction method and technology that has been adopted. On the other hand, these companies typically own several pieces of heavy equipment that can be used for performing these activities but are not sufficient for satisfaction of all simultaneous demands.

To resolve this problem, current practice in the construction industry is to implement a practically developed deployment strategy for pieces of heavy equipment so that they are rotated among sites and are available upon demand. This strategy is supplemented with the option of renting equipment locally if owned equipment is either unavailable or it is not economical to move it to another location. To address this complex problem each company develops its own deployment strategy based on practicality considerations and professional standards and preferences. However, as mentioned previously, the level of optimality of these deployment strategies are questionable. So, proposing a model for optimal treatment of this problem has been long overdue. Figure 3.1 shows a graphical representation of this problem.

Figure 3.1- Graphical representation of RCPSP – Problem redefined based on considerations of the construction industry

The objective of this research is to propose a practically implementable optimization model for solving the above problem. Such system should operate within limitations of economic interests of the company and all physical and schedule related constraints.

Also, it is worth mentioning that this system operates at the company level and integrates management of all projects within the company's portfolio. So in order to provide the required input for it, all projects' data should be consolidated into a single database.

3.2. Modeling/solution approaches and underlying frameworks

The problem of activity scheduling and equipment allocation planning can be broken down into three separate but interrelated sub problems. These are activity scheduling, equipment allocation and leveling problems. This means a feasible solution to the master problem is feasible to each of sub-problems which is an indication of the fact that a feasible solution can be found through trial and error and iterative procedure.

In this approach a solution for one sub problem can be found and examined for feasibility in other sub problems. If it solves other sub problems it is an acceptable solution and if not, this process should be repeated with another initial guess until a solution is found. In order to further expedite the process, a convergence criterion should also be established. Although, this approach seems reasonable for finding feasible solutions in small problems, it becomes inefficient and numerically burdensome when it comes to finding the solution(s) for medium size problems.

This being said, integrated modeling/solving approaches through application of mathematical programming techniques are generally known as more efficient alternatives for iterative approaches. If structured properly, an integrated formulation can solve the practical problem to optimality within a reasonable amount of time. The model that has been proposed in this research is an instance of the latter approach. Figure 3.2 is a graphical representation of scheduling, resource allocation and resource profile leveling sub-problems, their interactions and formation of the master problem as a result of bundling all these sub-problems.

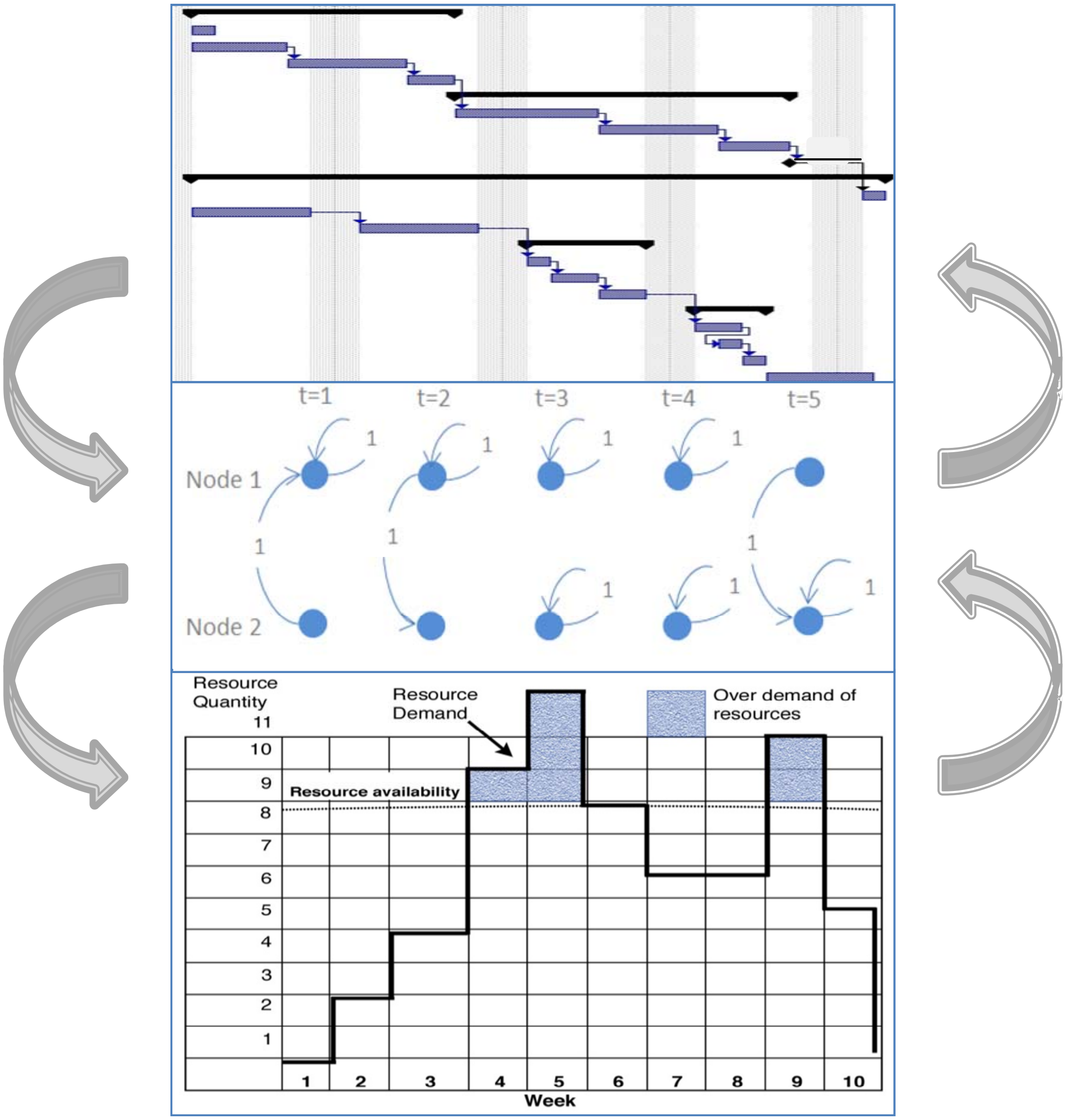


Figure 3.2- Problem breakdown- Sub problems (Activity scheduling, resource allocation and resource leveling) and their interactions

The following sub-sections of current section are devoted to introduction of underlying frameworks that have been used for modeling in this study.

3.2.1. Earned Value Management framework (EVM) and Modified EVM (MEVM)

In this section Earned Value Management (EVM) framework as a platform that has been used by the proposed model is introduced and modifications applied to this system are discussed. In practice, EVM is known as the platform for integration of major components of project control. Components of project control are shown in Figure 3.3.

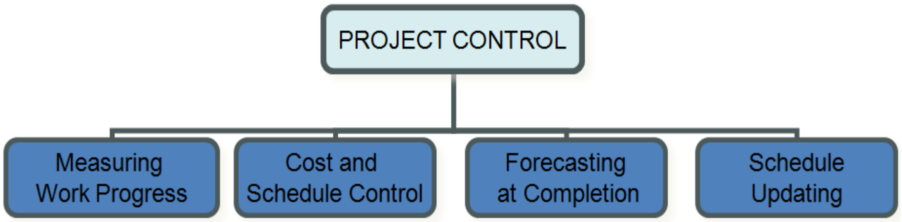


Figure 3.3- Major components of project control

To be more specific, EVM is defined as a systematic approach for integration and measurement of cost, schedule, and scope of a project. Also, EVM is known as a project management tool that integrates the schedule and cost parameters of a given contract. In this platform, all activities are scheduled and budgeted in time-phased increments. This schedule is referred to as Planned Value (PV). Then as progress in performance is realized, it is controlled against the established baseline of PV. Following is a brief introduction of EVM major parameters.

Cost Variance ($): $CV = EV - AC = BCWP - ACWP$ [3.1]

Schedule Variance ($): $SV = EV - PV = BCWP - BCWS$ [3.2]

Cost Performance Index: $CPI = EV / AC = BCWP / ACWP$ [3.3]

Schedule Performance Index: $SPI = EV / PV = BCWP / BCWS$ [3.4]

Critical Ratio: $CR = SPI \times CPI$ [3.5]

Schedule Variance (t): SV(t) = EV(t) – PV(t) = BCWP(t) – BCWS(t) [3.6]

To tie the proposed optimization model to EVM framework, modifications have been applied to EVM which are as follows.

- Use of each time slot by each activity has been associated with a specific cost (time price). Price of each time slot is a function of schedule structure, liquidated damages (LD), actual damages (AD) and other contractual terms and obligations. Generally, price of time slots increase as they get farther from the start mile stone of the schedule. A thorough discussion of time price functions and their structure is presented later in this chapter.

  This being granted, the ES schedule incurs minimum schedule delay cost due to the usage of the least expensive time slots. The more activities get shifted from ES toward LS, the higher the cost of using those time slots will be. More specifically, time price acts as an additional layer of cost (-) /value (+) which should be considered in calculation of both PV (BCWS) and EV (BCWP) parameters. By addition of this simple concept to the original EVM, an extremely useful monetary measure of a project's deviance from its baseline will be established which hereafter is called Schedule Deviance (SD-$). In other words, schedule deviance is the cumulative cost (-) or saving / value (+) that is incurred as a result of using time slots other than those which would be used according to the baseline plan. Typically, the baseline plan is the ES schedule as it is in this study. In this setting, SD is directly used as the tying parameter between the proposed optimization model and the EVM framework. More specifically, in the objective function of the proposed model the absolute value of the SD is being minimized.

- Original EVM and consequently all of its parameters have been modified as a result of introduction of SD and implementation of optimal activity schedule as the new baseline.

The new setting will be referred to as Modified Earned Value Management (MEVM) hereafter. MEVM parameters are described below.

Schedule Deviance ($): SD = OPV - PV = OBCWS – BCWS [3.7]

Optimal Cost Variance ($): OCV = OEV – AC = OBCWP – ACWP [3.8]

Optimal Schedule Variance ($): OSV = OEV – OPV = OBCWP – OBCWS [3.9]

Optimal Cost Performance Index: OCPI = OEV / AC = OBCWP / ACWP [3.10]

Optimal Schedule Performance Index: OSPI = OEV / OPV = OBCWP / OBCWS [3.11]

Optimal Critical Ratio: OCR = OSPI × OCPI [3.12]

Optimal Schedule Variance (t): OSV(t) = OEV(t)–OPV(t)=OBCWP(t)–BCWS(t) [3.13]

Figure 3.4 graphically demonstrates underlying concepts and parameters of both EVM and MEVM. The main purpose of this graph is a comparison of PV and EV as the baseline parameters of EVM with OPV and OEV as their equivalent parameters in MEVM.

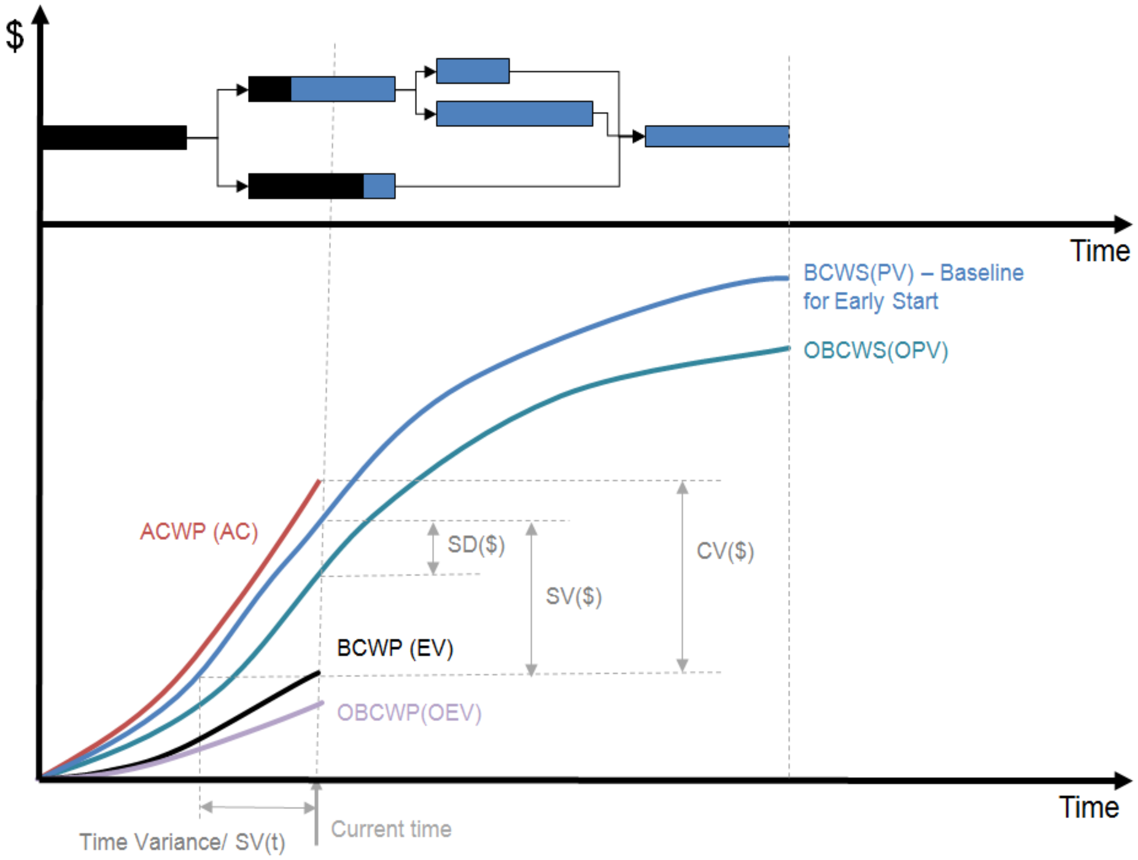


Figure 3.4- Concepts and parameters – EVM vs. MEVM

It is worth mentioning that the use of the MEVM framework in lieu of standard EVM has numerous benefits. Following is a list of these advantages with a brief discussion on each of them.

- In MEVM the effects of incremental delays and their contribution to overall delay of the project are magnified in comparison to EVM as a result of the addition of the time price component. In other words, the structure of schedule and position of each time slot are taken into account for keeping track of delays and their effects in a more realistic fashion. As a result, for a given schedule generally the equation 3.14 holds.

$$|OBCWS\ (OPV)| \leq |BCWS\ (PV)| \Rightarrow |OBCWP\ (OEV)| \leq |BCWP\ (EV)| \quad [3.14]$$

- According to the literature, EVM reports of project progress lose validity toward the end of the project if progress is tracked by SV ($) and SPI parameters. This deficiency is due to the special structure of these key parameters of EVM and the concept of Earned Schedule (ES) has been introduced as a remedial solution for this deficiency in the literature.

  As another remedy, the addition of time price element to the EVM framework improves this major deficiency. Improvements applied to MEVM enable project managers to use OSV($) and OSPI from the beginning to the end of the project without meaningful loss of accuracy in project progress reports even toward the end of the project. In other words, as the result of implication of this modification the latter two simple parameters (in $ scale) will replace the more complex Earned Schedule parameters (in time scale) without causing any inaccuracy in reporting the progress of project.

  The dynamics of this improvement for both Variance parameters and Performance index parameters are demonstrated in Figure 3.5.

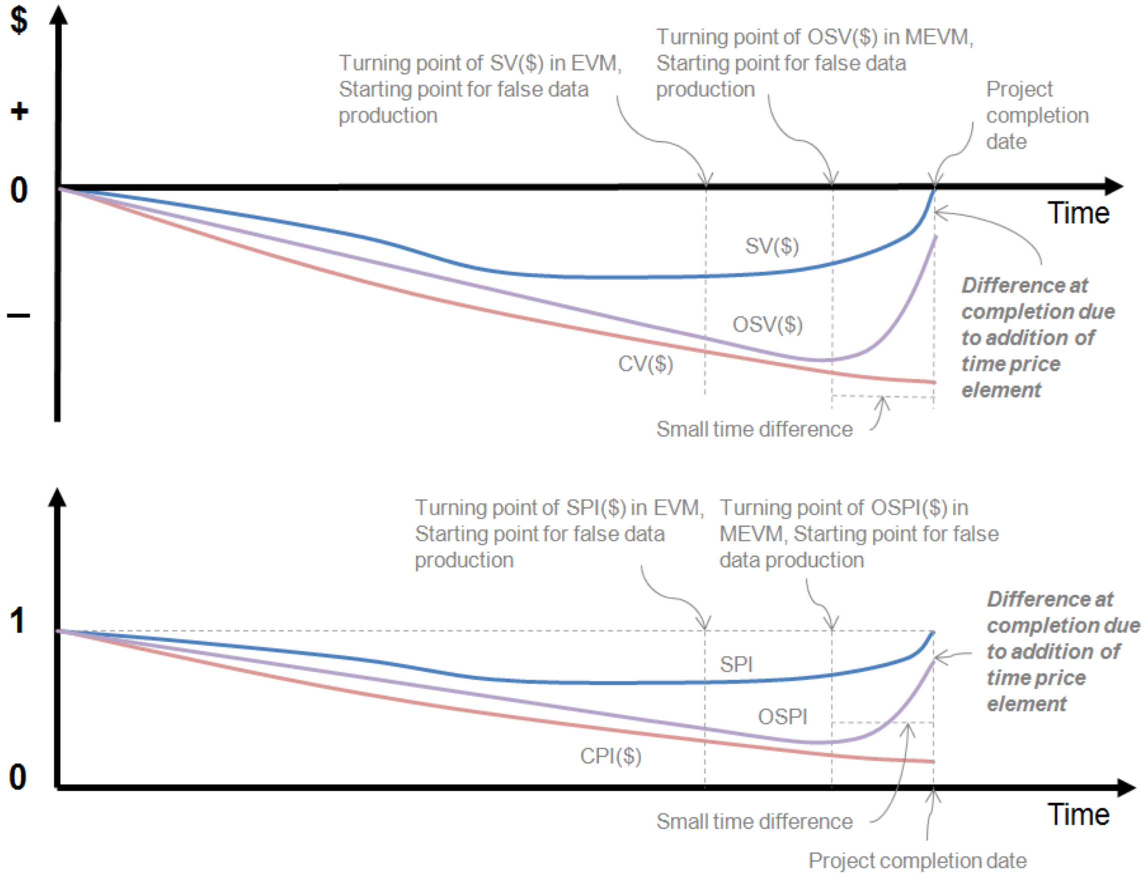


Figure 3.5- Improvement of EVM deficiencies in MEVM framework

- MEVM along with the proposed model establishes a sound system for linking overall liquidated and/or actual damages of the portfolio to activities that were incremental contributors to the overall delay. This system facilitates exact and fair assignment of each liable party's their share of incurred financial losses. This is a valuable mechanism which is currently missing in the industry and can be used as a helpful basis for dispute resolution in schedule and delay related claims.

3.2.2. Binary integer framework for modeling scheduling module

In this study in order to model the scheduling component of the problem a binary integer platform has been adopted. Not only this platform is compatible with the nature of activity scheduling but its implementation allows for a non-path-dependent modeling of the activity schedule network while respecting the time window and logical constraints of the schedule.

This platform provides a simpler approach for modeling activity schedules in comparison to conventional A-cyclic network structures. As a result, its implementation in the modeling process facilitates the addition of other types of the resource allocation modules to the scheduling component with slight modifications. In this platform three types of indicators are identified for each activity which are start time slot, finish time slot and active time slots. The modeling platform, three activity indicators and their interactions for modeling a sample activity schedule are shown in Figure 3.6.

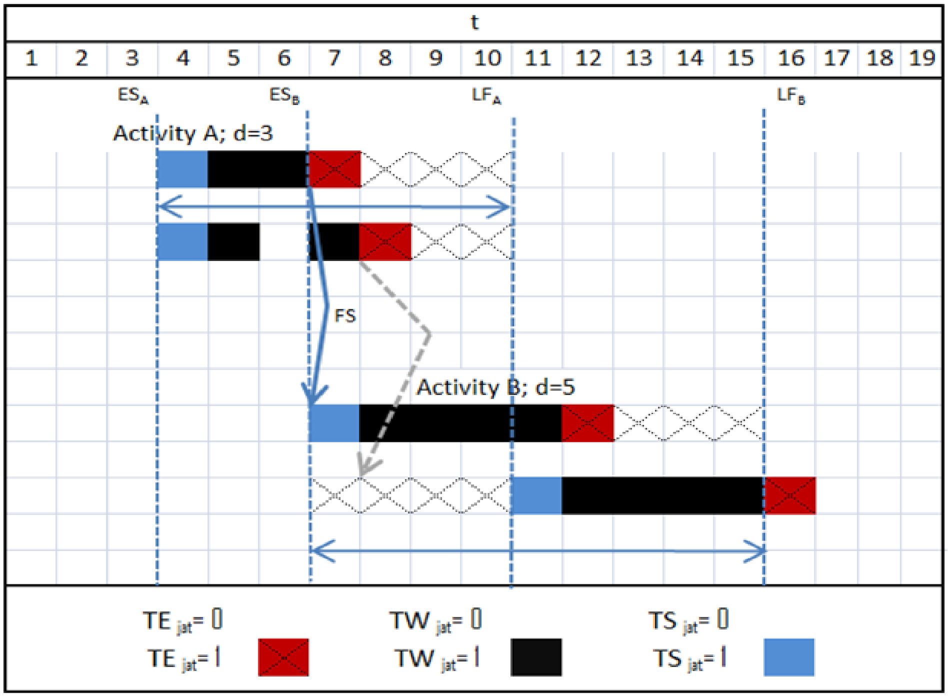


Figure 3.6- Binary integer framework for modeling scheduling module

3.2.3. Time-Space Network for modeling equipment allocation module

In the equipment allocation module, the flow of each type of equipment among all nodes (locations) over the duration of the whole planning horizon (PH) is controlled by network flow constraints. However, this does not translate into tracking each piece of equipment since it numerically over-burdens the model and renders it impractical. This being said, the problem should be solved simultaneously over space and time domains. In doing so, first a two dimensional network of project locations should be constructed. Then, this network will be extruded into the temporal space to encompass different states of the network with respect to resource demand along the time axis. A typical structure of a time-space network is shown in Figure 3.7.

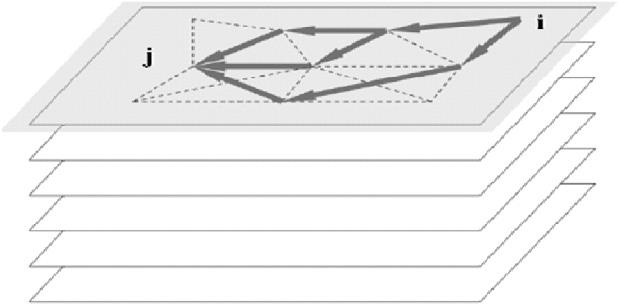


Figure 3.7- Concept of time-space network

In order to feed the equipment allocation component of the model, the resource demand schedule across all projects and over the full length of a given PH should be consolidated. However, this consolidated demand is not fixed and it changes as a result of interactions between activity scheduling and equipment allocation components of the model. Figure 3.8 illustrates a schematic view of the proposed network for modeling equipment allocation component of the model. This network system is comprised of three project locations and two time steps.

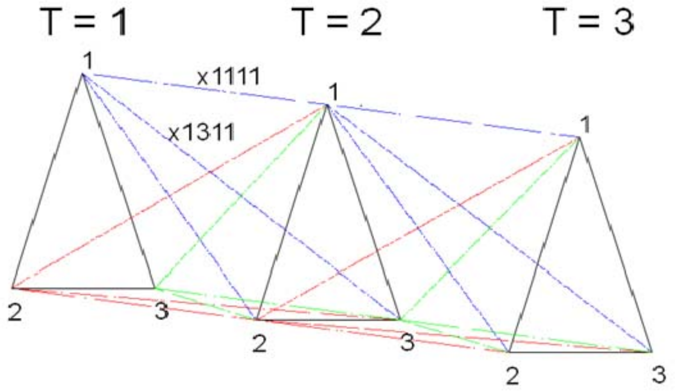


Figure 3.8- Two dimensional network of project locations extruded to temporal dimension

3.3. Assumptions and concepts

Assumptions of this model can be divided into two major categories which are discussed separately in this section. The first category includes contractual, legal and scheduling related concepts and assumptions while the second category covers assumptions, constraints and limitations which are more related to the mathematical modeling side of the problem.

3.3.1. Practical and legal concepts and assumptions

Following are some major practical assumptions based on which this model has been constructed.

- It is assumed that the portfolio for which the company is planning consists of already awarded projects. This indicates that the demands for equipment and the location at which they arise are known based on an approved activity schedule and changes can only happen in accordance with flexibilities that are available within the structure of the activity schedule.
- Typical duration of each deterministic PH over which the model provides sufficiently accurate output is between 6 to 12 weeks. Considering this, to cover the whole duration of a project, the concept of rolling time horizon has been adopted. This means the planning time horizon will be shifted from each point of update in time to the next in order to cover the total duration of a project. Through marriage of deterministic PH and the concept of rolling horizon, a practical deterministic approach toward solving scheduling problems is established. Usage of the deterministic PH framework with above-mentioned spans is common practice in the scheduling and resource planning field. Moreover, this framework can only be replaced by a stochastic approach which is out of the scope of this research.

  The mechanism through which the model captures the characteristics of the updated activity schedule up to the project's completion point is shown in the input side of Figure 3.9. The PH concept based on which the model provides its output is demonstrated in the output side of the same figure.

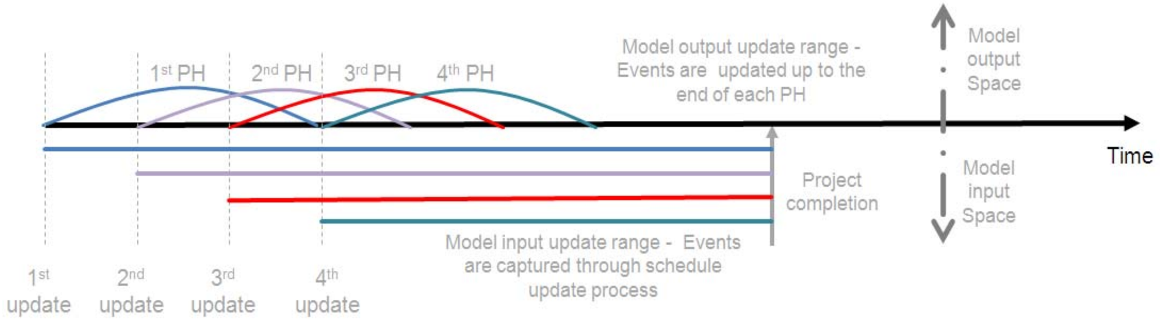


Figure 3.9- Deterministic PH and concept of rolling horizon

- As one of the advantages of this model, various contractual and legal obligations can be implanted either into its input data or into its constraints and/or objective function. For instance, AD and LD which are major contractual terms can be incorporated in the model and leverage the output through the time price parameter. This can be accomplished by assigning the appropriate price to each time slot which can be done through use of a variety of time price functions such as exponential (ae $^{(bt)}$), logarithmic (aLog(bt)) and flat (k) functions.

  All these functions are either constant or increasing which is due to the fact that generally the contribution of later time slots to overall financial damages is higher. However, the rate of this contribution which varies among different categories of time functions is relevant to the type of activity to which the time price is being assigned.

  As a general trend, for typical construction activities such as earth moving and concrete placement, flat or exponential functions are better fits because in these activities the effect of technical defects or delayed operations in the earlier stages of the activity accumulates and is transferred to the later stages. This causes the rate of contribution to overall financial damages (LD and/or AD) for the later stages of the activity to be either constant or higher.

On the other hand, for activities such as typical installations, generally logarithmic time price function is a better fit since these activities are typically a conglomeration of series of separate activities in which later parts are smaller (simpler) and can be completed (at least partially) regardless of status of major (more critical and more difficult) earlier sections of the same activity. Thus, the rate of contribution to overall financial damages (LD and/or AD) is a decreasing function of time.

Typical time functions are also shown in Figure 3.10.

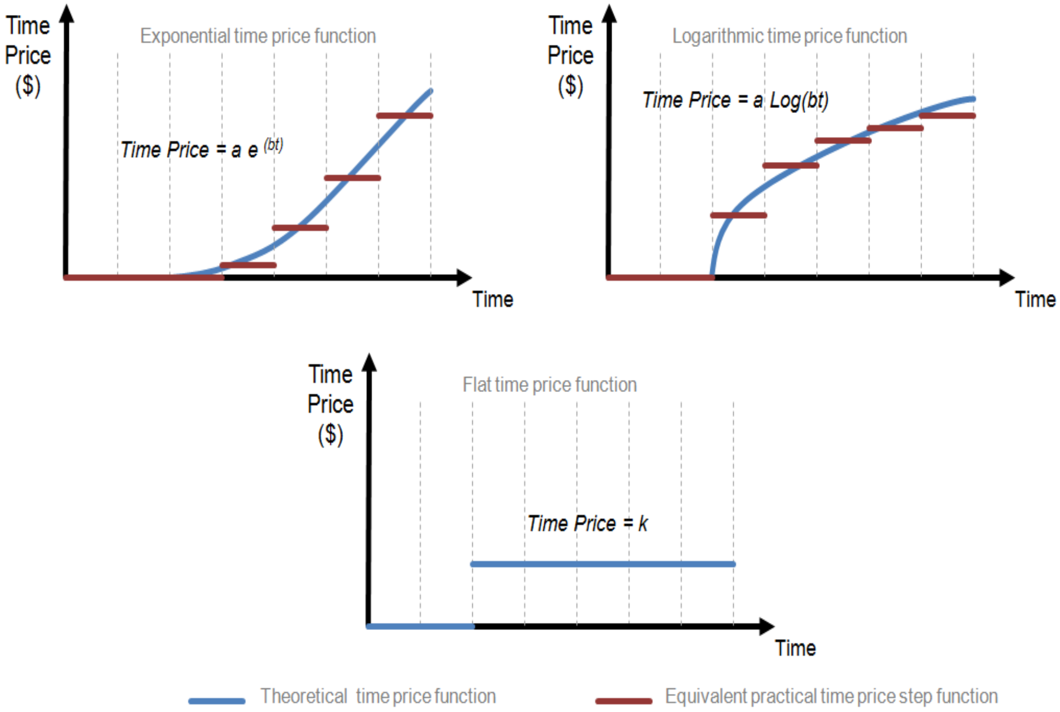


Figure 3.10- Exponential, Logarithmic and flat time price functions

Coefficients of these functions (a, b and/or k) are calibrated according to specifics of each contract, project schedule and involved activities in order to best represent the properties of that particular project.

3.3.2. Modeling assumptions

Following are some major modeling assumptions.

- Task duration, time windows and logical/technological dependencies are input data which are provided through the activity schedule for the model. These are fixed for a given problem.
- The model provides results (output) which are valid for a given deterministic PH. However, through its input parameters which directly come from the updated schedule, it captures the effects of changes over the whole duration of projects. Updates to the schedule are done whenever new data becomes available (upon emergence of new events). Figure 3.9 provides graphical representation of these assumptions.
- The proposed model uses several deterministic PHs to cover the whole duration of projects. So, a critical part of the modeling is to connect two consecutive PHs such that the network flow is not disturbed. Figure 3.11 demonstrates the mechanics of an appropriate connection as it is formulated.

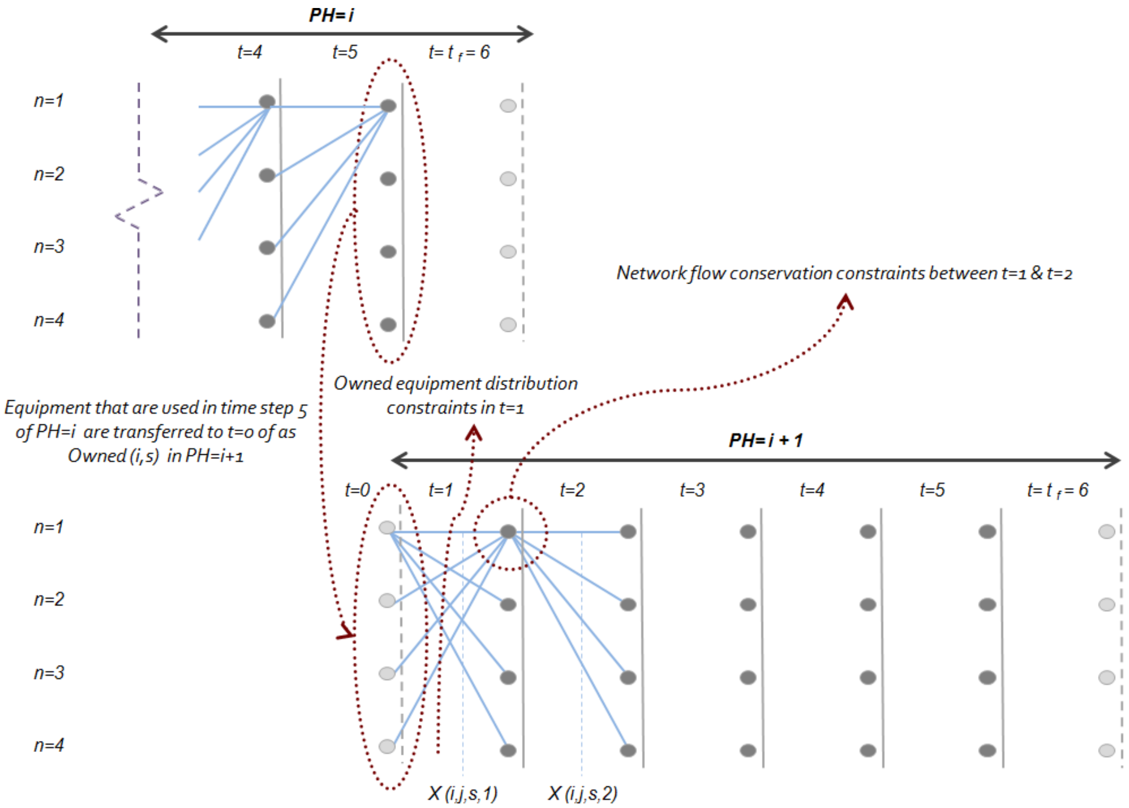


Figure 3.11- Connecting two consecutive PHs

- According to the literature, the time unit for planning purposes is typically a week. As a byproduct, this assumption prevents the model from producing impractical equipment allocation plans with sharp and close peaks and valleys. In technical terms, the choice of this time unit helps to increase the levelness of the equipment operation plan.
- The time unit of the model being at least a week implies that the travel time between any origin and destination node is insignificant in comparison to the size of the selected time unit. Additionally, since the main intention behind development of this model is to allocate heavy pieces of equipment, it is safe to assume that no less than a truck load should be transported and each piece of equipment is at least a full cargo to be shipped. As a result, when a trailer is

loaded it will travel from the origin to the destination directly, immediately and without any lapse of time. All these being accepted, it means that the transportation operations will not interfere with the flow of activities in the schedule network an thus, travel times can be eliminated from the model without any problem.

- Additionally, it is assumed that all costs are given constants (input to the model) and remain constant at least over each PH. Moreover, it is assumed that when an activity should be performed according to the schedule, its resource requirements must be assigned through allocation of owned or rental equipment fleet and no other option is available.
- It is assumed that this model is used for planning purposes. So, the running time of the model is of minimum relevance to its practicality.
- The input of this model is the data which should be driven out of the master activity schedule of the company's portfolio and the company's owned/rental equipment availability plan. Also, its output is useful for decision making in the level of the company's portfolio of projects. As a result, it can be concluded that this model is a decision support system which is helpful for making decisions at the company level and not the project level.

  Yet, even at the company level, the decision to buy pieces of heavy equipment belongs to a higher decision-making hierarchy in comparison to decisions related to portfolio planning, operation and control. Consequently, although the option of making decisions regarding purchase of heavy equipment is available in the proposed model, in majority of case studies solved in chapter 4 and 5 this option has not been exercised.

- Components of costs incurred as a result of allocation of owned and rental equipment are shown in equations 3.15 and 3.16.

$$\textit{Supply cost} = \textit{Transportation cost} + \textit{Equipment operation cost} + \textit{Maintenance cost} \quad [3.15]$$

$$\textit{Rent} = \textit{Direct rental cost} + \textit{Equipment operation cost} + \textit{Maintenance cost} \quad [3.16]$$

Additionally, since we know that the problem is structurally NP Hard, it's essential to reduce the number of decision variables as much as possible in order to increase the efficiency of the proposed model and reduce the solution time. This being said, since operation and maintenance costs are incurred for both owned and rental pieces of equipment at each working time unit, their elimination from both sides will not affect the result of optimization. Conversely, if not eliminated, a new set of decision variables should be added to the model to keep track of operation and maintenance cost of the owned pieces of equipment. This is because current decision variable that interacts with owned pieces of equipment (***X***), can only keep track of their shipments. As a result, the trick of elimination of these two cost categories and their relevant decision variables helps to reduce the computational burden and improve the efficiency of the formulation.

-The proposed model is classified under category of dynamic models, since it considers variability of the input data along the time axis and updates the output accordingly. Additionally, since the proposed model reaches solution relatively fast, it can be loaded with input and run upon emergence of any new piece of information. This capability makes it a real time model if the input data is fed into it on a real time basis.

3.4 Mathematical model

The intent of this research is to propose a model for solving the previously stated problem within a practically reasonable amount of time. In summary, solving this problem translates into finding the cost optimal pattern of both activity schedule and equipment allocation plan for an available heavy equipment fleet.

In a given solution of this problem, activities are either active or inactive in each time slot within their time window. Also, pieces of equipment are allocated to nodes in the network of projects over predefined PH(s). The structure of the solution highlights appropriateness of binary integer and space-time network platforms for modeling scheduling and equipment allocation modules respectively. These structures are the most capable of capturing the nature of this problem. The proposed formulation is an IP model that has both general and binary integer variables.

In previous sections, all underlying frameworks, practical and modeling assumptions and the model functioning mechanism have been discussed. At this stage it is possible to depict more detailed aspects of the formulation. In this section, notations and parameters of the formulation are introduced. After that, the decision variables are defined and lastly, the objective function and the constraints of the formulation are presented.

3.4.1. Sets

Set indicators (indices) which represent levels of details that are considered in the model are as follows.

i: Index of equipment origin nodes

j: Index of equipment destination or operation nodes

a: Index of activity in each node

s: Equipment type

t: First time counter

p: Second time counter

q: Third time counter

3.4.2. Parameters

Right Hand Side (RHS) matrices which contain model constants are as follows.

SUPPLY_COST(i,j,s,t): Cost of supplying equipment type ***s*** from node ***i*** to ***j*** in time period ***t***

RENT(j,s,t): Rental cost of equipment type ***s*** at node ***j*** in time period ***t***

*TIME_PRICE (j,a,t):*Price of using each time slot by each activity which is determined based on the schedule structure and contractual terms such as LD and/or AD

d (j,a) : Predicted duration of activity ***a*** at node ***j***

ES(j,a) : Early start of activity ***a*** at node ***j*** (Time window constant)

EF(j,a) : Early finish of activity ***a*** at node ***j*** (Time window constant)

LS(j,a) : Late start of activity ***a*** at node ***j*** (Time window constant)

LF(j,a) : Late finish of activity ***a*** at node ***j*** (Time window constant)

OWNED_PRICE(i,s) : Purchase price ($) of company owned equipment type ***s*** that is located in node ***i*** at ***t=0***.

DEMAND (j,a,s,t) **:** Demand for equipment type ***s*** to perform activity ***a*** at node ***j*** in time period ***t*** (# of required pieces of equipment)

C(j,s,t) : Upper bound for leveling constraint

L(j,s,t) : Lower bound for leveling constraint

U(i,j,s,t) : Upper bound on number of equipment type ***s*** transported from node ***i*** to ***j*** at time ***t*** (i.e due to transportation limitations)

F (i,j,s,t) : lower bound on number of equipment type ***s*** transported from node ***i*** to ***j*** at time ***t***. (i.e due to management policies)

CRENT(j,s,t): Local rental capacity of equipment type ***s*** at node ***j*** in time ***t***

$Cap^{1,2}(s,t)$:Owned equipment transportation cap for equipment type ***s*** in time step ***t*** between clusters ***1*** and ***2.***

Parameters introduced above, are input data (constants) for the model. Considering all of them, it can be observed that a vast amount of input data is required for running this model. This is one of the main sources of uncertainty in the results obtained from the model. In practice, input data required for this model can be provided by either generating artificial data or use of actual historical data obtained from the industry. Regardless of the source, obtained data should be trimmed and arranged in order to fit the input structure of the problem. This makes the task of feeding the model with appropriate input data extremely time consuming.

3.4.3. Decision variables

Generally, there are six sets of decision variables in this model which is important for the user to be familiar with all of them. These decision variables are as follows.

$$\mathrm{TS}_{jat} = \begin{cases} 0 & \text{if activity } \boldsymbol{a} \text{ at node } \boldsymbol{j} \text{ does not start at time slot } \boldsymbol{t} \\ 1 & \text{if activity } \boldsymbol{a} \text{ at node } \boldsymbol{j} \text{ starts at time slot } \boldsymbol{t} \end{cases}$$

$$\mathrm{TE}_{jat} = \begin{cases} 0 & \text{if activity } \boldsymbol{a} \text{ at node } \boldsymbol{j} \text{ does not end at time slot } \boldsymbol{t} \\ 1 & \text{if activity } \boldsymbol{a} \text{ at node } \boldsymbol{j} \text{ ends at time slot } \boldsymbol{t} \end{cases}$$

$$\mathrm{T}W_{jat} = \begin{cases} 0 & \text{if activity } \boldsymbol{a} \text{ at node } \boldsymbol{j} \text{ is not active at time slot } \boldsymbol{t} \\ 1 & \text{if activity } \boldsymbol{a} \text{ at node } \boldsymbol{j} \text{ is active at time slot } \boldsymbol{t} \end{cases}$$

Note: In this formulation start of each working day is considered as the basis for schedule calculations. For example, if early start of an activity is 3 and its early finish is 6 it means that working time units for that activity are time units 3, 4 and 5.

X_{ijst} = Number of equipment type ***s*** that are sent from node ***i*** and received at node ***j*** at time step ***t*** (General integer)

Y_{jst} = Number of equipment type ***s*** that are rented at node ***j*** at time step ***t*** (General integer)

OWNED_{is} = Number of company owned pieces of equipment type ***s*** that is located in node ***i*** at ***t=0***. (General integer)

3.4.4. Objective function

The objective function of the proposed formulation minimizes the operation cost which is previously defined as the summation of the costs of schedule delay and equipment allocation. This objective function is shown in equation 3.17.

$$Min\left(\begin{array}{c}\left[\sum_{j=1}^{n}\sum_{a=1}^{A(j)}\sum_{t=EF(j,a)}^{LF(j,a)}\left[(t-EF(j,a))\times TE_{jat}\times\overline{TIME\_PRICE(j,a,t)}\right]\right]\\+\left[\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{s=1}^{k}\sum_{t=1}^{tf}SUPPLY\_COST(i,j,s,t)\times X_{ijst}+\sum_{j=1}^{n}\sum_{s=1}^{k}\sum_{t=1}^{tf}RENT(j,s,t)\times Y_{jst}\right]\\+\left[\sum_{i=1}^{n}\sum_{s=1}^{k}OWNED\_PRICE(i,s)\times OWNED(i,s)\right]\end{array}\right) \quad [3.17]$$

The first term represents the cost of schedule delays which is stored in the SD parameter. This parameter stores cost of schedule delays which are incurred as a result of deviance from ES schedule baseline.

The second term represents costs of equipment allocation plan which includes cost of owned equipment transportation between origins and destinations, rental equipment costs and the initial ownership (purchasing and/or leasing) cost of heavy equipment which belong to company's owned fleet.

As mentioned previously, since this model is generally designed to be used over the course of a single PH for making short terms decisions, the value of the decision variable OWNED (i,s) is typically set to fixed values that are the number of the pieces of heavy equipment currently owned by the company. As a result, in these cases the ownership cost of heavy equipment becomes a constant value. Thus, it loses relevance to decision making and will be eliminated from the objective function.

3.4.5. Constraints

The model constraints are as follows.

Schedule module constraints:

1-The first group of constraints are time window assignment constraints.

The following set of constraints ensures that each activity has only one finish time slot.

$$\sum_{t=EF(j,a)}^{LF(j,a)} TE_{jat} = 1 \quad \text{for all } \{j = 1 \ldots n ; a = 1 \ldots A(j)\} \qquad [3.18]$$

The following set of constraints ensures that each activity has only one start time slot.

$$\sum_{t=ES(j,a)}^{LS(j,a)} TS_{jat} = 1 \quad \text{for all } \{j = 1 \ldots n ; a = 1 \ldots A(j)\} \qquad [3.19]$$

2-The second group of constraints represents logical links within the activity schedule. There are four types of these links which are Finish to Start (FS), Start to Start (SS), Finish to Finish (FF) and Start to Finish (SF). Also, each of these links can be combined with Lead or Lag components in the activity schedule. All types of precedence relationships in addition to leads and lags can be modeled by use of constraints from this set.

The following set of constraints models Finish to Start (FS) linkage between activities.

$$\sum_{t=1}^{tf} t\, TE_{j_0 a_0 t} \le \sum_{t=1}^{tf} t\, TS_{j_1 a_1 t} \qquad [3.20]$$

The following set of constraints models Start to Start (SS) linkage between activities.

$$\sum_{t=1}^{tf} t\, TS_{j_0 a_0 t} \le \sum_{t=1}^{tf} t\, TS_{j_1 a_1 t} \qquad [3.21]$$

The following set of constraints models Start to Finish (SF) linkage between activities.

$$\sum_{t=1}^{tf} t\, TS_{j_0 a_0 t} \le \sum_{t=1}^{tf} t\, TE_{j_1 a_1 t} \qquad [3.22]$$

The following set of constraints models Finish to Finish (FF) linkage between activities.

$$\sum_{t=1}^{tf} t\ TE_{j_0 a_0 t} \leq \sum_{t=1}^{tf} t\ TE_{j_1 a_1 t} \qquad [3.23]$$

3-By use of the following set of constraints for a given task, its duration will be locked. This means a task for which the duration has been locked, can float within its available time window but cannot be split into stages. Also, any task dividing pattern can be enforced by use of variations of this constraint.

$$\sum_{t=1}^{tf} t\ TE_{jat} - \sum_{t=1}^{tf} t\ TS_{jat} = \mathrm{d}(j,a) \qquad Forall\{j=1...n; a=1...A(j)\} \qquad [3.24]$$

4- By use of the following set of constraint duration requirements of each task are enforced.

$$\sum_{t=1}^{tf} TW_{jat} = \mathrm{d}(j,a) \qquad forall\{j=1...n; a=1...A(j)\} \qquad [3.25]$$

5-The following set of constraints establishes logical relation between TS- TW and TW-TE. This set of constraints ensures that for none of the activities a working period is assigned before start time slot or after finish time slot.

$$(LF(j,a)-p)\ (1-TE_{jap}) \geq \sum_{t=p}^{tf} TW_{jat}$$
$$forall\{j=1...n; a=1...A(j);\ p: EF(j,a)...LF(j,a)\}$$

[3.26]

$$(q-ES(j,a))(1-TS_{jaq}) \geq \sum_{t=1-1=0}^{q-1} TW_{jat} \qquad [3.27]$$
$$for\,all\{j=1...n; a=1...A(j);\ q: ES(j,a)...LS(j,a)\}$$

* Logic for tying TS, TW, TE

$$\left\{\begin{array}{l} If\ \ TE_{jap} \geq 1\ \ Then\ \ \sum_{t=p}^{tf} TW_{jat} \leq 0 \qquad for\,all \left\{ j = 1...n; a = 1...A(j);\ p: EF(j,a)...LF(j,a) \right\} \\ If\ \ TS_{jaq} \geq 1\ \ Then\ \ \sum_{t=1-1=0}^{q-1} TW_{jat} \leq 0 \quad for\,all \left\{ j = 1...n; a = 1...A(j);\ q: ES(j,a)...LS(j,a) \right\} \end{array}\right\}$$

Equipment operation module constraints:

6-The following set of constraints enforces the initial conditions of the problem regarding the owned pieces of equipment.

$$\sum_{j=1}^{n} X_{ijs1} = OWNED(i,s) \quad for\ all \left\{\ i = 1...n; s = 1...k\ \right\} \tag{3.28}$$

7-The following set of constraints enforces the requirements of demand satisfaction. It ensures that the number of owned pieces of equipment plus the number of rented pieces of equipment meets or exceeds the demand for each type of equipment in each project location at each time slot.

$$\sum_{i=1}^{n} X_{ijst} + Y_{jst} \geq \sum_{a=1}^{A(j)} [DEMAND\ (j,a,s,t)\ TW_{jat}] \\ for\ all \left\{ j = 1...n;\ s = 1...k;\ t = 1...t_f \right\} \tag{3.29}$$

8-The following set of constraints enforces the conservation of flow for owned pieces of equipment over the time-space network.

$$\sum_{i=1}^{n} X_{ijst} = \sum_{i=1}^{n} X_{jis(t+1)} \quad for\ all \left\{ j = 1...n;\ s = 1...k;\ t = 1...t_f - 2 \right\} \tag{3.30}$$

9-The following set of constraints enforces the levelness requirements for the allocation plan of each equipment type. In other words, it ensures that the summation of the number of allocated owned and rental pieces of each type of equipment is within a given band in each time slot.

Upper bound for leveling constraint:

$$\sum_{i=1}^{n} X_{ijst} + Y_{jst} \le C(j,s,t) \quad \mathit{for\ all} \left\{ j=1 \ldots n;\ s=1 \ldots k;\ t=1 \ldots t_f - 1 \right\} \qquad [3.31]$$

Lower bound for leveling constraint:

$$\sum_{i=1}^{n} X_{ijst} + Y_{jst} \ge L(j,s,t) \quad \mathit{for\ all} \left\{ j=1 \ldots n;\ s=1 \ldots k;\ t=1 \ldots t_f - 1 \right\} \qquad [3.32]$$

10-The following set of constraints is used for enforcement of any type of limitation on utilization of the owned pieces of equipment (i.e. strategic or physical constraints).

Utilization upper bound:

$$X_{ijst} \le U(i,j,s,t) \quad \mathit{for\ all} \left\{ i=1 \ldots n;\ j=1 \ldots n; s=1 \ldots k; t=1 \ldots t_f \right\} \qquad [3.33]$$

Utilization lower bound:

$$X_{ijst} \ge F(i,j,s,t) \quad \mathit{for\ all} \left\{ i=1 \ldots n;\ j=1 \ldots n; s=1 \ldots k; t=1 \ldots t_f \right\} \qquad [3.34]$$

11- The following set of constraints is used for enforcement of availability limitations for each type of rental equipment, in each location and at each time slot.

$$Y_{jst} \le CRENT \quad (j,s,t) \quad \mathit{for\ all} \left\{ j=1 \ldots n; s=1 \ldots k; t=1 \ldots t_f \right\} \qquad [3.35]$$

12- The following set of constraints is used to enforce clustering among jobsites.

$$\sum_{i=First\ node\ of\ cluster\ 1}^{Last\ node\ of\ cluster\ 1} \ \sum_{j=First\ node\ of\ cluster\ 2}^{Last\ node\ of\ cluster\ 2} (X_{ijst} + X_{jist}) \le Cap^{1,2}(s,t)$$

$$\mathit{for\ all} \left\{ s \in S_c; t \in T_c \right\} \qquad [3.36]$$

This set of constraint enforces certain pattern of clustering for equipment types which belong to a given subset S_c during time slots which belong to a given subset T_c.The complete mathematical formulation of the proposed model is presented in Table 3.1

Objective Function [3.17]	
$Min\left(\begin{array}{c}\left[\sum_{j=1}^{n}\sum_{a=1}^{A(j)}\sum_{t=EF(j,a)}^{LF(j,a)}\left[(t-EF(j,a))\times TE_{jat}\times\overline{TIME\_PRICE(j,a,t)}\right]\right]\\+\left[\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{s=1}^{k}\sum_{t=1}^{tf}SUPPLY\_COST\,(i,j,s,t)\times X_{ijst}+\sum_{j=1}^{n}\sum_{s=1}^{k}\sum_{t=1}^{tf}RENT\,(j,s,t)\times Y_{jst}\right]\\+\left[\sum_{i=1}^{n}\sum_{s=1}^{k}OWNED\_PRICE\,(i,s)\times OWNED\,(i,s)\right]\end{array}\right)$	
Constraints	**Equation #**
$\sum_{t=EF(j,a)}^{LF(j,a)}TE_{jat}=1$ $for\ all\ \{j=1...n\,;a=1...A(j)\}$	3.18
$\sum_{t=ES(j,a)}^{LS(j,a)}TS_{jat}=1$ $for\ all\ \{j=1...n\,;a=1...A(j)\}$	3.19
$\sum_{t=1}^{tf}t\ TE_{j_0a_0t}\leq\sum_{t=1}^{tf}t\ TS_{j_1a_1t}$	3.20
$\sum_{t=1}^{tf}t\ TS_{j_0a_0t}\leq\sum_{t=1}^{tf}t\ TS_{j_1a_1t}$	3.21
$\sum_{t=1}^{tf}t\ TS_{j_0a_0t}\leq\sum_{t=1}^{tf}t\ TE_{j_1a_1t}$	3.22
$\sum_{t=1}^{tf}t\ TE_{j_0a_0t}\leq\sum_{t=1}^{tf}t\ TE_{j_1a_1t}$	3.23
$\sum_{t=1}^{tf}t\ TE_{jat}-\sum_{t=1}^{tf}t\ TS_{jat}=\mathrm{d}(j,a)$ $For\ all\ \{j=1...n\,;a=1...A(j)\}$	3.24

$\sum_{t=1}^{tf} TW_{jat} = \mathrm{d}(j,a)$ $\textit{for all}\ \{j = 1 \ldots n; a = 1 \ldots A(j)\}$	3.25
$(LF(j,a) - p)\ (1 - TE_{jap}) \geq \sum_{t=p}^{tf} TW_{jat}$ $\textit{for all}\ \{j = 1 \ldots n; a = 1 \ldots A(j); p : EF(j,a) \ldots LF(j,a)\}$	3.26
$(q - ES(j,a))(1 - TS_{jaq}) \geq \sum_{t=1-1=0}^{q-1} TW_{jat}$ $\textit{for all}\ \{j = 1 \ldots n; a = 1 \ldots A(j);\ q : ES(j,a) \ldots LS(j,a)\}$	3.27
$\sum_{j=1}^{n} X_{ijs1} = OWNED \quad (i,s)$ $\textit{for all}\ \{i = 1 \ldots n; s = 1 \ldots k\}$	3.28
$\sum_{i=1}^{n} X_{ijst} + Y_{jst} \geq \sum_{a=1}^{A(j)} [DEMAND\ (j,a,s,t)\ TW_{jat}]$ $\textit{for all}\ \{j = 1 \ldots n;\ s = 1 \ldots k;\ t = 1 \ldots t_f\}$	3.29
$\sum_{i=1}^{n} X_{ijst} = \sum_{i=1}^{n} X_{jis(t+1)}$ $\textit{for all}\ \{j = 1 \ldots n;\ s = 1 \ldots k;\ t = 1 \ldots t_f - 2\}$	3.30
$\sum_{i=1}^{n} X_{ijst} + Y_{jst} \leq C(j,s,t)$ $\textit{for all}\ \{j = 1 \ldots n;\ s = 1 \ldots k;\ t = 1 \ldots t_f - 1\}$	3.31
$\sum_{i=1}^{n} X_{ijst} + Y_{jst} \geq L(j,s,t)$ $\textit{for all}\ \{j = 1 \ldots n;\ s = 1 \ldots k;\ t = 1 \ldots t_f - 1\}$	3.32
$X_{ijst} \leq U(i,j,s,t)$ $\textit{for all}\ \{i = 1 \ldots n; j = 1 \ldots n; s = 1 \ldots k; t = 1 \ldots t_f\}$	3.33

$X_{ijst} \geq F(i, j, s, t)$ $for\ all\ \left\{ i = 1 \ldots n;\ j = 1 \ldots n;\ s = 1 \ldots k; t = 1 \ldots t_f \right\}$	3.34
$Y_{jst} \leq CRENT\ (j, s, t)$ $for\ all\ \left\{ j = 1 \ldots n; s = 1 \ldots k; t = 1 \ldots t_f \right\}$	3.35
$\sum_{i=First\ node\ of\ cluster\ 1}^{Last\ node\ of\ cluster\ 1} \sum_{j=First\ node\ of\ cluster\ 2}^{Last\ node\ of\ cluster\ 2} (X_{ijst} + X_{jist}) \leq Cap^{1,2}(s,t)$ $for\ all \left\{ s \in S_c; t \in T_c \right\}$	3.36

Table 3.1- Complete mathematical formulation of the proposed formulation

Chapter 4: Model Validation

This chapter is dedicated to discussion on validation process of the proposed mathematical formulation. To validate the model, its overall stability, functionality of its features, its sensitivity to input parameters and accuracy of its output should be verified. This chapter includes five small examples that are set up to accomplish above-mentioned goals. More specifically, in each problem one key input parameter or feature of the model is tested and outputs are compared against accurate manually obtained solutions. At the end of this stage the model is validated and will be ready to be used for solving practical size problems with real world data.

4.1. Computational set up (System hardware and software package)

In this research a system with the following specifications has been used.

- CPU: Intel Core duo E8200 @ 2.66 GHz
- Installed memory (RAM): 4 GB
- Operation System (OS): Windows 7 enterprise; service pack 3; 64 bit
- Optimization solver: Xpress optimizer 7.0; 64 bit
- Coding language: Xpress Mosel

Xpress is a commercial optimization package from FICO^{TM} Company that solves mathematical formulations in the forms of linear programs (LP), integer programs (IP), quadratic programs (QP) and nonlinear programs (NLP). Xpress solver has its own code editor (Mosel) which has been used in this study.

4.2. Formulation and code validation problems

In this section small size examples for validation of the formulation and the code are designed and solved. Results are interpreted and checked for accuracy against manual solution. The general scenario is defined below.

- The company has 2 earth moving projects in 2 different localities
- Each project has 2 activities (i.e. cut and fill)
- 2 types of equipment (i.e. bulldozer and dump truck) and 2 pieces of each type form the owned fleet of the company are available for the operation
- Each job site has 1 piece of each equipment type at the beginning of planning horizon (t=1)

- Deterministic PH is 5 time units
- Availability of rental equipment for each type of equipment in each location is 4 units
- Rent for all different equipment types in all locations is $200 in time slots 1,2 and 5 while it is $400 in time slots 3 and 4.

$$\text{Rent}(j,s,t) = \$200 \quad \text{for } t=1,2,5\ ;\ \text{Rent}(j,s,t) = \$400 \quad \text{for } t=3,4$$

- ES schedule and resource demand are given
- The problem is designed so that the owned equipment fleet does not satisfy the equipment demand of the portfolio and should be supplemented with a rental fleet.

Both projects' schedules are integrated into a single master schedule for each example. The major product of this master schedule is the equipment demand schedule that becomes available for internal use by the equipment allocation module of the formulation. This is a schedule that simply states the number of required pieces of equipment, in each time slot for each task in each project when that particular task is active in that time slot.

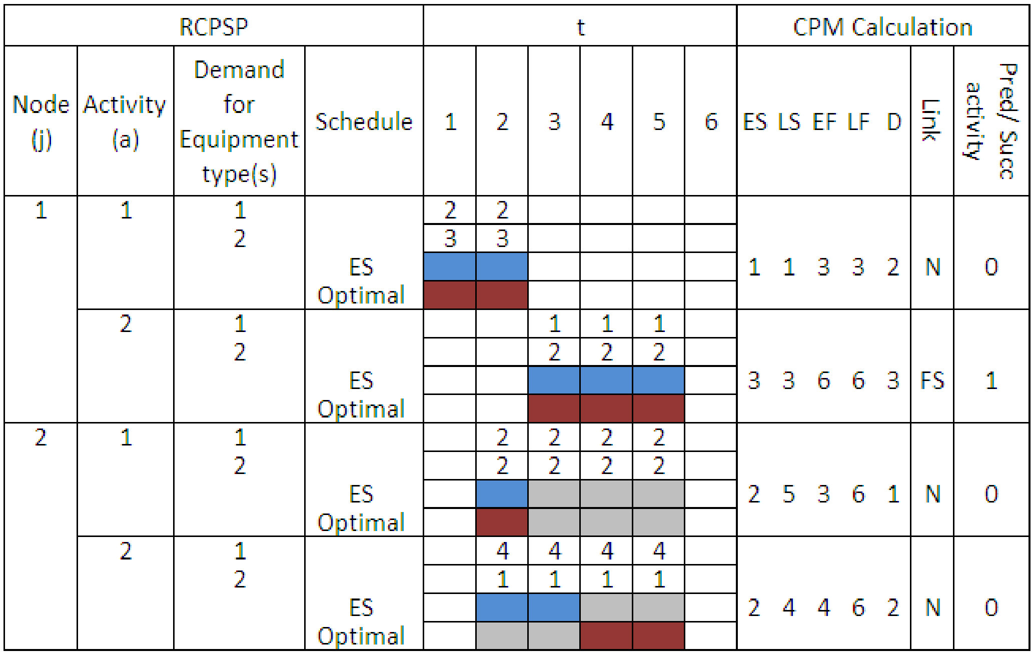
Along with circumstances that are the same in all examples, there are other parameters that are variable for different examples. However, all these pieces of information are assumed to be known constants for each example and are fed into the model in the format of input matrices. Also, all validation examples #1 to #4 have 92 constraints and 107 decision variables while example #5 has 131 constraints.

4.2.1. Example #1

The variable parameters for the first example are described below.

- A flat price function has been assigned to time slots; Time Price(j, a, t) = $ 100
- Cost of transportation for all different types of equipment from each node to another is $ 100 and the cost of transportation from each node to itself is $ 0.
  - Supply cost(i , j, s, t) = $100 for i ≠j and for i=j Supply cost(i , j, s, t) = $ 0
- Tasks are locked and cannot be split into stages

The question is to determine the optimal activity schedule and equipment allocation plan. The ES master schedule along with the optimal schedule for the first example is shown in Figure 4.1.



RCPSP				t						CPM Calculation						
Node (j)	Activity (a)	Demand for Equipment type(s)	Schedule	1	2	3	4	5	6	ES	LS	EF	LF	D	Link	Pred/ Succ activity
1	1	1		2	2					1	1	3	3	2	N	0
		2		3	3											
			ES	🟦	🟦											
			Optimal	🟥	🟥											
	2	1				1	1	1		3	3	6	6	3	FS	1
		2				2	2	2								
			ES			🟦	🟦	🟦								
			Optimal			🟥	🟥	🟥								
2	1	1			2	2	2	2		2	5	3	6	1	N	0
		2			2	2	2	2								
			ES		🟦	▨	▨	▨								
			Optimal		🟥	▨	▨	▨								
	2	1			4	4	4	4		2	4	4	6	2	N	0
		2			1	1	1	1								
			ES		🟦	🟦	▨	▨								
			Optimal		▨	▨	🟥	🟥								

Note: Start of the day is the measuring point

Figure 4.1- ES vs. Optimal activity schedule for example #1

The resource utilization plan for both the ES and the optimal schedules are shown in Figure 4.2 for each type of equipment.

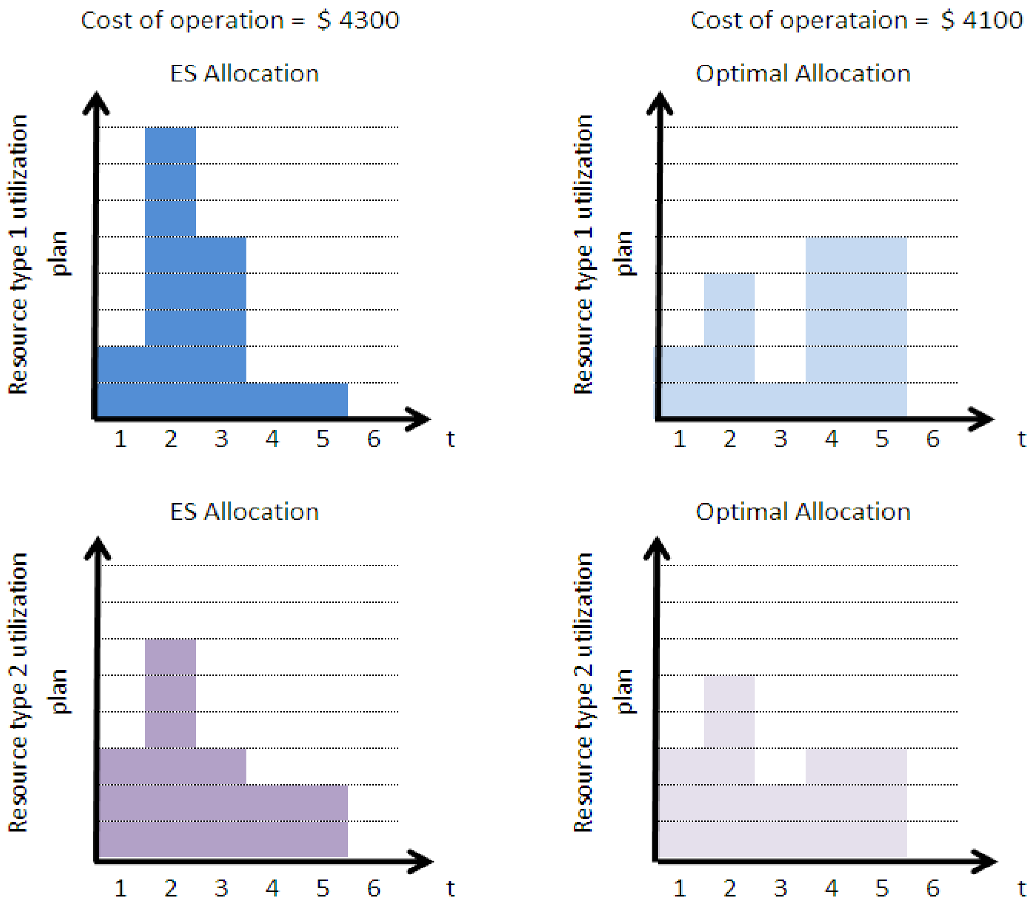


Figure 4.2- Resource utilization plan for example #1

The deployment plan for owned pieces of equipment in the example #1 is shown in Figure 4.3. To improve the understanding of the reader about the deployment plan and the correct approach for its interpretation, the following notes are important to consider.

From a practical point of view, each time unit (week) is divided into two segments. The first segment which is the non-working period of the time unit (i.e. weekend of week # n-1) is allocated to shipping activities. This section is followed by a working period (i.e.

weekdays of the week #n) in which pieces of equipment are already in place and the work is being performed. Therefore, shipping activities will not interfere with the equipment's designated operation plans.

Also, when a piece of equipment stays at a location over more than one time period, from a modeling perspective it still has been shipped from the origin node to the destination node which in this case are identical, in order to fulfill constraints related to the problem's time space network. This particular type of shipment has not been eliminated from the graphical representations of the deployment plans and is shown with circular arrows, in Figure 4.3, to make these plans more understandable for the readers. Also, in some cases this stay might be associated with a holding cost and as a result having this particular piece of information in the output becomes important.

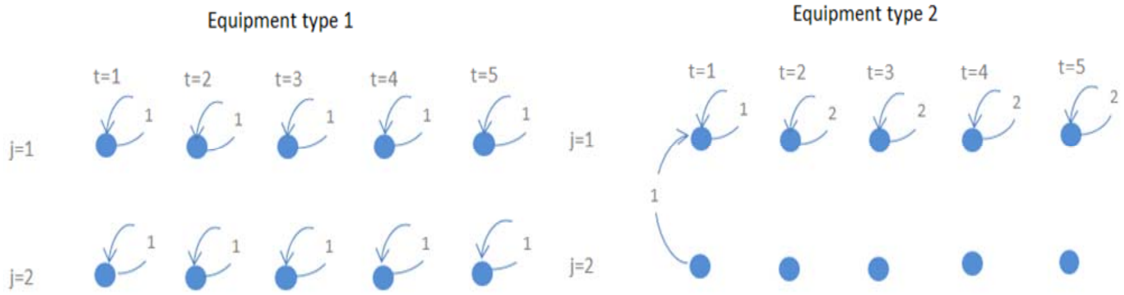
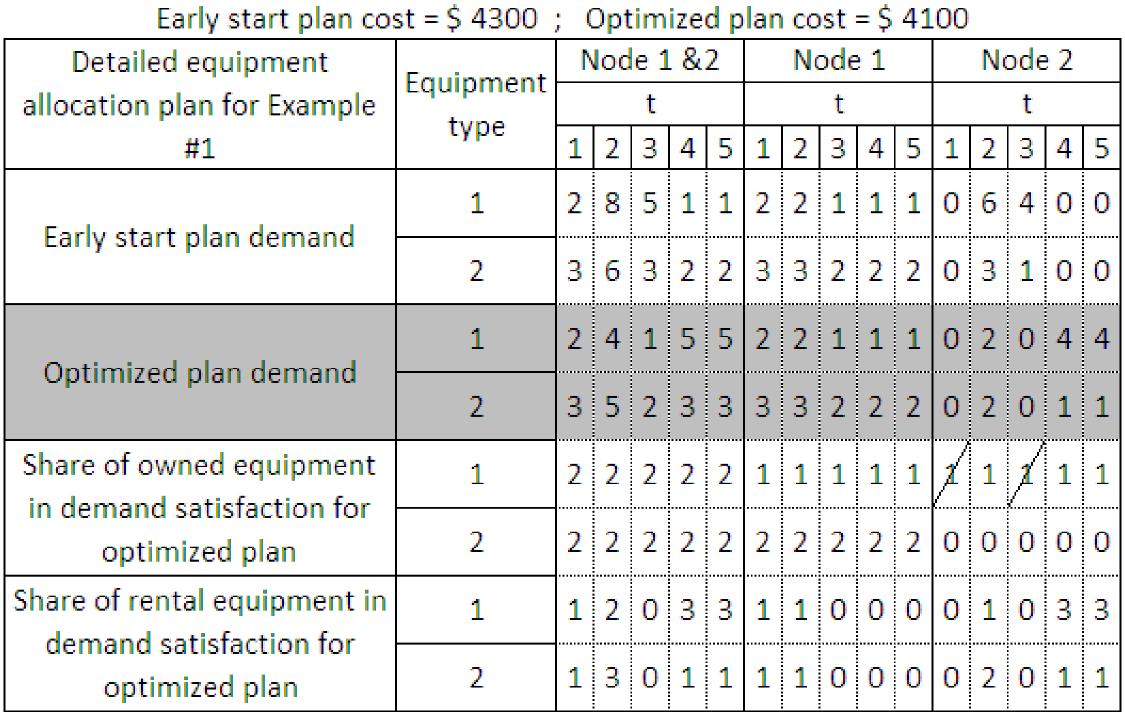


Figure 4.3- Owned equipment fleet deployment plan in example #1 (Numbers shown on arrows are number of shipped pieces of owned equipment)

As a result of combining outputs shown in Figures 4.2 and 4.3, the number of pieces of equipment that should be rented in each time slot and in each location can be calculated. The detailed equipment allocation plan for example # 1 is presented in Table 4.1. The highlighted section of the table shows the optimal schedule equipment demand and crossed cells represent idle pieces of equipment.



Early start plan cost = $ 4300 ; Optimized plan cost = $ 4100

Detailed equipment allocation plan for Example #1	Equipment type	Node 1 &2					Node 1					Node 2				
		t					t					t				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Early start plan demand	1	2	8	5	1	1	2	2	1	1	1	0	6	4	0	0
	2	3	6	3	2	2	3	3	2	2	2	0	3	1	0	0
Optimized plan demand	1	2	4	1	5	5	2	2	1	1	1	0	2	0	4	4
	2	3	5	2	3	3	3	3	2	2	2	0	2	0	1	1
Share of owned equipment in demand satisfaction for optimized plan	1	2	2	2	2	2	1	1	1	1	1	~~1~~	1	~~1~~	1	1
	2	2	2	2	2	2	2	2	2	2	2	0	0	0	0	0
Share of rental equipment in demand satisfaction for optimized plan	1	1	2	0	3	3	1	1	0	0	0	0	1	0	3	3
	2	1	3	0	1	1	1	1	0	0	0	0	2	0	1	1

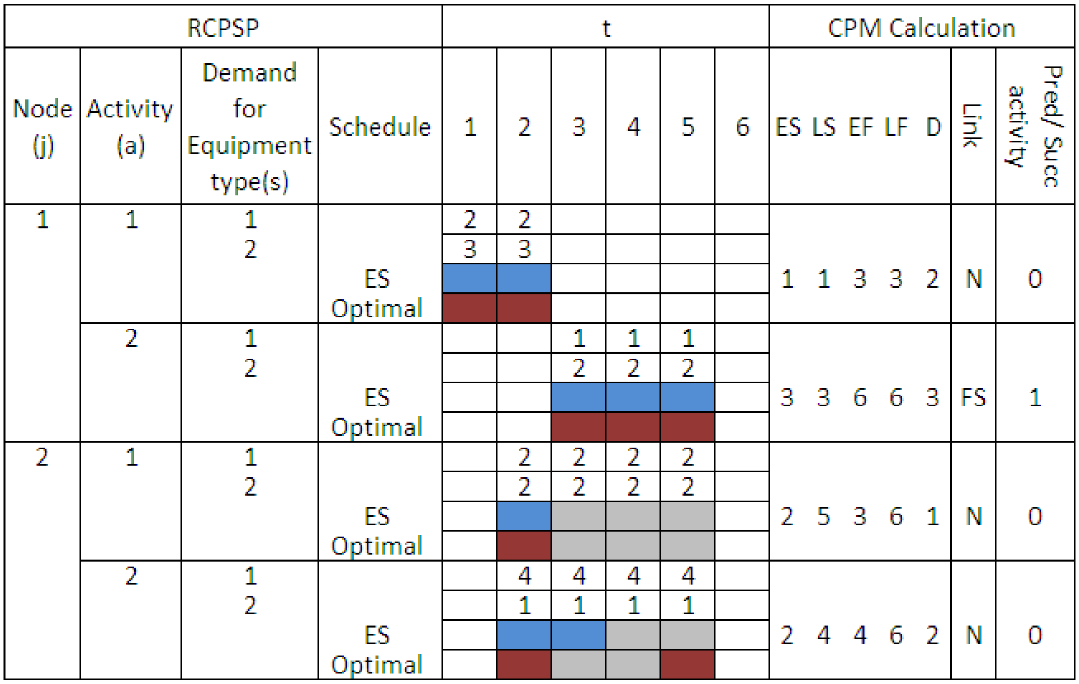
Table 4.1- Detailed equipment allocation plan for example #1

By having this optimized schedule, equipment utilization plan, owned equipment deployment plan and detailed equipment allocation breakdown for owned and rental equipment, all required pieces of information for optimal operation are revealed for the portfolio managers to appropriately act on.

4.2.2. Example #2

The variable parameters for the second example are described below. The only difference between examples #1 and #2 is the fact that tasks are unlocked so they can be split into stages if required in example #2.

The question is to determine the optimal activity schedule and equipment allocation plan. The ES master schedule along with the optimal schedule for the second example is shown in Figure 4.4.



RCPSP				t						CPM Calculation						
Node (j)	Activity (a)	Demand for Equipment type(s)	Schedule	1	2	3	4	5	6	ES	LS	EF	LF	D	Link	Pred/ Succ activity
1	1	1		2	2											
		2		3	3											
			ES	🟦	🟦					1	1	3	3	2	N	0
			Optimal	🟥	🟥											
	2	1				1	1	1								
		2				2	2	2								
			ES			🟦	🟦	🟦		3	3	6	6	3	FS	1
			Optimal			🟥	🟥	🟥								
2	1	1			2	2	2	2								
		2			2	2	2	2								
			ES		🟦	▨	▨	▨		2	5	3	6	1	N	0
			Optimal		🟥	▨	▨	▨								
	2	1			4	4	4	4								
		2			1	1	1	1								
			ES		🟦	🟦	▨	▨		2	4	4	6	2	N	0
			Optimal		🟥	▨	▨	🟥								

Note: Start of the day is the measuring point

Figure 4.4- ES vs. Optimal activity schedule for example #2

The resource utilization plan for both the ES and the optimal schedules are shown in Figure 4.5 for each type of equipment.

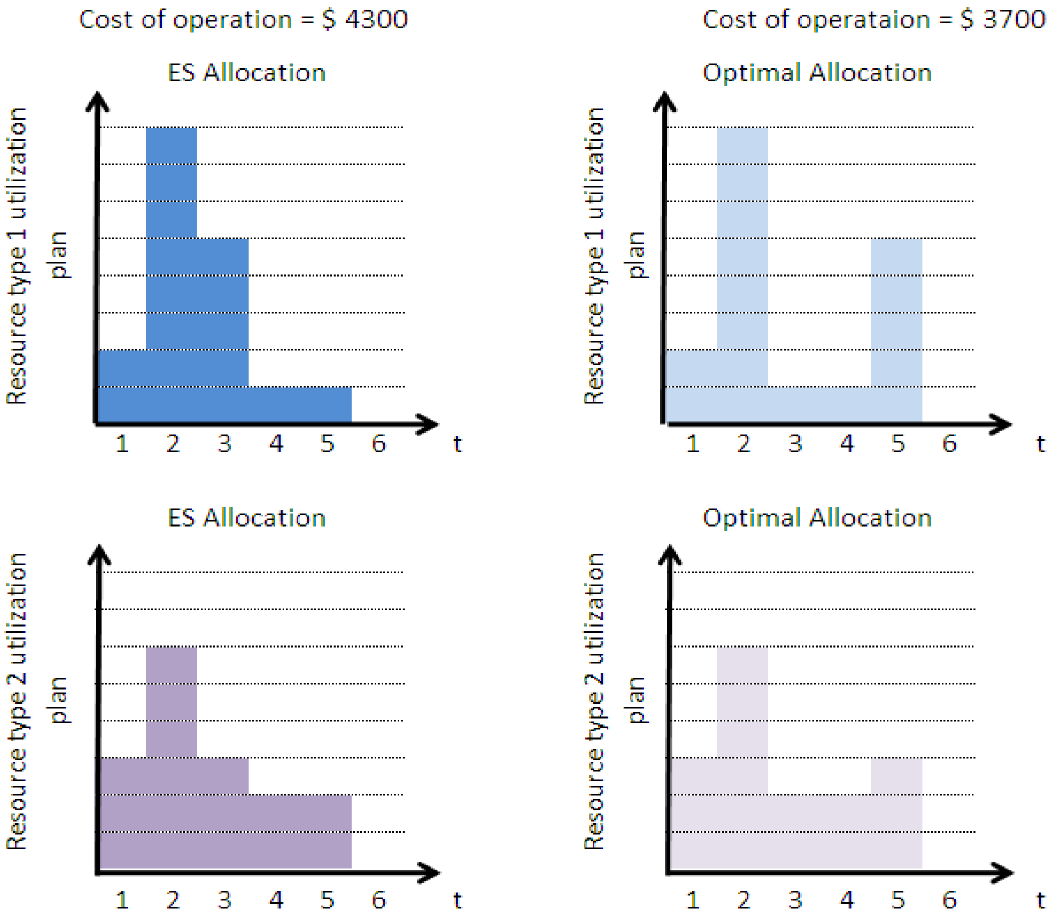


Figure 4.5- Resource utilization plan for example #2

The deployment plan for owned pieces of equipment are shown in Figure 4.6

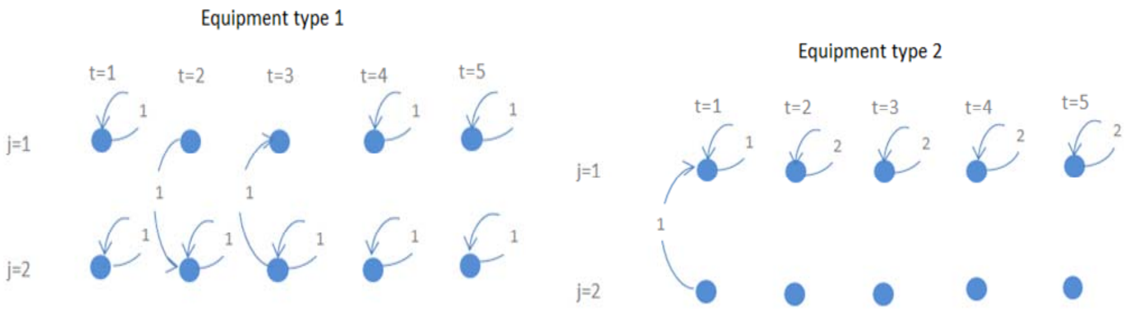
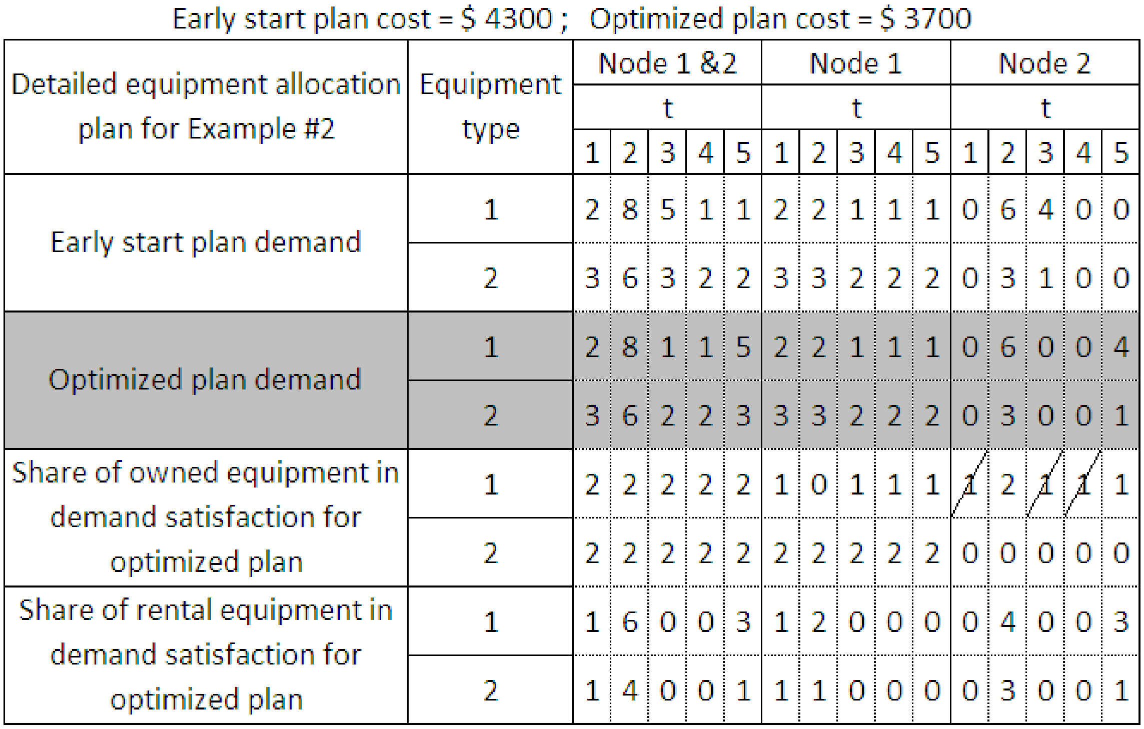


Figure 4.6- Owned equipment fleet deployment plan in example #2 (Numbers shown on arrows are number of shipped pieces of owned equipment)

As a result of combining outputs shown in Figures 4.5 and 4.6, the number of rental pieces of equipment that should be rented in each time slot and in each location can be calculated.

The detailed equipment allocation plan for example # 2 is presented in Table 4.2. The highlighted section of the table shows the optimal schedule equipment demand and crossed cells represent idle pieces of equipment.



Early start plan cost = $ 4300 ;   Optimized plan cost = $ 3700

Detailed equipment allocation plan for Example #2	Equipment type	Node 1 &2					Node 1					Node 2				
		t					t					t				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Early start plan demand	1	2	8	5	1	1	2	2	1	1	1	0	6	4	0	0
	2	3	6	3	2	2	3	3	2	2	2	0	3	1	0	0
Optimized plan demand	1	2	8	1	1	5	2	2	1	1	1	0	6	0	0	4
	2	3	6	2	2	3	3	3	2	2	2	0	3	0	0	1
Share of owned equipment in demand satisfaction for optimized plan	1	2	2	2	2	2	1	0	1	1	1	~~1~~	2	~~1~~	~~1~~	1
	2	2	2	2	2	2	2	2	2	2	2	0	0	0	0	0
Share of rental equipment in demand satisfaction for optimized plan	1	1	6	0	0	3	1	2	0	0	0	0	4	0	0	3
	2	1	4	0	0	1	1	1	0	0	0	0	3	0	0	1

Table 4.2- Detailed equipment allocation plan for example #2

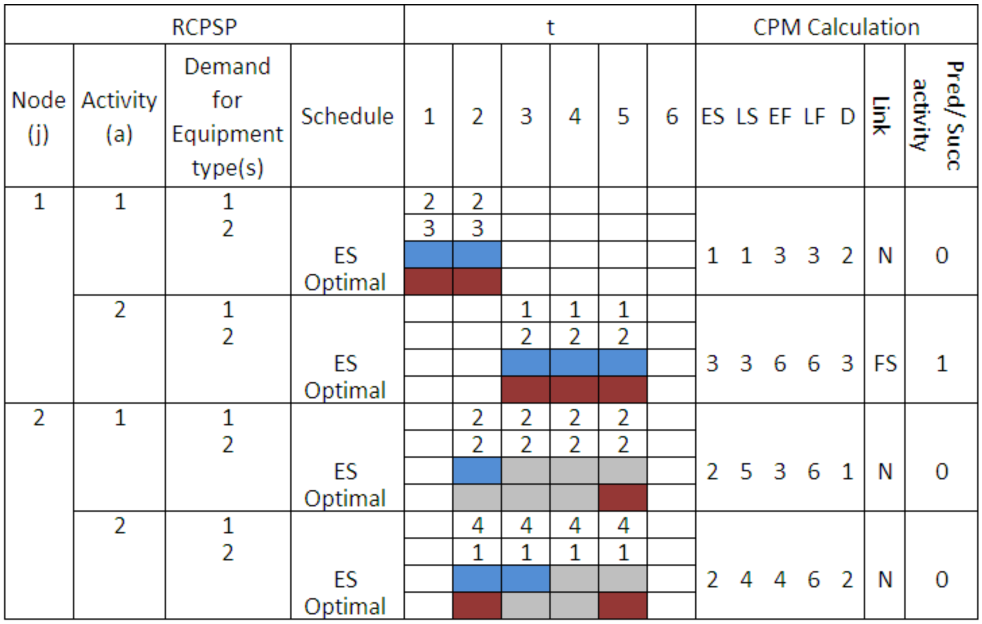
4.2.3. Example #3

The variable parameters for the third example are described below. The only difference between this example and example #2 is the change in supply costs.

- Cost of transportation for all different types of equipment from each node to another is \$ 100 in time slots 1,2 and 5 and it is \$ 1,000 in time slots 3 and 4. Cost of transportation from each node to itself is \$ 0.

$$\text{Supply cost}(i,j,s,t) = \$100 \text{ for } i \neq j \text{ and } t = 1,2,5 \text{ Supply cost}(i,j,s,t) = \$\,1{,}000 \text{ for } i \neq j \text{ and } t = 3,4 \text{ and for } i = j \text{ Supply cost}(i,j,s,t) = \$0$$

The question is to determine the optimal activity schedule and the equipment allocation plan. The ES master schedule along with the optimal schedule for the third example is shown in Figure 4.7.



RCPSP				t						CPM Calculation						
Node (j)	Activity (a)	Demand for Equipment type(s)	Schedule	1	2	3	4	5	6	ES	LS	EF	LF	D	Link	Pred/ Succ activity
1	1	1		2	2					1	1	3	3	2	N	0
		2		3	3											
			ES	🟦	🟦											
			Optimal	🟥	🟥											
	2	1				1	1	1		3	3	6	6	3	FS	1
		2				2	2	2								
			ES			🟦	🟦	🟦								
			Optimal			🟥	🟥	🟥								
2	1	1			2	2	2	2		2	5	3	6	1	N	0
		2			2	2	2	2								
			ES		🟦	▨	▨	▨								
			Optimal		▨	▨	▨	🟥								
	2	1			4	4	4	4		2	4	4	6	2	N	0
		2			1	1	1	1								
			ES		🟦	🟦	▨	▨								
			Optimal		🟥	▨	▨	🟥								

Note: Start of the day is the measuring point

Figure 4.7- ES vs. Optimal activity schedule for example #3

The resource utilization plan for both the ES and the optimal schedules are shown in Figure 4.8 for each type of equipment.

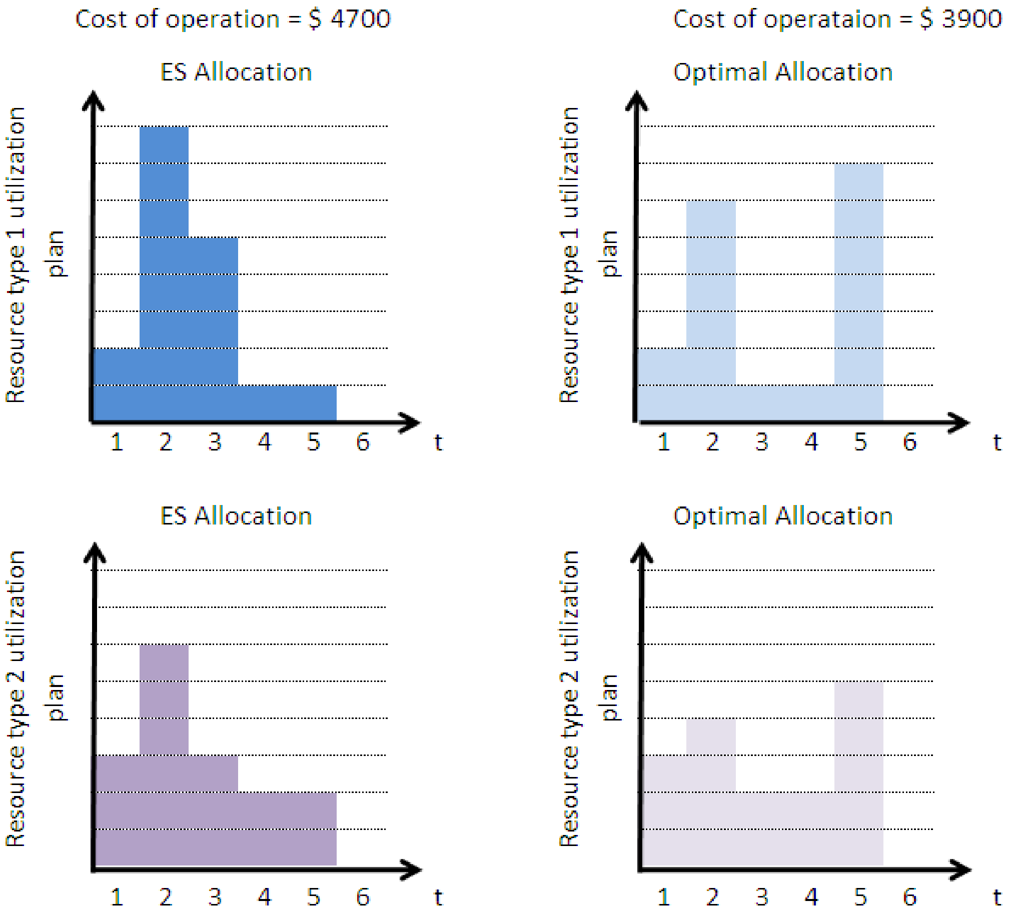


Figure 4.8- Resource utilization plan for example #3

The deployment plan for owned pieces of equipment are shown in Figure 4.9

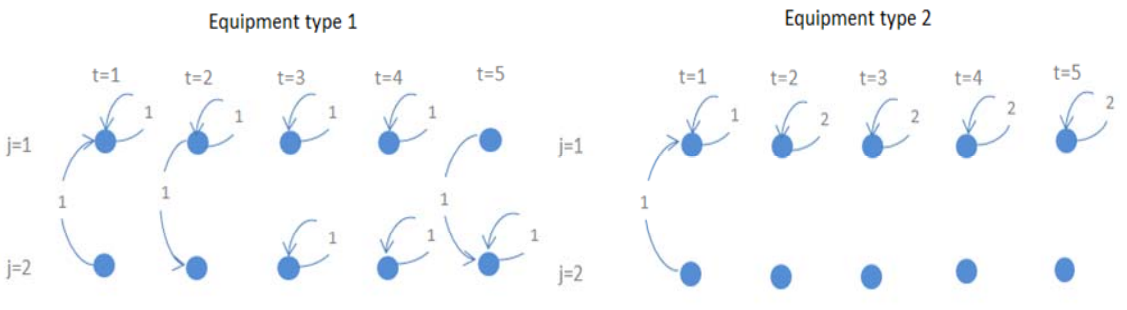
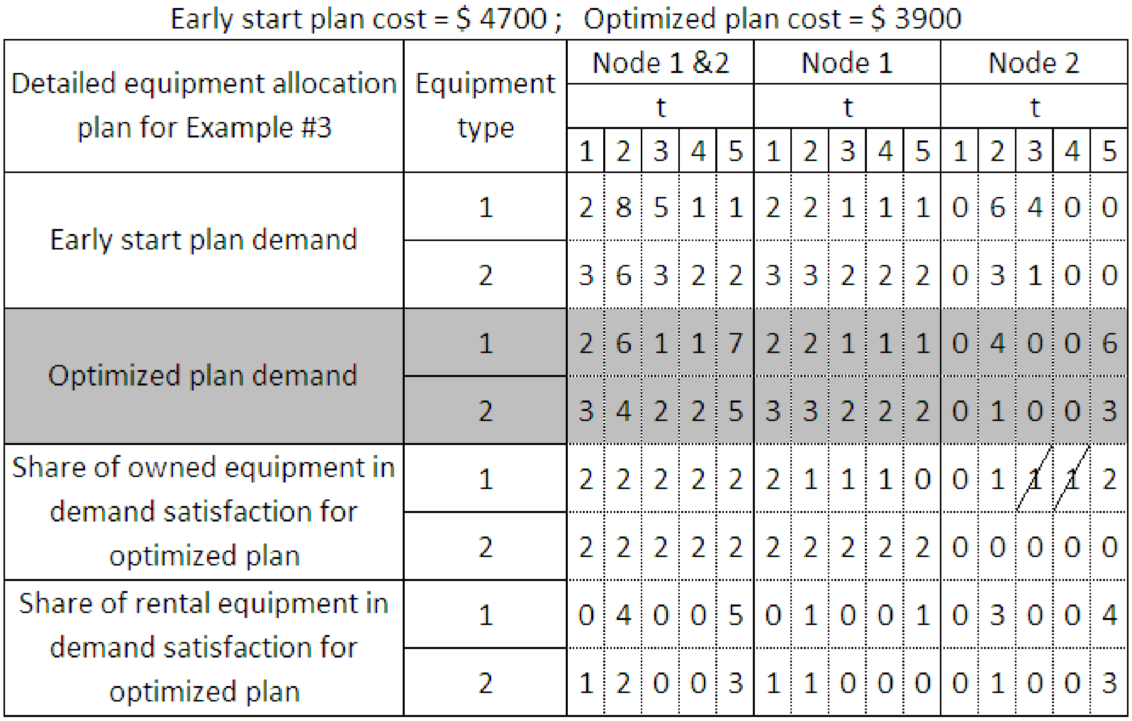


Figure 4.9- Owned equipment fleet deployment plan in example #3 (Numbers shown on arrows are number of shipped pieces of owned equipment)

As a result of combining outputs shown in Figures 4.8 and 4.9, the number of pieces of equipment that should be rented in each time slot and in each location can be calculated.

The detailed equipment allocation plan for example # 3 is presented in Table 4.3. The highlighted section of the table shows the optimal schedule equipment demand and crossed cells represent idle pieces of equipment.



Early start plan cost = $ 4700 ; Optimized plan cost = $ 3900

Detailed equipment allocation plan for Example #3	Equipment type	Node 1 &2					Node 1					Node 2				
		t					t					t				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Early start plan demand	1	2	8	5	1	1	2	2	1	1	1	0	6	4	0	0
	2	3	6	3	2	2	3	3	2	2	2	0	3	1	0	0
Optimized plan demand	1	2	6	1	1	7	2	2	1	1	1	0	4	0	0	6
	2	3	4	2	2	5	3	3	2	2	2	0	1	0	0	3
Share of owned equipment in demand satisfaction for optimized plan	1	2	2	2	2	2	2	1	1	1	0	0	1	~~1~~	~~1~~	2
	2	2	2	2	2	2	2	2	2	2	2	0	0	0	0	0
Share of rental equipment in demand satisfaction for optimized plan	1	0	4	0	0	5	0	1	0	0	1	0	3	0	0	4
	2	1	2	0	0	3	1	1	0	0	0	0	1	0	0	3

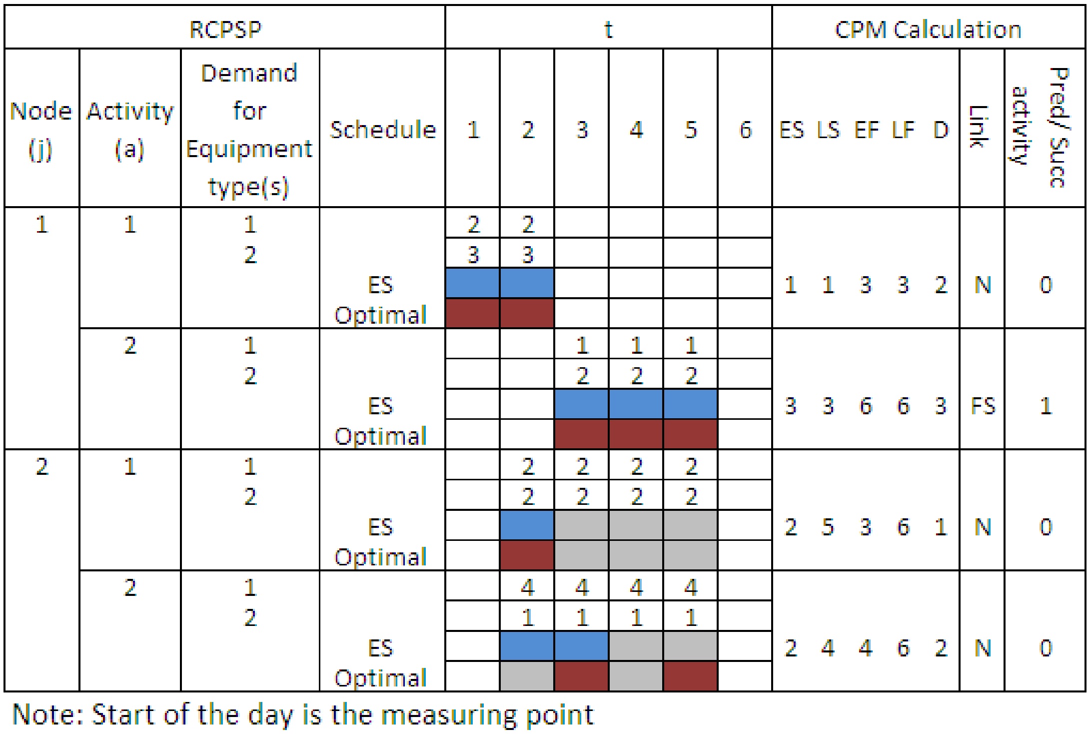
Table 4.3- Detailed equipment allocation plan for example #3

4.2.4. Example #4

The variable parameters for the fourth example are described below. The only difference between this example and example #3 is the fact that the time slot prices are not constant.

- Time Price(j,a,t) = \$100 for $j \neq 2, a \neq 1, t \neq 4,5,6$; Time Price(2,1,4) = \$ 2,000 ; Time Price(2,1,5) = \$3,000 ; Time Price(2,1,6) = \$ 4,000

The question is to determine the optimal activity schedule and the equipment allocation plan. The ES master schedule along with the optimal schedule for the fourth example is shown in Figure 4.10.



RCPSP				t						CPM Calculation						
Node (j)	Activity (a)	Demand for Equipment type(s)	Schedule	1	2	3	4	5	6	ES	LS	EF	LF	D	Link	Pred/ Succ activity
1	1	1		2	2											
		2		3	3											
			ES	🟦	🟦					1	1	3	3	2	N	0
			Optimal	🟥	🟥											
	2	1				1	1	1								
		2				2	2	2								
			ES			🟦	🟦	🟦		3	3	6	6	3	FS	1
			Optimal			🟥	🟥	🟥								
2	1	1			2	2	2	2								
		2			2	2	2	2								
			ES		🟦	▨	▨	▨		2	5	3	6	1	N	0
			Optimal		🟥	▨	▨	▨								
	2	1			4	4	4	4								
		2			1	1	1	1								
			ES		🟦	🟦	▨	▨		2	4	4	6	2	N	0
			Optimal		▨	🟥	▨	🟥								

Note: Start of the day is the measuring point

Figure 4.10- ES vs. Optimal activity schedule for example #4

The resource utilization plan for both the ES and the optimal schedules are shown in Figure 4.11 for each type of equipment.

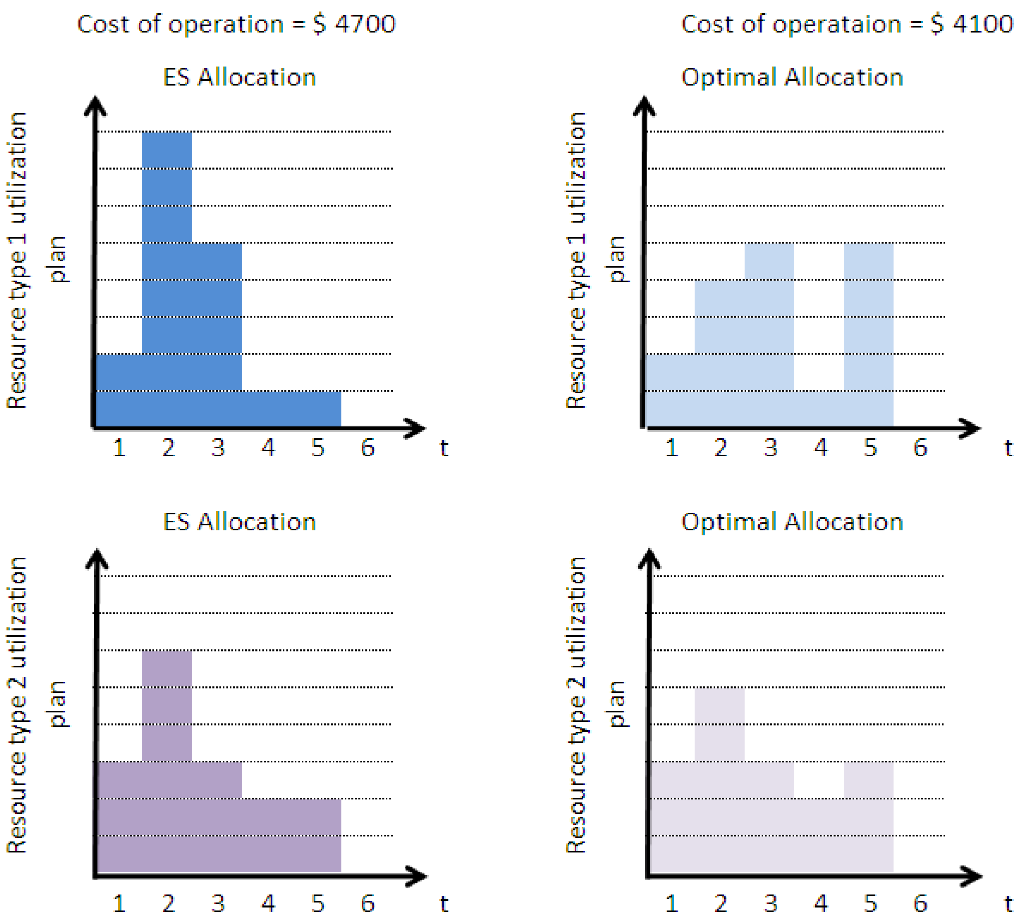


Figure 4.11- Resource utilization plan for example #4

The deployment plan for the owned pieces of equipment are shown in Figure 4.12

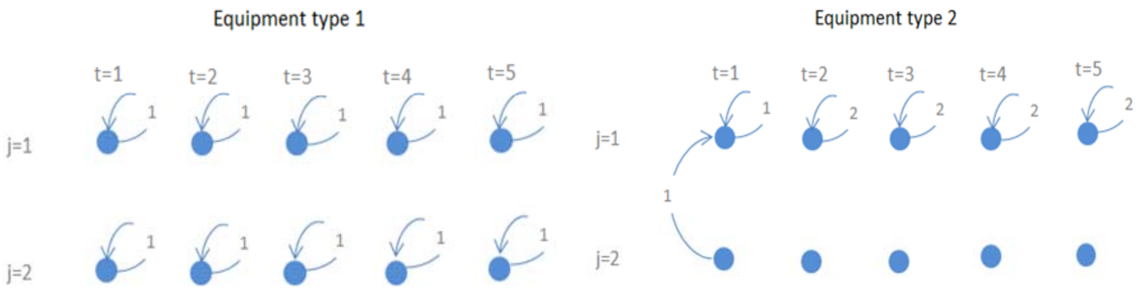


Figure 4.12- Owned equipment fleet deployment plan in example #4 (Numbers shown on arrows are number of shipped pieces of owned equipment)

As a result of combining outputs shown in Figures 4.11 and 4.12, the number of pieces of equipment that should be rented in each time slot and in each location can be calculated.

The detailed equipment allocation plan for example # 4 is presented in Table 4.4. The highlighted section of the table shows the optimal schedule equipment demand and crossed cells represent idle pieces of equipment.

Early start plan cost = $ 4700 ; Optimized plan cost = $ 4100

Detailed equipment allocation plan for Example #4	Equipment type	Node 1 &2					Node 1					Node 2				
		t					t					t				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Early start plan demand	1	2	8	5	1	1	2	2	1	1	1	0	6	4	0	0
	2	3	6	3	2	2	3	3	2	2	2	0	3	1	0	0
Optimized plan demand	1	2	4	5	1	5	2	2	1	1	1	0	2	4	0	4
	2	3	5	3	2	3	3	3	2	2	2	0	2	1	0	1
Share of owned equipment in demand satisfaction for optimized plan	1	2	2	2	2	2	1	1	1	1	1	$\cancel{1}$	1	1	$\cancel{1}$	1
	2	2	2	2	2	2	2	2	2	2	2	0	0	0	0	0
Share of rental equipment in demand satisfaction for optimized plan	1	1	2	3	0	3	1	1	0	0	0	0	1	3	0	3
	2	1	3	1	0	1	1	1	0	0	0	0	2	1	0	1

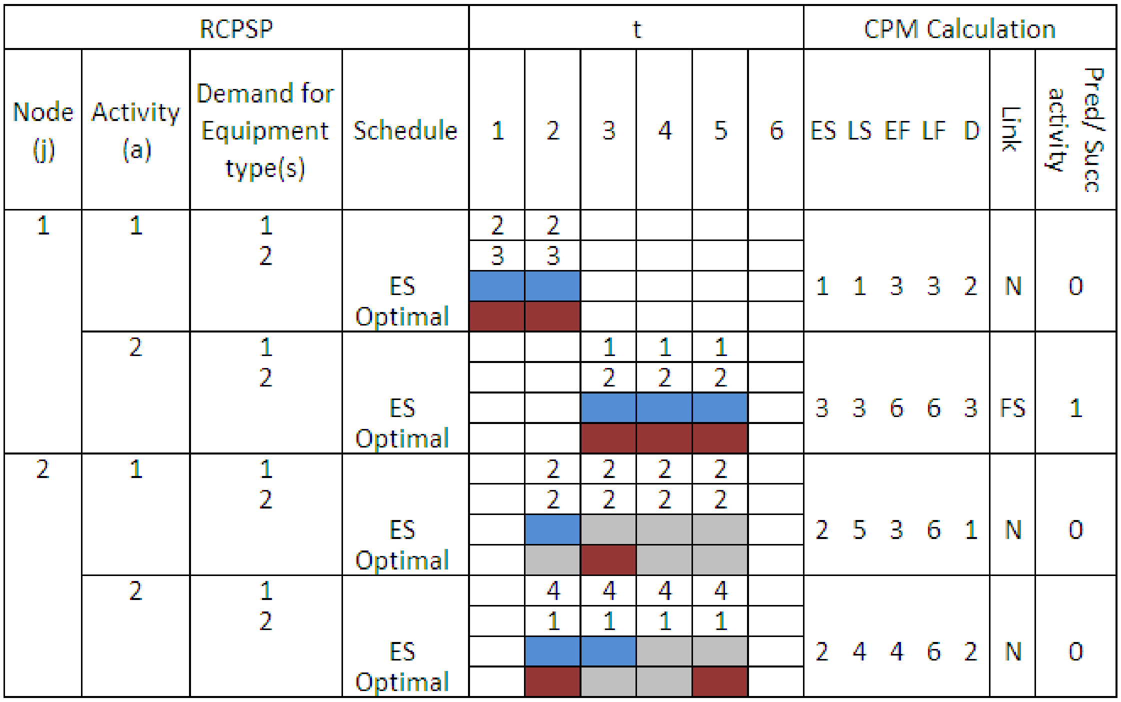
Table 4.4- Detailed equipment allocation plan for example #4

4.2.5. Example #5

Example #5 has been built upon example #2.The only difference between example #2 and #5 is the fact that leveling constraints are applied.

- Summation of number of owned and rental equipment of each type at each node and in each time step should remain between ***l*** and ***c*** which are lower and upper limits of leveling constraints respectively. In this case ***l*** is set to be 0 and ***c*** is set to be 4.

The question is to determine the optimal activity schedule and equipment allocation plan. The ES master schedule along with the optimal schedule for the second example is shown in Figure 4.13.



RCPSP				t						CPM Calculation						
Node (j)	Activity (a)	Demand for Equipment type(s)	Schedule	1	2	3	4	5	6	ES	LS	EF	LF	D	Link	Pred/ Succ activity
1	1	1		2	2					1	1	3	3	2	N	0
		2		3	3											
			ES	🟦	🟦											
			Optimal	🟥	🟥											
	2	1				1	1	1		3	3	6	6	3	FS	1
		2				2	2	2								
			ES			🟦	🟦	🟦								
			Optimal			🟥	🟥	🟥								
2	1	1			2	2	2	2		2	5	3	6	1	N	0
		2			2	2	2	2								
			ES		🟦	▨	▨	▨								
			Optimal		▨	🟥	▨	▨								
	2	1			4	4	4	4		2	4	4	6	2	N	0
		2			1	1	1	1								
			ES		🟦	🟦	▨	▨								
			Optimal		🟥	▨	▨	🟥								

Note: Start of the day is the measuring point

Figure 4.13- ES vs. Optimal activity schedule for example #5

The resource utilization plan for both the ES and the optimal schedules are shown in Figure 4.14 for each type of equipment.

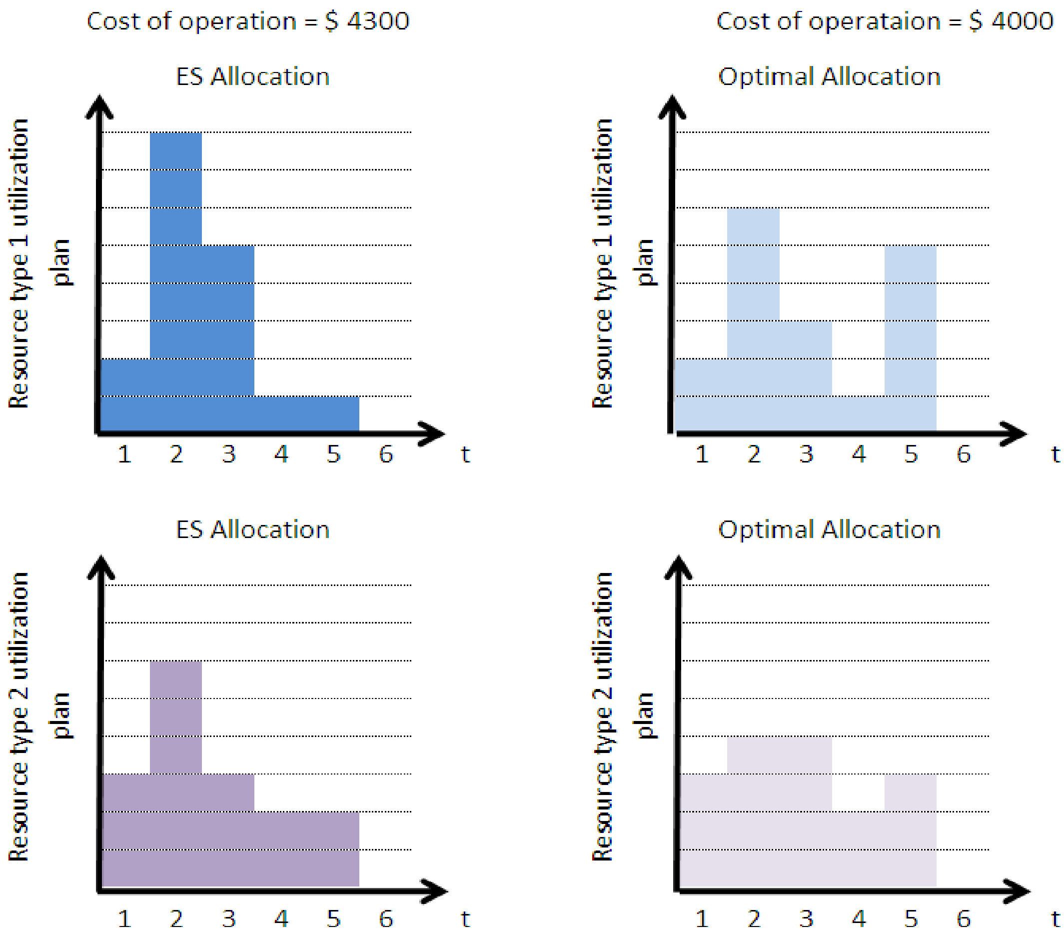


Figure 4.14- Resource utilization plan for example #5

The deployment plan for owned pieces of equipment are shown in Figure 4.15

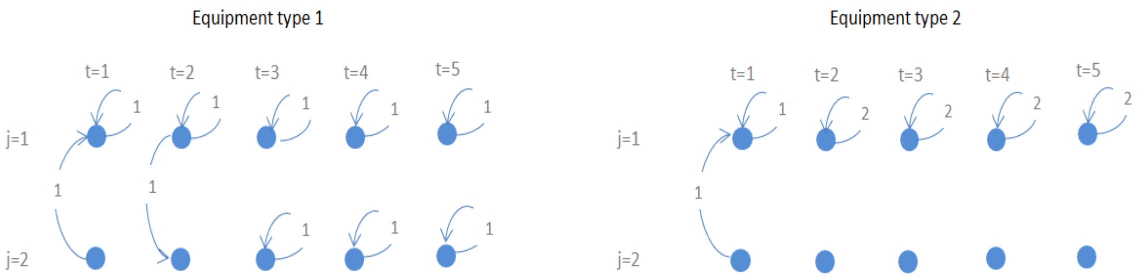


Figure 4.15- Owned equipment fleet deployment plan in example #5 (Numbers shown on arrows are number of shipped pieces of owned equipment)

As a result of combining outputs shown in Figures 4.14 and 4.15, the number of rental pieces of equipment that should be rented in each time slot and in each location can be calculated.

Detailed equipment allocation plan for example # 5 is presented in Table 4.5. The highlighted section of the table shows the optimal schedule equipment demand and crossed cells represent idle pieces of equipment.

Early start plan cost = $ 4300 ; Optimized plan cost = $ 4000

Detailed equipment allocation plan for Example #5	Equipment type	Node 1 &2					Node 1					Node 2				
		t					t					t				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Early start plan demand	1	2	8	5	1	1	2	2	1	1	1	0	6	4	0	0
	2	3	6	3	2	2	3	3	2	2	2	0	3	1	0	0
Optimized plan demand	1	2	6	3	1	5	2	2	1	1	1	0	4	2	0	4
	2	3	4	4	2	3	3	3	2	2	2	0	1	2	0	1
Share of owned equipment in demand satisfaction for optimized plan	1	2	2	2	2	2	2	1	1	1	1	0	1	1	~~1~~	1
	2	2	2	2	2	2	2	2	2	2	2	0	0	0	0	0
Share of rental equipment in demand satisfaction for optimized plan	1	0	4	1	0	3	0	1	0	0	0	0	3	1	0	3
	2	1	2	2	0	1	1	1	0	0	0	0	1	2	0	1

Table 4.5- Detailed equipment allocation plan for example #5

4.3. Conclusions and discussion on results

For validation purposes the following items were checked in the validation examples:

- Checking for error and warning free compiling and running process
- Checking the reports provided by Xpress on solution finding process for any irregularity
- Checking the run time and overall stability of the model in providing a solution while different sets of input are loaded
- Comparing solutions obtained through running this model for the described examples against manual solutions obtained by use of Microsoft Excel 2007
- Checking accurate enforcement of various sets of constraints such as:
    - Demand satisfaction; superposition of shipped and rented pieces of equipment should exactly meet the demand
    - Time windows and durations constraints
    - Precedence constraints
    - Network flow conservation constraints
- Checking appropriate application of shifting and splitting options within each activity time window

The result of all these checks being acceptable, validates the formulation, ensures its accuracy and guarantees optimality of the provided solution.

Following are conclusions that are inferred as a result of further probing the model's outputs provided for the validation examples.

- In the initial cost setting (examples #1 and #2), the cost of running the portfolio according to the ES schedule is $ 4,300 which can be reduced to $ 4,100 by shifting tasks to the optimal position (example #1). This cost is further reduced to $ 3,700 by application of both shifting and splitting options simultaneously (example #2). So, shifting and splitting features of the model are fully functional and perform as intended.
- In example #3 since the cost of transportation in time slots 3 and 4 is extremely high, the required shipment activities are shifted out of this time window to avoid high shipment cost. This shows that the model is sensitive to one of its major components namely the cost of transportation.
- In example #4 which has the setting of example #3, the cost of using time slots 4, 5 and 6 for activity 1 in location 2 has been dramatically increased in comparison to the cost of using all other time slots. As a result, the whole operation plan has been modified to avoid using these time slots by this activity and this activity has been moved from time slot 5 (its active time slot in example #3) to time slot 2 in order to comply with the new time slot pricing policy. This indicates that the model is sensitive to the pricing pattern of time slots.
- In example #5 which has the same structure as example #2, through application of the leveling constraints, the intended result in terms of having leveled resource profiles is obtained at the cost of increasing the value of the objective function

from \$3,700 to \$4,000. This demonstrates the functionality of the leveling constraints.

- From the model output it can be inferred that the overall cost associated with the execution of the ES schedule is higher than the cost of any optimal substitute solution provided by the model regardless of whether splitting activities are allowed or not. This suggests that the application of the model always provides superior solutions in comparison to a strategy of pushing the activities toward their ES which is currently common practice in the construction industry.
- In current industry practice finding a feasible (not even optimal) operation plan is one of the portfolio manager's tasks. When resources are scarce this becomes an extremely demanding manual task even in the case of small problems and an unachievable target for practical size problems. However, through use of this model, not only feasible but optimal solutions for practical problems can be found in a reasonable time.
- As mentioned before, performance capacity of the owned equipment fleet can be gauged by considering the monetary value of the volume of work that is performed using that fleet over a certain period of time to be the metric (μ). Comparison of the metric for maximum performance (μ_{max}) with the same metric for current performance level (μ), reveals the efficiency of the owned fleet ($\varepsilon = \frac{\mu}{\mu\ max}$). As one of the major contributions of this research, application of the proposed model enables managers to calculate the optimal performance capacity of the owned equipment fleet while it is utilized for operation in different projects, in different geographical locations which are subject to their own schedule

constraints (μ_{optimal}). Therefore, the optimal efficiency of the owned fleet for each type of equipment can also be calculated ($\varepsilon_{\text{optimal}} = \frac{\mu\ \text{optimal}}{\mu\ \text{max}}$). The optimal efficiency ($\varepsilon_{\text{optimal}}$) for equipment type 1 is 80, 70, 80, 80 and 90 percent in Examples 1 through 5 respectively. The same metric is 100% for equipment type 2 in all of the examples.

A closer look at the situation reveals that in general for a portfolio in which its projects are scattered geographically $\mu_{\text{optimal}} \leq \mu_{\text{max}}$. As a special case if there is no idle time for any owned piece of equipment then $\mu_{\text{optimal}} = \mu_{\text{max.}}$ Ultimately, it can be concluded that the value of the parameter μ_{optimal} is highly dependent on properties of the portfolio.

- This being said, probing solved examples divulges that in examples #1, #2 and #4 although one piece of owned equipment type 1 is idle in location 2 at time step 1 while needed in location 1 at the same time, it is not shipped and remains idle at its initial location. At the same time a piece of rental equipment is used to fulfill the very same demand in location 1. A naive interpretation deems this solution absurd, inefficient and a glitch in the logic of the model. On the contrary, thorough examination of the situation along with the consideration of various costs matrices associated with the operation reveals the fact that the proposed solution is the cost optimal solution which is hardly detectable through regular procedures used even by highly experienced project managers. This is because when making such a decision, costs of utilizing owned and/or rental pieces of equipment and costs of altering the activity schedule should be compared together in all possible combinations.

In other words, according to the mathematical model's calculations, in these cases it is economically more favorable to keep certain pieces of owned equipment idle in the current location in order to utilize them for future operations while satisfying the current demand of other projects with rental equipment rather than utilizing the owned fleet with a higher efficiency rate. This happens to be the case due to the structure of the problem and properties of its cost matrices in these examples.

- As a general trend, when the demand is high and scattered (highly volatile demand), the response will be to utilize rental equipment. On the contrary, in the case of low demand which is constant over time (steady demand), higher utilization of the owned fleet is actually the optimal response. This logical trend is traceable in the shipment patterns provided for owned equipment and the acquisition plan provided for rental equipment by the model. For instance, the demand for equipment type 1 in node 2 is relatively high and scattered. As a result, considerable fraction of this demand is satisfied using the rental fleet. On the other hand, the demand for equipment type 2 in node 1 is considered to be steady, so it is mainly responded to by using the owned equipment fleet.
- Small validation examples were solved in 0.03 sec. using Xpress 7.0 and Figure 4.16 shows the convergence process.

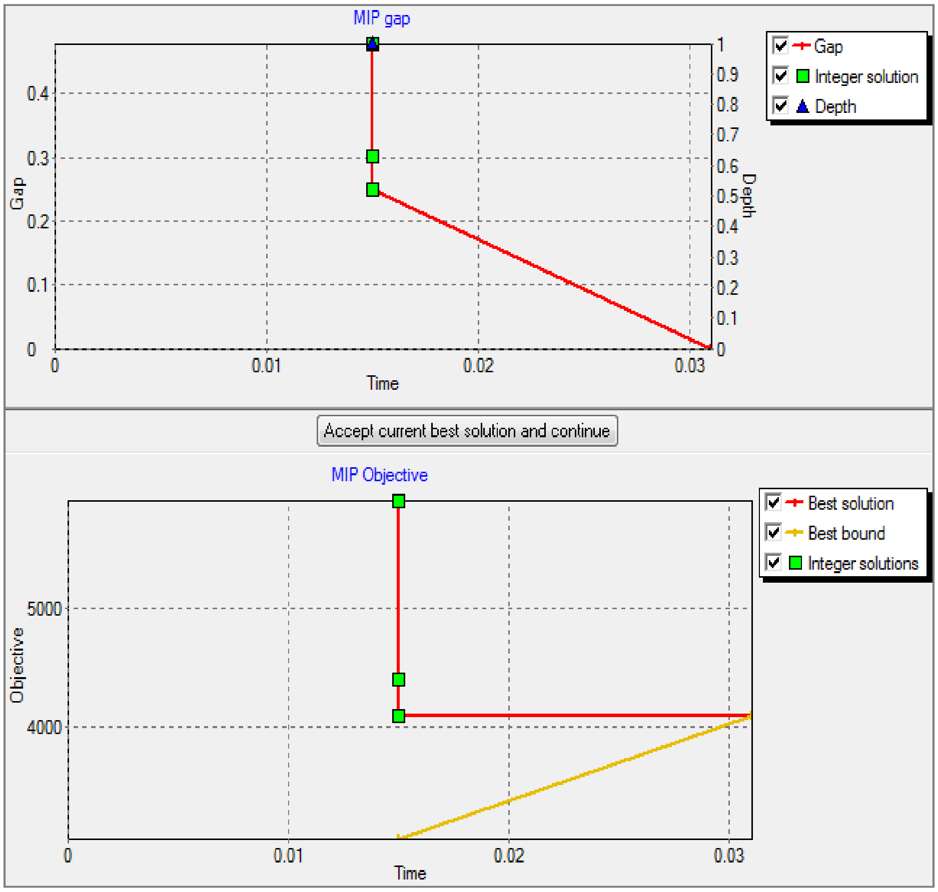


Figure 4.16- Solution tracking and convergence information reported by Xpress

The obtained results validate the proposed model and support its merits.

Chapter 5: Practical Case Studies

This chapter is dedicated to application of the proposed formulation to practical case studies which are set up based on real world data.

These problems are designed to demonstrate capabilities of the model in handling real world problems, to examine the rationality of the output of a practical-scale model, to perform a thorough sensitivity analyses with real world data and to draw quantitative conclusions regarding the efficiency of operation in the construction industry under different scenarios. Finally, problems in this chapter are designed to demonstrate prospective commercial applications of the proposed model.

5.1. Defining the real world problem

To build a practical size model of the problem that has been stated in this study with real world data, huge amounts of sensitive schedule and cost data for a given portfolio of a construction company should be gathered. Given the highly competitive nature of the construction industry, attaining such information as a whole is almost impossible.

As a result, the author decided to collect different pieces of information from different sources and assemble them in a compatible manner in order to build a meaningful practical size problem.

Thus, the detailed schedule data (schedule that is used for construction operation on-site) for a real world portfolio of projects and the related heavy equipment availability plan were collected from a company. The location of these projects has been reflected on the U.S. map such that the geographical (spatial) properties of the projects' network remain unchanged.

This information is supplemented with the cost information obtained from the market in the form of average of several collected quotes. Cost information which is collected from the market includes heavy equipment shipment costs, rental costs and ownership costs. Moreover, the contractual (actual/liquidated) damages are extracted from the contracts of these projects.

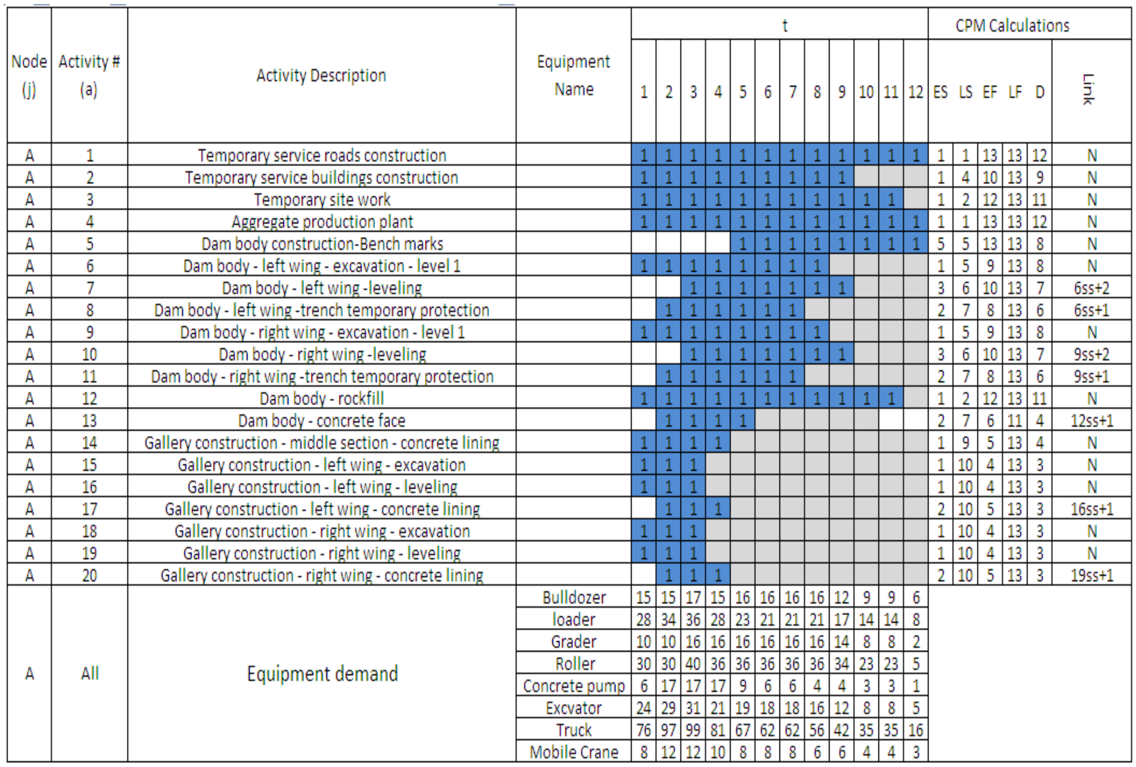
Following is a brief technical description of each project, its activity schedule (ES schedule) and its equipment demand schedule.

Project A:

Project A is the construction of a large reservoir earth dam. This is a Concrete Face Rockfill Dam (CFRD) with the height of 113 m from the foundation, crest length of 270 m, crest width of 65 m and reservoir capacity of 115,000,000 m^3. Construction of this dam involves 1,200,000 m^3 of excavation, 2,640,000 m^3 of embankment, 4,100 tons of steel work and 78,000 m^3 concrete placement. The estimated cost of this project is $ 750,000,000 and during PH5 it has 20 active tasks which are mostly excavation and embankment activities. Figure 5.1 shows the construction site of this project.

Figure 5.1- Construction site of project A – Reservoir earth dam project

The activity schedule and the equipment demand schedule for this project are shown in Figure 5.2.



Node (j)	Activity # (a)	Activity Description	Equipment Name	t												CPM Calculations					
				1	2	3	4	5	6	7	8	9	10	11	12	ES	LS	EF	LF	D	Link
A	1	Temporary service roads construction		1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
A	2	Temporary service buildings construction		1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
A	3	Temporary site work		1	1	1	1	1	1	1	1	1	1	1		1	2	12	13	11	N
A	4	Aggregate production plant		1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
A	5	Dam body construction-Bench marks						1	1	1	1	1	1	1	1	5	5	13	13	8	N
A	6	Dam body - left wing - excavation - level 1		1	1	1	1	1	1	1	1					1	5	9	13	8	N
A	7	Dam body - left wing -leveling				1	1	1	1	1	1	1				3	6	10	13	7	6ss+2
A	8	Dam body - left wing -trench temporary protection			1	1	1	1	1	1						2	7	8	13	6	6ss+1
A	9	Dam body - right wing - excavation - level 1		1	1	1	1	1	1	1	1					1	5	9	13	8	N
A	10	Dam body - right wing -leveling				1	1	1	1	1	1	1				3	6	10	13	7	9ss+2
A	11	Dam body - right wing -trench temporary protection			1	1	1	1	1	1						2	7	8	13	6	9ss+1
A	12	Dam body - rockfill		1	1	1	1	1	1	1	1	1	1	1		1	2	12	13	11	N
A	13	Dam body - concrete face			1	1	1	1								2	7	6	11	4	12ss+1
A	14	Gallery construction - middle section - concrete lining		1	1	1	1									1	9	5	13	4	N
A	15	Gallery construction - left wing - excavation		1	1	1										1	10	4	13	3	N
A	16	Gallery construction - left wing - leveling		1	1	1										1	10	4	13	3	N
A	17	Gallery construction - left wing - concrete lining			1	1	1									2	10	5	13	3	16ss+1
A	18	Gallery construction - right wing - excavation		1	1	1										1	10	4	13	3	N
A	19	Gallery construction - right wing - leveling		1	1	1										1	10	4	13	3	N
A	20	Gallery construction - right wing - concrete lining			1	1	1									2	10	5	13	3	19ss+1
A	All	Equipment demand	Bulldozer	15	15	17	15	16	16	16	16	12	9	9	6						
			loader	28	34	36	28	23	21	21	21	17	14	14	8						
			Grader	10	10	16	16	16	16	16	16	14	8	8	2						
			Roller	30	30	40	36	36	36	36	36	34	23	23	5						
			Concrete pump	6	17	17	17	9	6	6	4	4	3	3	1						
			Excvator	24	29	31	21	19	18	18	16	12	8	8	5						
			Truck	76	97	99	81	67	62	62	56	42	35	35	16						
			Mobile Crane	8	12	12	10	8	8	8	6	6	4	4	3						

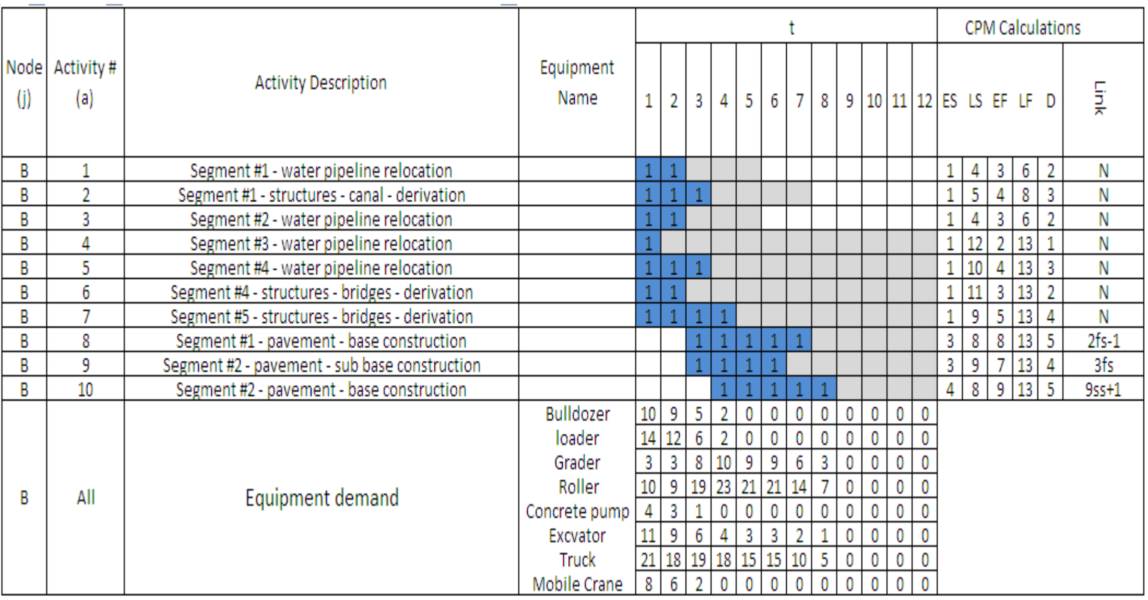
Figure 5.2- Activity schedule and the equipment demand schedule of project A

Project B:

Project B is a medium size road improvement project. Length of the segment under improvement is 23 km. The operation involves 300,000 m^3 of earthwork, 40,000 m^3 of concrete work and 10,000 m^3 of masonry work. The estimated cost of this project is $ 150,000,000 and during PH5 it has 10 active tasks which are mostly earthwork activities. Figure 5.3 shows construction site of this project.

Figure 5.3- Construction site of project B – Road improvement project

The activity schedule and the equipment demand schedule for this project are shown in Figure 5.4.



Node (j)	Activity # (a)	Activity Description	Equipment Name	t												CPM Calculations					
				1	2	3	4	5	6	7	8	9	10	11	12	ES	LS	EF	LF	D	Link
B	1	Segment #1 - water pipeline relocation		1	1											1	4	3	6	2	N
B	2	Segment #1 - structures - canal - derivation		1	1	1										1	5	4	8	3	N
B	3	Segment #2 - water pipeline relocation		1	1											1	4	3	6	2	N
B	4	Segment #3 - water pipeline relocation		1												1	12	2	13	1	N
B	5	Segment #4 - water pipeline relocation		1	1	1										1	10	4	13	3	N
B	6	Segment #4 - structures - bridges - derivation		1	1											1	11	3	13	2	N
B	7	Segment #5 - structures - bridges - derivation		1	1	1	1									1	9	5	13	4	N
B	8	Segment #1 - pavement - base construction				1	1	1	1	1						3	8	8	13	5	2fs-1
B	9	Segment #2 - pavement - sub base construction				1	1	1	1							3	9	7	13	4	3fs
B	10	Segment #2 - pavement - base construction					1	1	1	1	1					4	8	9	13	5	9ss+1
B	All	Equipment demand	Bulldozer	10	9	5	2	0	0	0	0	0	0	0	0						
			loader	14	12	6	2	0	0	0	0	0	0	0	0						
			Grader	3	3	8	10	9	9	6	3	0	0	0	0						
			Roller	10	9	19	23	21	21	14	7	0	0	0	0						
			Concrete pump	4	3	1	0	0	0	0	0	0	0	0	0						
			Excvator	11	9	6	4	3	3	2	1	0	0	0	0						
			Truck	21	18	19	18	15	15	10	5	0	0	0	0						
			Mobile Crane	8	6	2	0	0	0	0	0	0	0	0	0						

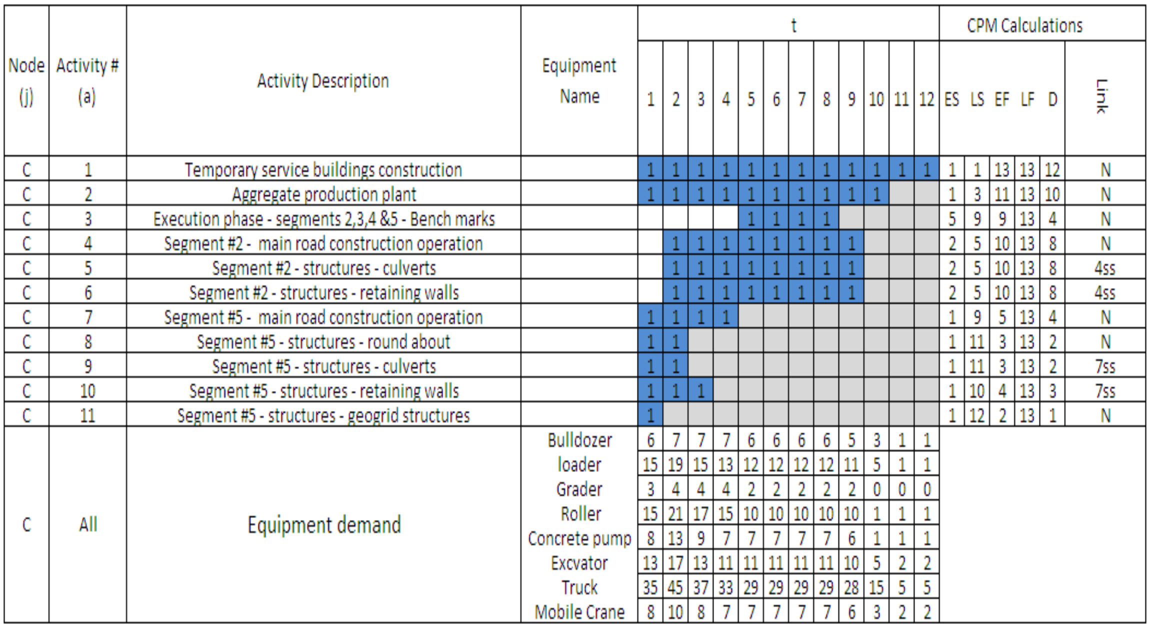
Figure 5.4- Activity schedule and the equipment demand schedule of project B

Project C:

Project C is a large road construction project. The length of this road is 21.5 km. The construction operation involves 1,200,000 m^3 of earthwork and 80,000 m^3 of concrete work which includes construction of 93 culverts and 12.2 km of reinforced concrete retaining walls. The estimated cost of this project is $ 500,000,000 and during PH5 it has 11 active tasks which are mostly earthwork, concrete placement and sub base /base placement activities. Figure 5.5 shows the construction site of this project.

Figure 5.5- Construction site of project C – Road construction project

The activity schedule and the equipment demand schedule for this project are shown in Figure 5.6.



Node (j)	Activity # (a)	Activity Description	Equipment Name	t												CPM Calculations					
				1	2	3	4	5	6	7	8	9	10	11	12	ES	LS	EF	LF	D	Link
C	1	Temporary service buildings construction		1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
C	2	Aggregate production plant		1	1	1	1	1	1	1	1	1	1			1	3	11	13	10	N
C	3	Execution phase - segments 2,3,4 &5 - Bench marks						1	1	1	1					5	9	9	13	4	N
C	4	Segment #2 - main road construction operation			1	1	1	1	1	1	1	1				2	5	10	13	8	N
C	5	Segment #2 - structures - culverts			1	1	1	1	1	1	1	1				2	5	10	13	8	4ss
C	6	Segment #2 - structures - retaining walls			1	1	1	1	1	1	1	1				2	5	10	13	8	4ss
C	7	Segment #5 - main road construction operation		1	1	1	1									1	9	5	13	4	N
C	8	Segment #5 - structures - round about		1	1											1	11	3	13	2	N
C	9	Segment #5 - structures - culverts		1	1											1	11	3	13	2	7ss
C	10	Segment #5 - structures - retaining walls		1	1	1										1	10	4	13	3	7ss
C	11	Segment #5 - structures - geogrid structures		1												1	12	2	13	1	N
C	All	Equipment demand	Bulldozer	6	7	7	7	6	6	6	6	5	3	1	1						
			loader	15	19	15	13	12	12	12	12	11	5	1	1						
			Grader	3	4	4	4	2	2	2	2	2	0	0	0						
			Roller	15	21	17	15	10	10	10	10	10	1	1	1						
			Concrete pump	8	13	9	7	7	7	7	7	6	1	1	1						
			Excvator	13	17	13	11	11	11	11	11	10	5	2	2						
			Truck	35	45	37	33	29	29	29	29	28	15	5	5						
			Mobile Crane	8	10	8	7	7	7	7	7	6	3	2	2						

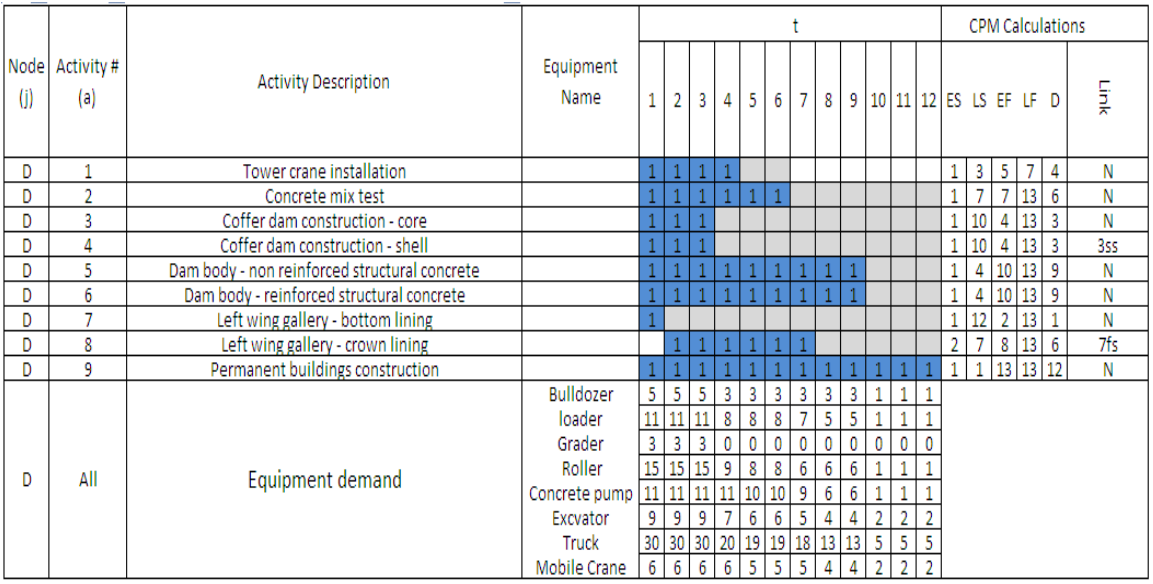
Figure 5.6- Activity schedule and the equipment demand schedule of project C

Project D:

Project D is a large reservoir concrete dam. This is a Roller Compacted Concrete (RCC) Dam with the height of 55.5 m from the foundation, crest length of 360 m and reservoir capacity of 69,000,000 m^3. Construction of this dam involves 110,000 m^3 of excavation, 40,000 m^3 of embankment and 211,000 m^3 of concrete placement. The estimated cost of this project is $ 600,000,000 and during PH5 it has 9 active tasks which are mostly heavy equipment installation, service buildings construction and excavation activities. Figure 5.7 shows the construction site of this project.

Figure 5.7- Construction site of project D – Reservoir concrete dam project

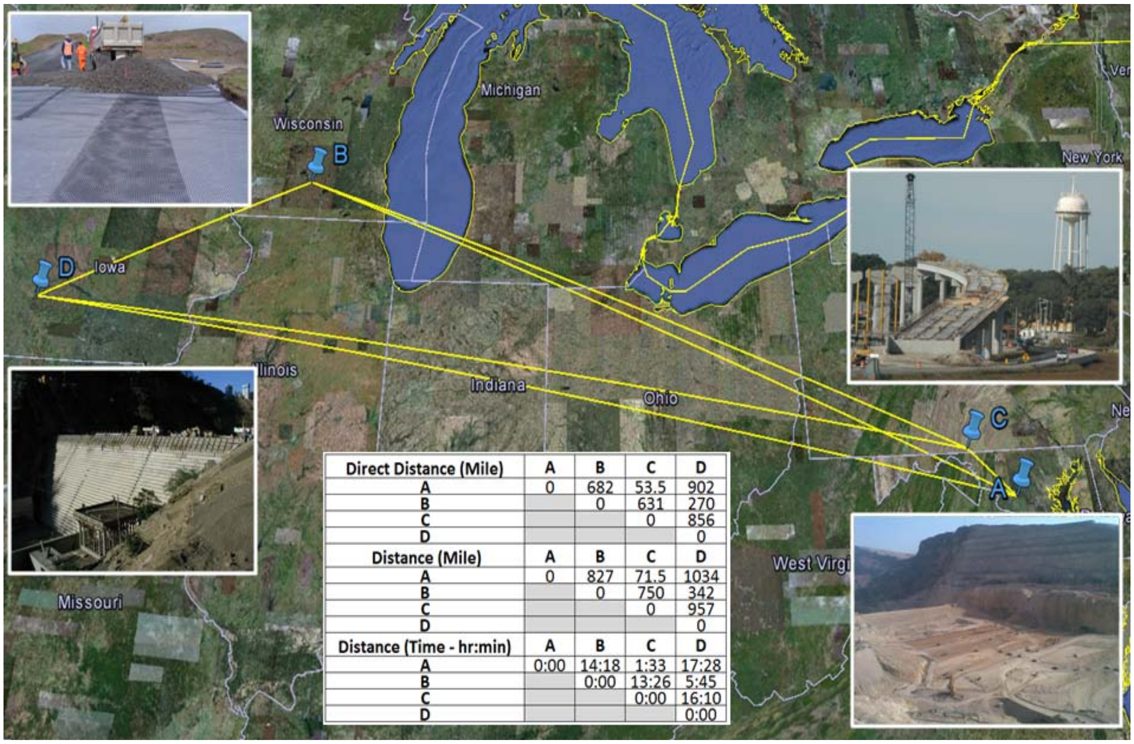
The activity schedule and the equipment demand schedule for this project are shown in Figure 5.8.



Node (j)	Activity # (a)	Activity Description	Equipment Name	t												CPM Calculations					
				1	2	3	4	5	6	7	8	9	10	11	12	ES	LS	EF	LF	D	Link
D	1	Tower crane installation		1	1	1	1									1	3	5	7	4	N
D	2	Concrete mix test		1	1	1	1	1	1							1	7	7	13	6	N
D	3	Coffer dam construction - core		1	1	1										1	10	4	13	3	N
D	4	Coffer dam construction - shell		1	1	1										1	10	4	13	3	3ss
D	5	Dam body - non reinforced structural concrete		1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
D	6	Dam body - reinforced structural concrete		1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
D	7	Left wing gallery - bottom lining		1												1	12	2	13	1	N
D	8	Left wing gallery - crown lining			1	1	1	1	1	1						2	7	8	13	6	7fs
D	9	Permanent buildings construction		1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
D	All	Equipment demand	Bulldozer	5	5	5	3	3	3	3	3	3	1	1	1						
			loader	11	11	11	8	8	8	7	5	5	1	1	1						
			Grader	3	3	3	0	0	0	0	0	0	0	0	0						
			Roller	15	15	15	9	8	8	6	6	6	1	1	1						
			Concrete pump	11	11	11	11	10	10	9	6	6	1	1	1						
			Excvator	9	9	9	7	6	6	5	4	4	2	2	2						
			Truck	30	30	30	20	19	19	18	13	13	5	5	5						
			Mobile Crane	6	6	6	6	5	5	5	4	4	2	2	2						

Figure 5.8- Activity schedule and the equipment demand schedule of project D

Following is the consolidated information regarding the portfolio of projects as a whole. Selected portfolio has 4 infrastructure projects (Projects A, B, C and D) with a total cost of $ 2,000,000,000 which encompass $ 1,400,000,000 of direct and $ 600,000,000 of indirect cost. Figure 5.9 shows the network of these projects with some of its relevant data.



Direct Distance (Mile)	A	B	C	D
A	0	682	53.5	902
B		0	631	270
C			0	856
D				0

Distance (Mile)	A	B	C	D
A	0	827	71.5	1034
B		0	750	342
C			0	957
D				0

Distance (Time - hr:min)	A	B	C	D
A	0:00	14:18	1:33	17:28
B		0:00	13:26	5:45
C			0:00	16:10
D				0:00

Figure 5.9- Projects A, B, C and D spatial network

The overall duration of the portfolio of these projects from the start of the first project to the finish of the last project is 192 weeks (time units). This time span has been divided into 16 PHs, each with the duration of 12 weeks. In the majority of the case studies that are solved in this chapter, one planning horizon is selected and the master schedule and the master equipment demand plan are compiled for the given portfolio over this particular PH. This information constitutes a significant portion of the model's input.

In addition to above- mentioned data, there are obligations regarding delay damages mainly concentrated in the liquidated damages clause of contracts. Due to lack of information, for the purpose of simplification and without hurting the concept it is assumed that the liquidated damage clause is similar in all four contracts and all projects within the portfolio are considered as a single master project with one start and one finish mile-stone. In this case, liquidated damages clause assumes that the maximum amount of cumulative liquidated delay damages is 5% of the value of the contract. It is also assumed that this financial damage will be incurred linearly over a delay period equivalent to 10% of the project's total duration. Therefore, the maximum cumulative amount of liquidated damages predicted by the contract is:

$$0.05 \times \$2{,}000{,}000{,}000 = \$\ 100{,}000{,}000 \qquad [5.1]$$

Also, this financial damage can be incurred over 10% of the duration of the portfolio which in this case is:

$$0.1 \times 192 \cong 20 \qquad [5.2]$$

As a common practice in the construction industry, delay damage calculations are performed based on the following simple linear function.

$$LD\ (T) = K + BT \qquad [5.3]$$

Where:

LD(T): Total Liquidated Damages ($) for the portfolio when T delay time units have been incurred;

K: Immediate penalty for entering delay period ($);

B: Penalty per time unit of delay ($/week);

T: Number of time units of incurred delay

For this particular portfolio the weekly damage (B) is assumed to be \$ 3,725,000 per week and the constant penalty for entering the delay period of the portfolio (K) is assumed to be \$ 25,500,000.

As a requirement of the model, a time price function should be selected to assign a dollar value to each time slot. This function should both match the nature of the activities which are in the schedule and be calibrated for given contractual terms of a portfolio. To assign appropriate time-price functions to each problem, typically following steps should be taken by considering the data and assumptions of that particular problem.

i. *Selection of the function type:* Per discussion provided in chapter 3 regarding various time price functions (exponential, logarithmic and flat functions), since the majority of activities in this particular portfolio are construction-related activities, one appropriate choice would be exponential function with the following format.

$$\text{Time Price}\ (t) = a\, e^{(bt)} \qquad [\,5.4]$$

ii. *Calibration:* Parameters ***a*** and ***b*** should be determined through calibration. In the case of this particular problem calibration is done based on two following assumptions:

  - Considering equation 5.3, if all activities in the last PH (PH 16) are delayed to their latest possible time, the contribution of the last PH to the overall liquidated damages will be equal to $K+B\times 1$.
  - Considering equation 5.3, if all activities in all PHs are delayed to their latest possible time, the contribution of all PHs to the overall liquidated damages will be equal to the total amount of liquidated damages predicted

by the contract ($ 100,000,000), which is calculated by the following equation:

$$K+B\ T_{final} \qquad [5.5]$$

Considering above steps: $\boldsymbol{a} = 500$ and $\boldsymbol{b} = 0.0288795$.

Thus, in this case the time price function based on which prices of time slots are calculated will be: $500e^{(0.0288795\ t)}$

Figure 5.10 shows both the theoretical fit and the practical fit (rounded values) of this function.

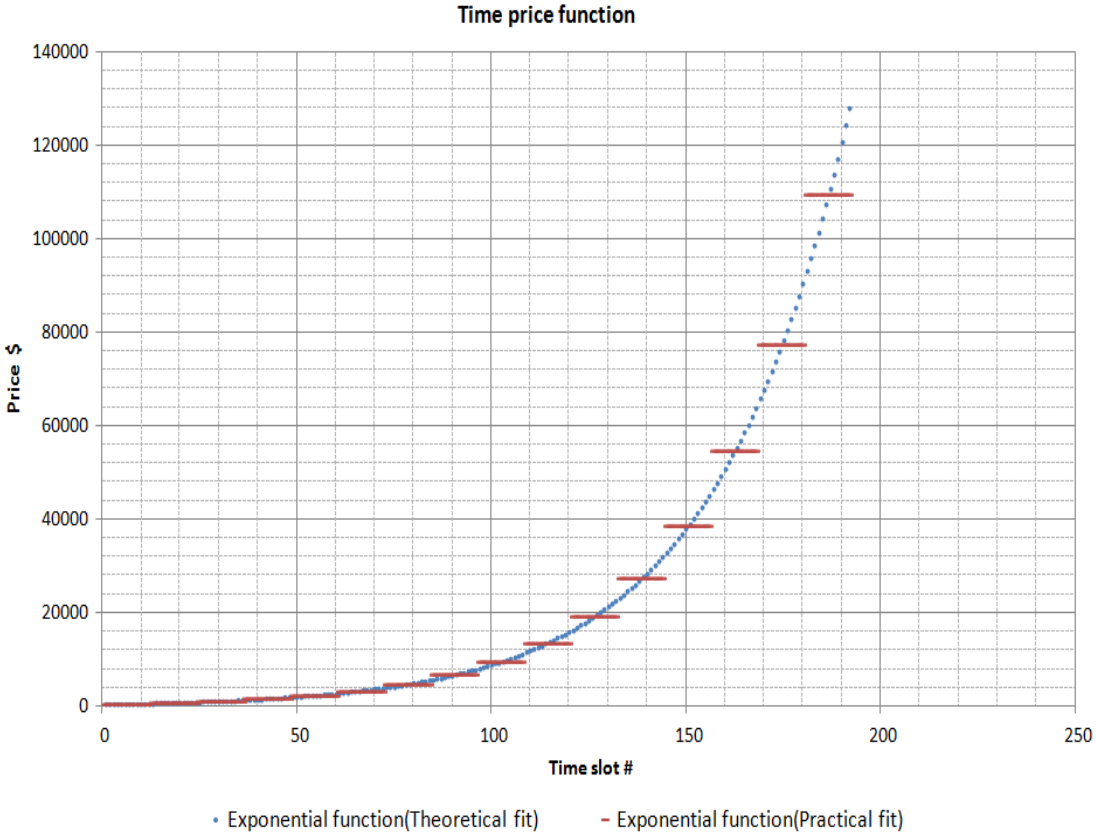


Figure 5.10 - Theoretical and practical fit of the exponential time price function

Another important part of model's input is the data regarding a company's owned equipment fleet. For the purpose of this study the owned equipment fleet is divided into three major sectors.

The first category includes stationary equipment such as concrete batch plants and tunnel boring machines (TBMs). Due to their stationary nature and extremely high relocation costs, these pieces of equipment are excluded from the model and are not shared among job sites.

The second category includes very small pieces of equipment such as grout injection pumps and small electric generators. These pieces of equipment are considered minor equipment (tools). By comparing their purchase price and shipping cost it can be concluded that shipping is not an option for these pieces of equipment and they can be purchased upon need.

The third category of equipment includes heavy construction/mining equipment such as bulldozers and loaders. Due to the relatively low relocation costs relative to their high purchase price, shipping and sharing among different job sites is an economically viable and attractive option for these pieces of equipment. However, not all of these pieces of equipment enter the sharing plan. By reviewing the equipment demand plan of each jobsite it can be concluded that certain types of equipment are just needed on one jobsite while some others are required in more than one project over a given PH. Obviously, the ones that are needed on more than one jobsite over the duration of a given PH should be considered in the sharing plan of that particular PH.

Examining the equipment demand plan of the given portfolio shows that bulldozer, loader, grader, roller, truck mounted concrete pump, excavator, truck and mobile crane are eight types of equipment which are required simultaneously on more than one jobsite during PH5. So, they enter the equipment sharing plan. Figure 5.11 is the graphical representation of the above described categorization.

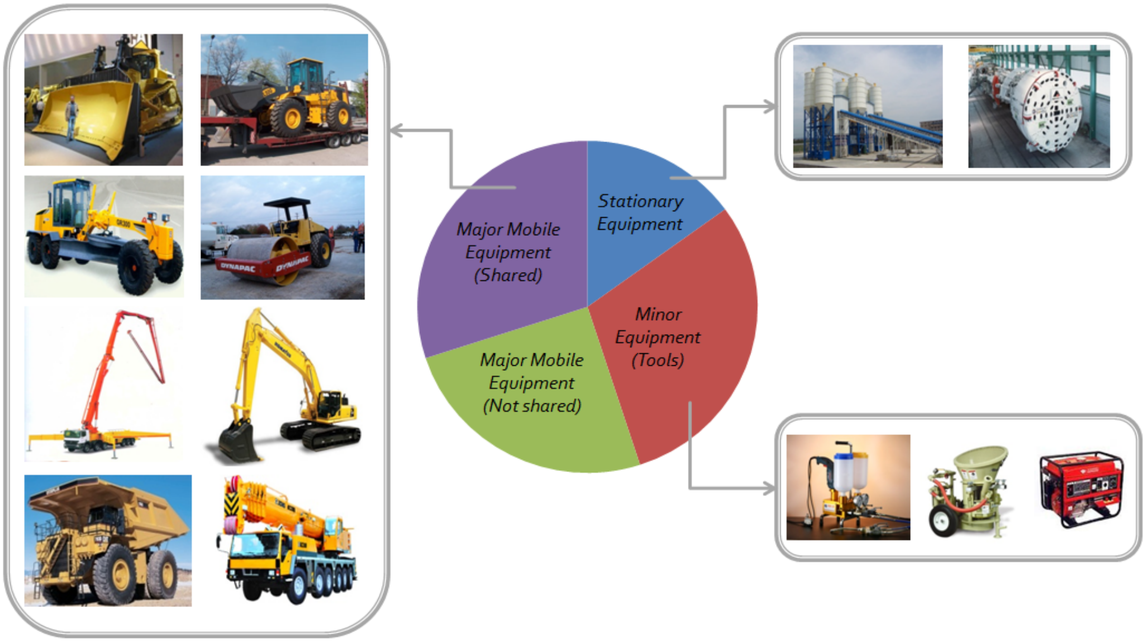
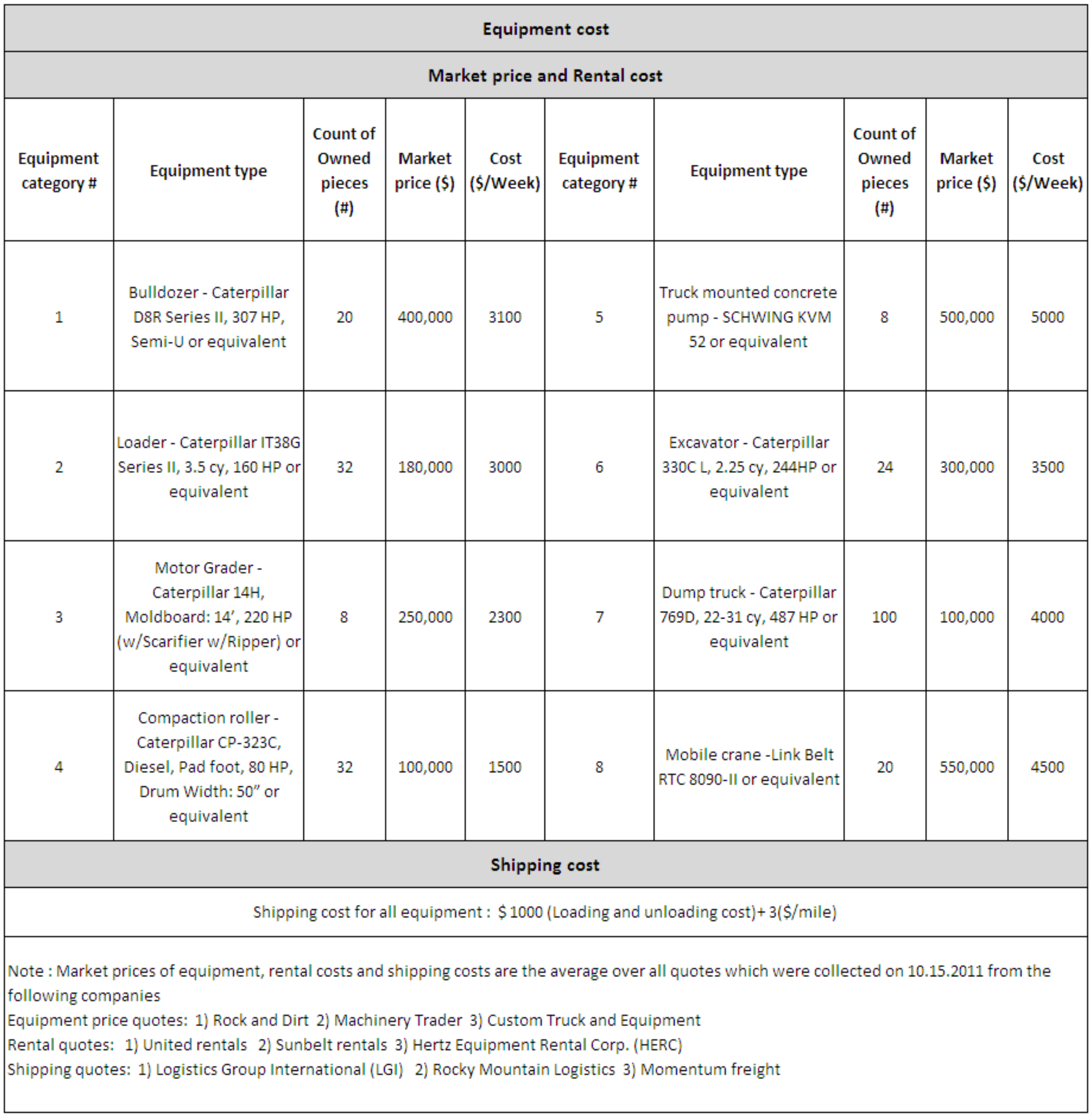


Figure 5.11- Equipment categorization; Types of equipment which enter the equipment sharing plan

Detailed specifications of each type of equipment, the number of owned pieces of each type of equipment, their purchase price in the market, rent and shipping costs are shown in table 5.1. This table contains a large portion of the input data for the model.



Equipment cost

Market price and Rental cost

Equipment category #	Equipment type	Count of Owned pieces (#)	Market price ($)	Cost ($/Week)	Equipment category #	Equipment type	Count of Owned pieces (#)	Market price ($)	Cost ($/Week)
1	Bulldozer - Caterpillar D8R Series II, 307 HP, Semi-U or equivalent	20	400,000	3100	5	Truck mounted concrete pump - SCHWING KVM 52 or equivalent	8	500,000	5000
2	Loader - Caterpillar IT38G Series II, 3.5 cy, 160 HP or equivalent	32	180,000	3000	6	Excavator - Caterpillar 330C L, 2.25 cy, 244HP or equivalent	24	300,000	3500
3	Motor Grader - Caterpillar 14H, Moldboard: 14', 220 HP (w/Scarifier w/Ripper) or equivalent	8	250,000	2300	7	Dump truck - Caterpillar 769D, 22-31 cy, 487 HP or equivalent	100	100,000	4000
4	Compaction roller - Caterpillar CP-323C, Diesel, Pad foot, 80 HP, Drum Width: 50" or equivalent	32	100,000	1500	8	Mobile crane -Link Belt RTC 8090-II or equivalent	20	550,000	4500

Shipping cost

Shipping cost for all equipment : $ 1000 (Loading and unloading cost)+ 3($/mile)

Note : Market prices of equipment, rental costs and shipping costs are the average over all quotes which were collected on 10.15.2011 from the following companies
Equipment price quotes: 1) Rock and Dirt 2) Machinery Trader 3) Custom Truck and Equipment
Rental quotes: 1) United rentals 2) Sunbelt rentals 3) Hertz Equipment Rental Corp. (HERC)
Shipping quotes: 1) Logistics Group International (LGI) 2) Rocky Mountain Logistics 3) Momentum freight

Table 5.1- Detail technical specifications and price information of owned heavy equipment fleet

According to the information provided in table 5.1, 244 pieces of heavy equipment of the company's owned fleet are involved in the construction operation. This number represents the pieces of equipment which are needed on more than one site during PH5.

5.2. Solving case studies and sensitivity analysis

In general, the purpose of performing sensitivity analysis is to:

- Check the sensitivity of the model's output to variations of input parameters
- Check the stability of the model
- Gain insight into the dynamics of the model.

Although model's sensitivity to its major input parameters (i.e. supply cost, rent time price and etc.) were examined during the validation process (section 4.2), in this section, a thorough sensitivity analysis, including 16 practical case studies in five categories is performed.

In these cases effects of changing some major objective function coefficients, right hand side parameters and structural properties of the model on solutions are studied. These case studies are designed to fulfill the requirements of the sensitivity analysis process while each of them also represents a practical scenario. Additionally, since all of these case studies are prepared based on real world data, their output values and conclusions are valid for the purpose of practical recommendations.

Moreover, in order to correctly interpret the results which are obtained from solving these cases studies it should be noted that case studies of set #1, #2 are designed to examine short term (operational level) capabilities of the model. On the other hand, case studies belonging to set #4 and #5 are designed to examine model's capabilities in facilitating long term decision making processes such as equipment purchase decisions. Table 5.2 presents a list of case studies in addition to a brief description for each case study.

Practical case studies			
Case study #	Comparison base case #	Case description	Target parameter/ situation
1-1	-	ES plan/ Actual shipment and rental costs/ Exponential time price function/ No leveling constraint/ Jobsites totally isolated and no equipment sharing	Studying the cost efficiency of current practice of industry
1-2	1-1	LS plan/ Actual shipment and rental costs/ Exponential time price function/ No leveling constraint/ Jobsites totally isolated and no equipment sharing	Comparing ES and LS plan
1-3	1-1	ES plan/ Actual shipment and rental costs/ Exponential time price function/ No leveling constraint/ Distance base clustering (Cluster #1 : sites A&C and Cluster #2: sites B & D)	Studying the effects of distance base clustering
1-4	1-1	ES plan/ Actual shipment and rental costs/ Exponential time price function/ No leveling constraint/ No clustering	Studying the effects of equipment sharing
2-1	1-4	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/No Leveling constraint/ No clustering	Studying the effects of optimizing the operation plan without resource leveling and clustering
2-2	2-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/Leveling constraint in place/No clustering	Studying the effects of optimizing the operation plan with enforcement of resource leveling but not clustering constraints
2-3	2-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ No Leveling constraint / Distance base clustering (Cluster #1 : sites A&C and Cluster #2: sites B & D)	Studying the effects of optimizing the operation plan with no resource leveling constraint and enforcement of distance base clustering constraints
2-4	2-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/Leveling constraint in place/ Distance base clustering (Cluster #1 : sites A&C and Cluster #2: sites B & D)	Studying the effects of optimizing the operation plan with enforcement of resource leveling and distance base clustering constraints
2-5	2-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/No Leveling constraint / Jobsites totally isolated and no equipment sharing	Studying the effects of complete isolation of jobsites on the optimized plan's cost
3-1	2-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function /No Leveling constraint /No clustering/ Shifting the schedule activities from current PH 5 to PH16	Studying the effects of time price function
3-2	3-1	LS plan/ Actual shipment and rental costs/ Exponential time price function /No Leveling constraint /No clustering/ Shifting the schedule of activities from PH5 to PH16	Studying the effects of time price function
4-1	-	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Actual market price for equipment /No Leveling constraint /No clustering/ Fix (given) number of owned pieces of equipment	Finding the optimum number of owned equipment of each type in the owned equipment fleet for a given portfolio of projects
4-2	4-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Actual market price for equipment /No Leveling constraint /No clustering/ Variable number of owned pieces of equipment	Finding the optimum number of owned equipment of each type in the owned equipment fleet for a given portfolio of projects
5-1	-	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Actual market price for equipment / No Leveling constraint /No clustering/ Fix (given) number of owned pieces of equipment/ Maximum cap value for availability of rental equipment such that the problem is infeasible	Studying the effects of rental equipment availability
5-2	4-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Actual market price for equipment /No Leveling constraint /No clustering/ Fix (given) number of owned pieces of equipment/ Minimum cap value for availability of rental equipment such that the problem is feasible	Studying the effects of rental equipment availability
5-3	5-2	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Actual market price for equipment /No Leveling constraint /No clustering/ Fix (given) number of owned pieces of equipment/ No cap value for availability of rental equipment	Studying the effects of rental equipment availability

Table 5.2 - Brief description of 16 cases studied in five subsections of section 5.2

5.2.1. Set#1 case studies

Set #1 case studies (1-1, 1-2, 1-3 and 1-4) are generally designed to establish a base-line for the comparison of the efficiency level of the optimal operation plans (set #2 case studies) with the efficiency of the current industry practice of fixed schedule operations (i.e. ES, LS). Additionally, in this set of case studies effects of the application of various management strategies such as jobsite isolation, distance-based clustering, free equipment sharing and performing according to ES/LS schedules on different components of the projects, including the bottom-line operation cost are examined in detail.

Case study #1-1:

The first case is designed to study the cost efficiency of current practice in the construction industry regarding activity scheduling and equipment operation planning. In this problem the schedule is fixed to the ES schedule. Also, actual shipment and rental costs (Table 5.1) and the price assigned to time slots (Figure 5.10) form the inputs of the problem. Also, no leveling constraint is in place and jobsites are totally isolated with no equipment sharing.

Results:

- In this scenario the cost of operation (objective function value) is \$ 7,016,000. Comparison of this case study with case studies #1-3, #1-4 and #2-1shows that current practice in the industry in which the operation is not optimized is extremely inefficient.

- According to the structure of this case study, at least 4,023 Equipment-week should be provided in order to meet the demand. However, based on the output of the model, 4,844 Equipment-week is provided which shows presence of 821 Equipment-week of idle owned equipment in the plan. From this 4,844 Equipment-week, 2,928 is provided through the owned equipment fleet and 1,916 is provided through the available rental fleet.
- This case study also establishes a comparison baseline for case studies within set #1.

Case study #1-2:

This case study is designed to compare the cost efficiency of LS with the ES plan. So, in this problem the schedule is fixed to the LS schedule. Other than this difference, this case study has the exact structure of case #1-1.

Results:

- In this scenario the cost of operations (objective function value) is \$ 7,057,770 which shows a slight increase in comparison to case #1-1. This increase is mainly due to the increase in the delay related costs as the result of a shift in the activities' position.

- According to the structure of this case study, at least 4,023 Equipment-week should be provided in order to meet the demand. However, based on the output of the model

4,861 Equipment-week is provided which shows presence of 838 Equipment-week of idle owned equipment in the plan. From 4,861 Equipment-week 2,928 is provided through the owned equipment fleet and 1,933 is provided through the available rental fleet.

Case study #1-3:

This case study is designed to study the effects of distance based clustering of jobsites. In other words, in this scenario sites A and C are put in cluster #1 and sites B and D form cluster #2. In this setting, while intra-cluster equipment sharing is allowed, inter-cluster equipment sharing is not. Other than these differences, this case study has the exact structure as case study #1-1. Figure 5.12 shows how four jobsites are put into two clusters.

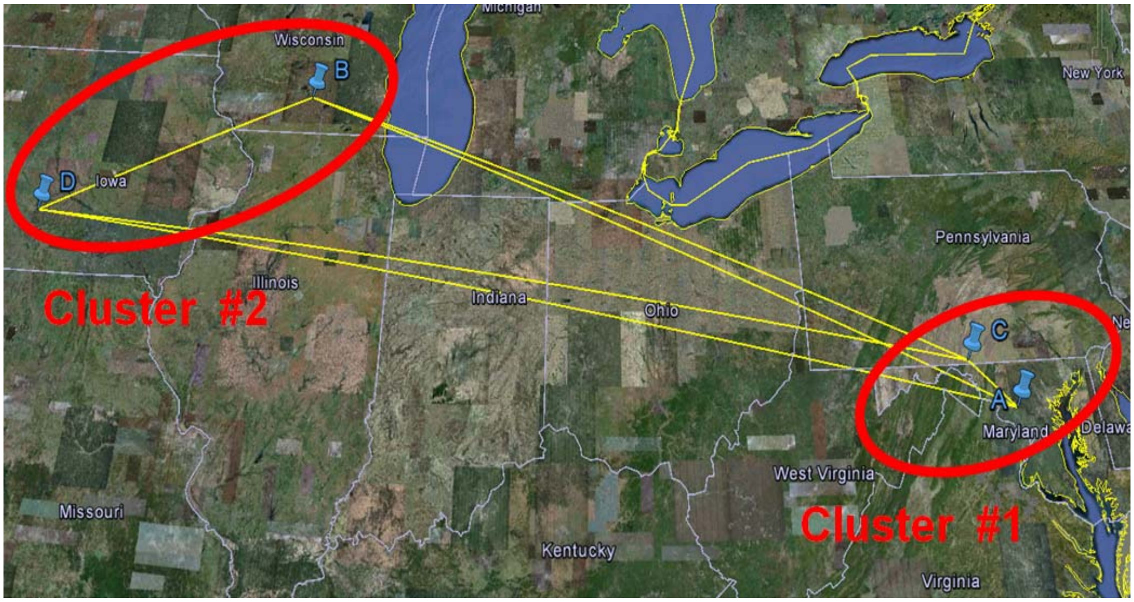


Figure 5.12- Distance based clustering pattern of jobsites

Results:

- In this scenario the cost of operations (objective function value) is $ 6,715,280 which is slightly lower in comparison to case studies #1-1 and #1-2. This shows that any type of equipment sharing strategy, even distance based clustering, is more efficient than total isolation of jobsites and improves the value of the objective function.

Case study #1-4:

This case is designed to study the results of implementation of free equipment sharing strategy among all jobsites. Other than this difference this case study has exactly the same structure as case study #1-1.

Results:

- In this scenario the cost of operations (objective function value) is $ 5,767,300 which is significantly lower than case studies #1-1, #1-2 and #1-3. This shows that the deployment of the optimal equipment sharing strategy is an effective mean for reducing the operation cost.
- According to the structure of this case study, at least 4,023 Equipment-week should be provided in order to meet the demand. However, based on the output of the model 4,434 Equipment-week is provided which shows presence of 411 Equipment-week of idle owned equipment in the plan. From 4,434 Equipment-week 2,928 is provided through the owned equipment fleet and 1,506 is provided through the available rental fleet.

5.2.2. Set#2 case studies

Set #2 case studies (2-1, 2-2, 2-3, 2-4 and 2-5) are generally designed to represent the optimal operation plan and to be compared against the current practice of industry (non-optimal operation plans) as represented by case studies of set#1. Additionally, effects of the application of various management strategies such as jobsite isolation, distance-based clustering, free equipment sharing strategy and resources leveling on different components of the projects, including the bottom-line operation cost, are examined in detail. The effects of these strategies are investigated when they are applied to an optimal operation plan individually or combined with each other.

Case study #2-1:

This case is designed to study the results of optimizing both the schedule and the equipment operations plan. In this case study the schedule and the equipment operation plans are simultaneously optimized while actual shipment/rental costs (table 5.1) and the price assigned to time slots (Figure 5.10) form the input of the problem. Also, no leveling and no clustering constraints are in place.

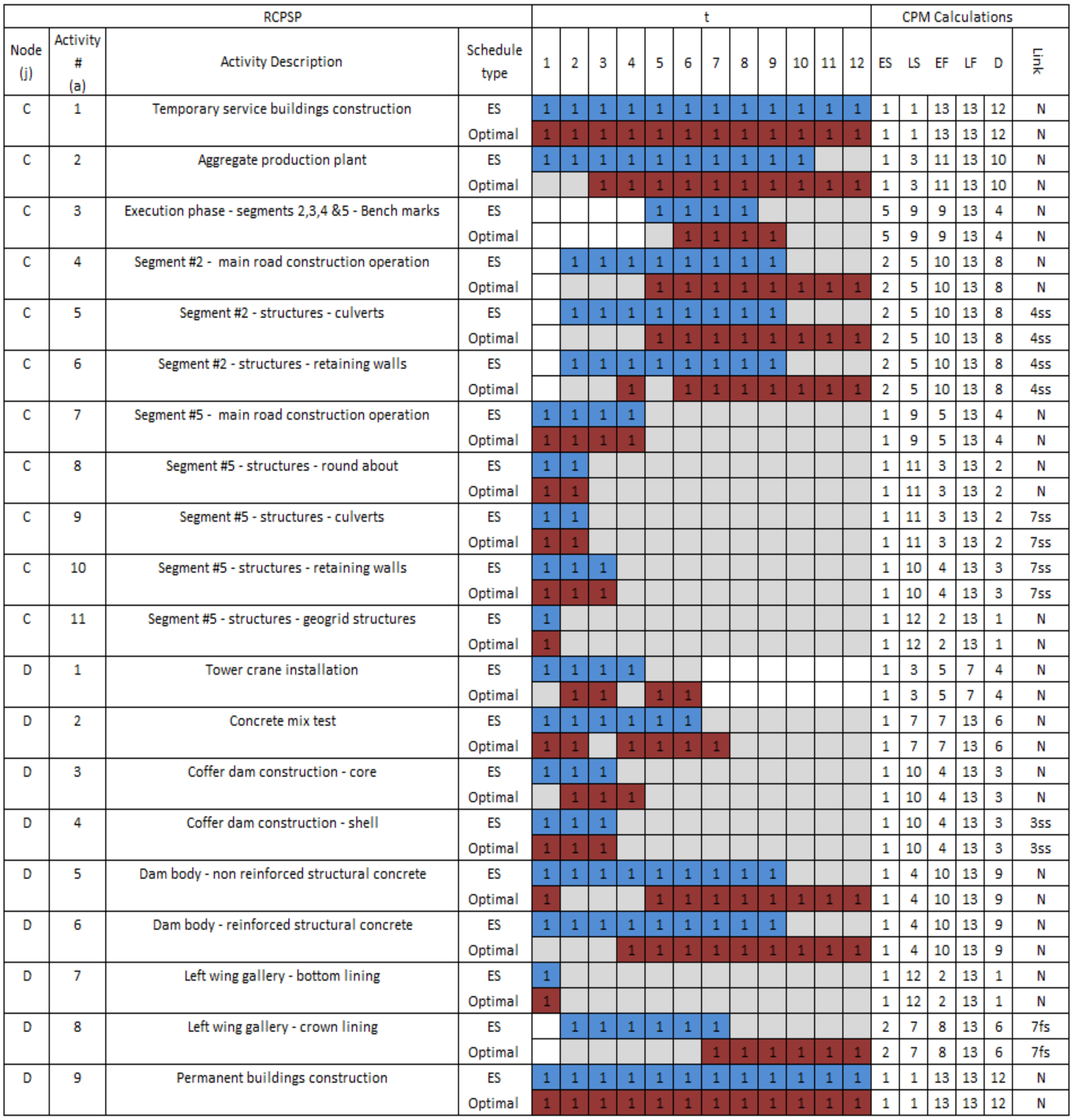
Figures 5.13 through 5.20 and table 5.3 present detailed output of the model for case study #2-1. Figure 5.13 shows solution convergence graphs which are direct outputs of Xpress solution process. Figure 5.14 illustrates both the ES and the optimal master schedule of the whole portfolio. Table 5.3 shows equipment demand and supply patterns for both ES and optimal schedules for each jobsite individually and for the portfolio as a whole. Also, figures 5.15 through 5.19 are graphical representation of the same table.

Finally, figure 5.20 illustrate the optimal equipment shipping pattern for each equipment type based on the model's output.

Detailed outputs of the model for other case studies also have the same structure. However, these excessive details for all case studies are not presented in the text and instead, for case studies which deemed necessary and informative they are presented in appendix I.

Figure 5.13- Solution tracking and convergence information for case study # 2-1; reported by Xpress

RCPSP				t												CPM Calculations					
Node (i)	Activity # (a)	Activity Description	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12	ES	LS	EF	LF	D	Link
A	1	Temporary service roads construction	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
A	2	Temporary service buildings construction	ES	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
			Optimal			1	1	1		1	1	1	1	1	1	1	4	10	13	9	N
A	3	Temporary site work	ES	1	1	1	1	1	1	1	1	1	1	1		1	2	12	13	11	N
			Optimal	1	1	1	1		1	1	1	1	1	1	1	1	2	12	13	11	N
A	4	Aggregate production plant	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
A	5	Dam body construction-Bench marks	ES					1	1	1	1	1	1	1	1	5	5	13	13	8	N
			Optimal					1	1	1	1	1	1	1	1	5	5	13	13	8	N
A	6	Dam body - left wing - excavation - level 1	ES	1	1	1	1	1	1	1	1					1	5	9	13	8	N
			Optimal	1	1				1	1	1		1	1	1	1	5	9	13	8	N
A	7	Dam body - left wing -leveling	ES			1	1	1	1	1	1	1				3	6	10	13	7	6ss+2
			Optimal						1	1	1	1	1	1	1	3	6	10	13	7	6ss+2
A	8	Dam body - left wing -trench temporary protection	ES		1	1	1	1	1	1						2	7	8	13	6	6ss+1
			Optimal				1	1	1		1	1	1			2	7	8	13	6	6ss+1
A	9	Dam body - right wing - excavation - level 1	ES	1	1	1	1	1	1	1	1					1	5	9	13	8	N
			Optimal	1	1		1	1	1	1	1	1				1	5	9	13	8	N
A	10	Dam body - right wing -leveling	ES			1	1	1	1	1	1	1				3	6	10	13	7	9ss+2
			Optimal						1	1	1	1	1	1	1	3	6	10	13	7	9ss+2
A	11	Dam body - right wing -trench temporary protection	ES		1	1	1	1	1	1						2	7	8	13	6	9ss+1
			Optimal			1	1	1	1	1	1					2	7	8	13	6	9ss+1
A	12	Dam body - rockfill	ES	1	1	1	1	1	1	1	1	1	1	1		1	2	12	13	11	N
			Optimal	1	1		1	1	1	1	1	1	1	1	1	1	2	12	13	11	N
A	13	Dam body - concrete face	ES		1	1	1	1								2	7	6	11	4	12ss+1
			Optimal		1				1	1	1					2	7	6	11	4	12ss+1
A	14	Gallery construction - middle section - concrete lining	ES	1	1	1	1									1	9	5	13	4	N
			Optimal									1	1	1	1	1	9	5	13	4	N
A	15	Gallery construction - left wing - excavation	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
A	16	Gallery construction - left wing - leveling	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
A	17	Gallery construction - left wing - concrete lining	ES		1	1	1									2	10	5	13	3	16ss+1
			Optimal		1				1	1						2	10	5	13	3	16ss+1
A	18	Gallery construction - right wing - excavation	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
A	19	Gallery construction - right wing - leveling	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
A	20	Gallery construction - right wing - concrete lining	ES		1	1	1									2	10	5	13	3	19ss+1
			Optimal		1			1	1							2	10	5	13	3	19ss+1
B	1	Segment #1 - water pipeline relocation	ES	1	1											1	4	3	6	2	N
			Optimal		1	1										1	4	3	6	2	N
B	2	Segment #1 - structures - canal - derivation	ES	1	1	1										1	5	4	8	3	N
			Optimal	1	1	1										1	5	4	8	3	N
B	3	Segment #2 - water pipeline relocation	ES	1	1											1	4	3	6	2	N
			Optimal	1	1											1	4	3	6	2	N
B	4	Segment #3 - water pipeline relocation	ES	1												1	12	2	13	1	N
			Optimal	1												1	12	2	13	1	N
B	5	Segment #4 - water pipeline relocation	ES	1	1	1										1	10	4	13	3	N
			Optimal			1	1	1								1	10	4	13	3	N
B	6	Segment #4 - structures - bridges - derivation	ES	1	1											1	11	3	13	2	N
			Optimal	1	1											1	11	3	13	2	N
B	7	Segment #5 - structures - bridges - derivation	ES	1	1	1	1									1	9	5	13	4	N
			Optimal	1	1				1	1						1	9	5	13	4	N
B	8	Segment #1 - pavement - base construction	ES			1	1	1	1	1						3	8	8	13	5	2fs-1
			Optimal								1	1	1	1	1	3	8	8	13	5	2fs-1
B	9	Segment #2 - pavement - sub base construction	ES			1	1	1	1							3	9	7	13	4	3fs
			Optimal			1	1	1	1							3	9	7	13	4	3fs
B	10	Segment #2 - pavement - base construction	ES				1	1	1	1	1					4	8	9	13	5	9ss+1
			Optimal							1	1	1		1	1	4	8	9	13	5	9ss+1

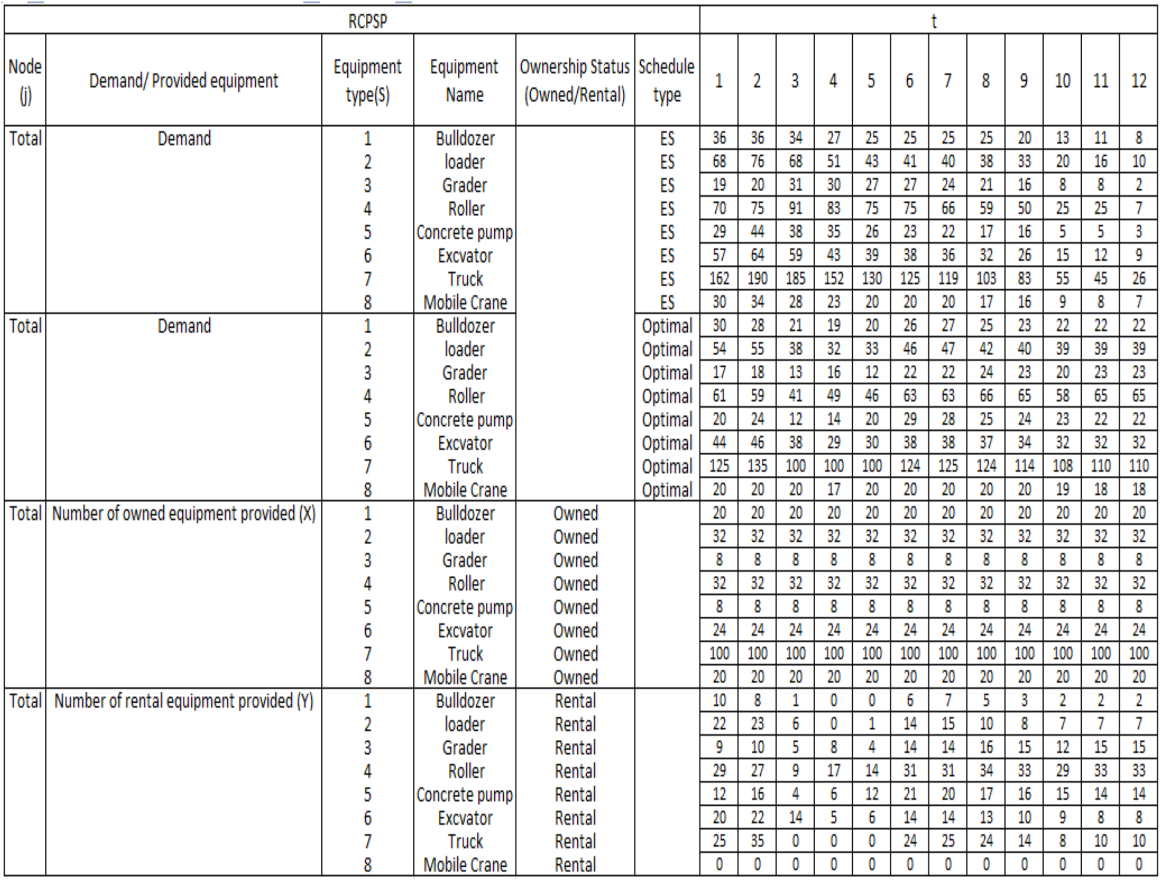


RCPSP				t												CPM Calculations					
Node (j)	Activity # (a)	Activity Description	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12	ES	LS	EF	LF	D	Link
C	1	Temporary service buildings construction	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
C	2	Aggregate production plant	ES	1	1	1	1	1	1	1	1	1	1			1	3	11	13	10	N
			Optimal			1	1	1	1	1	1	1	1	1	1	1	3	11	13	10	N
C	3	Execution phase - segments 2,3,4 &5 - Bench marks	ES					1	1	1	1					5	9	9	13	4	N
			Optimal						1	1	1	1				5	9	9	13	4	N
C	4	Segment #2 - main road construction operation	ES		1	1	1	1	1	1	1	1				2	5	10	13	8	N
			Optimal					1	1	1	1	1	1	1	1	2	5	10	13	8	N
C	5	Segment #2 - structures - culverts	ES		1	1	1	1	1	1	1	1				2	5	10	13	8	4ss
			Optimal					1	1	1	1	1	1	1	1	2	5	10	13	8	4ss
C	6	Segment #2 - structures - retaining walls	ES		1	1	1	1	1	1	1	1				2	5	10	13	8	4ss
			Optimal				1		1	1	1	1	1	1	1	2	5	10	13	8	4ss
C	7	Segment #5 - main road construction operation	ES	1	1	1	1									1	9	5	13	4	N
			Optimal	1	1	1	1									1	9	5	13	4	N
C	8	Segment #5 - structures - round about	ES	1	1											1	11	3	13	2	N
			Optimal	1	1											1	11	3	13	2	N
C	9	Segment #5 - structures - culverts	ES	1	1											1	11	3	13	2	7ss
			Optimal	1	1											1	11	3	13	2	7ss
C	10	Segment #5 - structures - retaining walls	ES	1	1	1										1	10	4	13	3	7ss
			Optimal	1	1	1										1	10	4	13	3	7ss
C	11	Segment #5 - structures - geogrid structures	ES	1												1	12	2	13	1	N
			Optimal	1												1	12	2	13	1	N
D	1	Tower crane installation	ES	1	1	1	1									1	3	5	7	4	N
			Optimal		1	1		1	1							1	3	5	7	4	N
D	2	Concrete mix test	ES	1	1	1	1	1	1							1	7	7	13	6	N
			Optimal	1	1		1	1	1	1						1	7	7	13	6	N
D	3	Coffer dam construction - core	ES	1	1	1										1	10	4	13	3	N
			Optimal		1	1	1									1	10	4	13	3	N
D	4	Coffer dam construction - shell	ES	1	1	1										1	10	4	13	3	3ss
			Optimal	1	1	1										1	10	4	13	3	3ss
D	5	Dam body - non reinforced structural concrete	ES	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
			Optimal	1				1	1	1	1	1	1	1	1	1	4	10	13	9	N
D	6	Dam body - reinforced structural concrete	ES	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
			Optimal				1	1	1	1	1	1	1	1	1	1	4	10	13	9	N
D	7	Left wing gallery - bottom lining	ES	1												1	12	2	13	1	N
			Optimal	1												1	12	2	13	1	N
D	8	Left wing gallery - crown lining	ES		1	1	1	1	1	1						2	7	8	13	6	7fs
			Optimal							1	1	1	1	1	1	2	7	8	13	6	7fs
D	9	Permanent buildings construction	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N

Figure 5.14- ES and optimal master schedule of the portfolio; case study # 2-1

RCPSP						t											
Node (j)	Demand/ Provided equipment	Equipment type(S)	Equipment Name	Ownership Status (Owned/Rental)	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12
A	Demand	1	Bulldozer		ES	15	15	17	15	16	16	16	16	12	9	9	6
		2	loader		ES	28	34	36	28	23	21	21	21	17	14	14	8
		3	Grader		ES	10	10	16	16	16	16	16	16	14	8	8	2
		4	Roller		ES	30	30	40	36	36	36	36	36	34	23	23	5
		5	Concrete pump		ES	6	17	17	17	9	6	6	4	4	3	3	1
		6	Excvator		ES	24	29	31	21	19	18	18	16	12	8	8	5
		7	Truck		ES	76	97	99	81	67	62	62	56	42	35	35	16
		8	Mobile Crane		ES	8	12	12	10	8	8	8	6	6	4	4	3
A	Demand	1	Bulldozer		Optimal	14	14	9	11	11	15	16	16	14	14	14	14
		2	loader		Optimal	25	31	19	16	16	26	25	23	21	21	21	21
		3	Grader		Optimal	10	10	4	9	7	16	16	16	15	15	15	15
		4	Roller		Optimal	29	29	14	25	21	35	36	36	35	35	35	35
		5	Concrete pump		Optimal	2	11	4	5	7	14	11	9	8	8	7	7
		6	Excvator		Optimal	21	24	19	13	13	19	19	19	16	16	15	15
		7	Truck		Optimal	66	81	46	52	53	72	69	67	57	57	54	54
		8	Mobile Crane		Optimal	5	7	8	7	8	8	8	8	8	8	7	7
A	Number of owned equipment provided (X)	1	Bulldozer	Owned		9	9	9	11	11	12	12	12	12	12	12	12
		2	loader	Owned		15	15	16	16	16	16	16	16	16	16	16	16
		3	Grader	Owned		2	2	2	3	3	3	3	3	3	3	3	3
		4	Roller	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		5	Concrete pump	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		6	Excvator	Owned		7	7	7	8	8	8	8	8	8	8	8	8
		7	Truck	Owned		46	46	46	52	53	53	53	53	53	53	53	53
		8	Mobile Crane	Owned		5	7	8	8	8	8	8	8	8	8	8	8
A	Number of rental equipment provided (Y)	1	Bulldozer	Rental		5	5	0	0	0	3	4	4	2	2	2	2
		2	loader	Rental		10	16	3	0	0	10	9	7	5	5	5	5
		3	Grader	Rental		8	8	2	6	4	13	13	13	12	12	12	12
		4	Roller	Rental		21	21	6	17	13	27	28	28	27	27	27	27
		5	Concrete pump	Rental		0	9	2	3	5	12	9	7	6	6	5	5
		6	Excvator	Rental		14	17	12	5	5	11	11	11	8	8	7	7
		7	Truck	Rental		20	35	0	0	0	19	16	14	4	4	1	1
		8	Mobile Crane	Rental		0	0	0	0	0	0	0	0	0	0	0	0
B	Demand	1	Bulldozer		ES	10	9	5	2	0	0	0	0	0	0	0	0
		2	loader		ES	14	12	6	2	0	0	0	0	0	0	0	0
		3	Grader		ES	3	3	8	10	9	9	6	3	0	0	0	0
		4	Roller		ES	10	9	19	23	21	21	14	7	0	0	0	0
		5	Concrete pump		ES	4	3	1	0	0	0	0	0	0	0	0	0
		6	Excvator		ES	11	9	6	4	3	3	2	1	0	0	0	0
		7	Truck		ES	21	18	19	18	15	15	10	5	0	0	0	0
		8	Mobile Crane		ES	8	6	2	0	0	0	0	0	0	0	0	0
B	Demand	1	Bulldozer		Optimal	8	8	4	1	1	2	2	0	0	0	0	0
		2	loader		Optimal	10	10	6	2	2	2	2	0	0	0	0	0
		3	Grader		Optimal	3	3	4	3	3	4	4	6	6	3	6	6
		4	Roller		Optimal	8	8	11	8	8	9	9	14	14	7	14	14
		5	Concrete pump		Optimal	2	2	2	1	1	0	0	0	0	0	0	0
		6	Excvator		Optimal	7	7	6	3	3	2	2	2	2	1	2	2
		7	Truck		Optimal	15	15	14	8	8	8	8	10	10	5	10	10
		8	Mobile Crane		Optimal	4	4	4	2	2	0	0	0	0	0	0	0
B	Number of owned equipment provided (X)	1	Bulldozer	Owned		5	5	4	1	1	0	0	0	0	0	0	0
		2	loader	Owned		4	4	4	2	2	2	0	0	0	0	0	0
		3	Grader	Owned		3	3	3	3	3	3	3	3	3	3	3	3
		4	Roller	Owned		8	8	8	8	8	8	9	10	10	10	10	10
		5	Concrete pump	Owned		2	2	2	1	1	0	0	0	0	0	0	0
		6	Excvator	Owned		6	4	4	3	3	2	2	2	2	2	2	2
		7	Truck	Owned		15	15	14	8	8	8	8	8	8	5	5	5
		8	Mobile Crane	Owned		4	4	4	4	2	0	0	0	0	0	0	0
B	Number of rental equipment provided (Y)	1	Bulldozer	Rental		3	3	0	0	0	2	2	0	0	0	0	0
		2	loader	Rental		6	6	2	0	0	0	2	0	0	0	0	0
		3	Grader	Rental		0	0	1	0	0	1	1	3	3	0	3	3
		4	Roller	Rental		0	0	3	0	0	1	0	4	4	0	4	4
		5	Concrete pump	Rental		0	0	0	0	0	0	0	0	0	0	0	0
		6	Excvator	Rental		1	3	2	0	0	0	0	0	0	0	0	0
		7	Truck	Rental		0	0	0	0	0	0	0	2	2	0	5	5
		8	Mobile Crane	Rental		0	0	0	0	0	0	0	0	0	0	0	0

RCPSP						t											
Node (j)	Demand/ Provided equipment	Equipment type(S)	Equipment Name	Ownership Status (Owned/Rental)	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12
C	Demand	1	Bulldozer		ES	6	7	7	7	6	6	6	6	5	3	1	1
		2	loader		ES	15	19	15	13	12	12	12	12	11	5	1	1
		3	Grader		ES	3	4	4	4	2	2	2	2	2	0	0	0
		4	Roller		ES	15	21	17	15	10	10	10	10	10	1	1	1
		5	Concrete pump		ES	8	13	9	7	7	7	7	7	6	1	1	1
		6	Excvator		ES	13	17	13	11	11	11	11	11	10	5	2	2
		7	Truck		ES	35	45	37	33	29	29	29	29	28	15	5	5
		8	Mobile Crane		ES	8	10	8	7	7	7	7	7	6	3	2	2
C	Demand	1	Bulldozer		Optimal	4	3	5	5	5	6	6	6	6	5	5	5
		2	loader		Optimal	11	9	9	9	9	12	12	12	12	11	11	11
		3	Grader		Optimal	3	2	2	2	2	2	2	2	2	2	2	2
		4	Roller		Optimal	15	12	8	8	8	10	10	10	10	10	10	10
		5	Concrete pump		Optimal	8	8	4	4	4	7	7	7	7	6	6	6
		6	Excvator		Optimal	10	9	8	8	8	11	11	11	11	10	10	10
		7	Truck		Optimal	25	22	24	24	24	29	29	29	29	28	28	28
		8	Mobile Crane		Optimal	7	6	5	5	5	7	7	7	7	6	6	6
C	Number of owned equipment provided (X)	1	Bulldozer	Owned		3	3	4	5	5	5	5	5	5	5	5	5
		2	loader	Owned		8	8	8	9	9	9	9	9	9	9	9	9
		3	Grader	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		4	Roller	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		5	Concrete pump	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		6	Excvator	Owned		6	8	8	8	8	9	9	9	9	9	9	9
		7	Truck	Owned		22	22	24	24	24	24	24	24	24	24	24	24
		8	Mobile Crane	Owned		7	6	5	5	5	7	7	7	7	7	7	7
C	Number of rental equipment provided (Y)	1	Bulldozer	Rental		1	0	1	0	0	1	1	1	1	0	0	0
		2	loader	Rental		3	1	1	0	0	3	3	3	3	2	2	2
		3	Grader	Rental		1	0	0	0	0	0	0	0	0	0	0	0
		4	Roller	Rental		7	4	0	0	0	2	2	2	2	2	2	2
		5	Concrete pump	Rental		6	6	2	2	2	5	5	5	5	4	4	4
		6	Excvator	Rental		4	1	0	0	0	2	2	2	2	1	1	1
		7	Truck	Rental		3	0	0	0	0	5	5	5	5	4	4	4
		8	Mobile Crane	Rental		0	0	0	0	0	0	0	0	0	0	0	0
D	Demand	1	Bulldozer		ES	5	5	5	3	3	3	3	3	3	1	1	1
		2	loader		ES	11	11	11	8	8	8	7	5	5	1	1	1
		3	Grader		ES	3	3	3	0	0	0	0	0	0	0	0	0
		4	Roller		ES	15	15	15	9	8	8	6	6	6	1	1	1
		5	Concrete pump		ES	11	11	11	11	10	10	9	6	6	1	1	1
		6	Excvator		ES	9	9	9	7	6	6	5	4	4	2	2	2
		7	Truck		ES	30	30	30	20	19	19	18	13	13	5	5	5
		8	Mobile Crane		ES	6	6	6	6	5	5	5	4	4	2	2	2
D	Demand	1	Bulldozer		Optimal	4	3	3	2	3	3	3	3	3	3	3	3
		2	loader		Optimal	8	5	4	5	6	6	8	7	7	7	7	7
		3	Grader		Optimal	1	3	3	2	0	0	0	0	0	0	0	0
		4	Roller		Optimal	9	10	8	8	9	9	8	6	6	6	6	6
		5	Concrete pump		Optimal	8	3	2	4	8	8	10	9	9	9	9	9
		6	Excvator		Optimal	6	6	5	5	6	6	6	5	5	5	5	5
		7	Truck		Optimal	19	17	16	16	15	15	19	18	18	18	18	18
		8	Mobile Crane		Optimal	4	3	3	3	5	5	5	5	5	5	5	5
D	Number of owned equipment provided (X)	1	Bulldozer	Owned		3	3	3	3	3	3	3	3	3	3	3	3
		2	loader	Owned		5	5	4	5	5	5	7	7	7	7	7	7
		3	Grader	Owned		1	1	1	0	0	0	0	0	0	0	0	0
		4	Roller	Owned		8	8	8	8	8	8	7	6	6	6	6	6
		5	Concrete pump	Owned		2	2	2	3	3	4	4	4	4	4	4	4
		6	Excvator	Owned		5	5	5	5	5	5	5	5	5	5	5	5
		7	Truck	Owned		17	17	16	16	15	15	15	15	15	18	18	18
		8	Mobile Crane	Owned		4	3	3	3	5	5	5	5	5	5	5	5
D	Number of rental equipment provided (Y)	1	Bulldozer	Rental		1	0	0	0	0	0	0	0	0	0	0	0
		2	loader	Rental		3	0	0	0	1	1	1	0	0	0	0	0
		3	Grader	Rental		0	2	2	2	0	0	0	0	0	0	0	0
		4	Roller	Rental		1	2	0	0	1	1	1	0	0	0	0	0
		5	Concrete pump	Rental		6	1	0	1	5	4	6	5	5	5	5	5
		6	Excvator	Rental		1	1	0	0	1	1	1	0	0	0	0	0
		7	Truck	Rental		2	0	0	0	0	0	4	3	3	0	0	0
		8	Mobile Crane	Rental		0	0	0	0	0	0	0	0	0	0	0	0



RCPSP						t											
Node (j)	Demand/ Provided equipment	Equipment type(S)	Equipment Name	Ownership Status (Owned/Rental)	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12
Total	Demand	1	Bulldozer		ES	36	36	34	27	25	25	25	25	20	13	11	8
		2	loader		ES	68	76	68	51	43	41	40	38	33	20	16	10
		3	Grader		ES	19	20	31	30	27	27	24	21	16	8	8	2
		4	Roller		ES	70	75	91	83	75	75	66	59	50	25	25	7
		5	Concrete pump		ES	29	44	38	35	26	23	22	17	16	5	5	3
		6	Excvator		ES	57	64	59	43	39	38	36	32	26	15	12	9
		7	Truck		ES	162	190	185	152	130	125	119	103	83	55	45	26
		8	Mobile Crane		ES	30	34	28	23	20	20	20	17	16	9	8	7
Total	Demand	1	Bulldozer		Optimal	30	28	21	19	20	26	27	25	23	22	22	22
		2	loader		Optimal	54	55	38	32	33	46	47	42	40	39	39	39
		3	Grader		Optimal	17	18	13	16	12	22	22	24	23	20	23	23
		4	Roller		Optimal	61	59	41	49	46	63	63	66	65	58	65	65
		5	Concrete pump		Optimal	20	24	12	14	20	29	28	25	24	23	22	22
		6	Excvator		Optimal	44	46	38	29	30	38	38	37	34	32	32	32
		7	Truck		Optimal	125	135	100	100	100	124	125	124	114	108	110	110
		8	Mobile Crane		Optimal	20	20	20	17	20	20	20	20	20	19	18	18
Total	Number of owned equipment provided (X)	1	Bulldozer	Owned		20	20	20	20	20	20	20	20	20	20	20	20
		2	loader	Owned		32	32	32	32	32	32	32	32	32	32	32	32
		3	Grader	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		4	Roller	Owned		32	32	32	32	32	32	32	32	32	32	32	32
		5	Concrete pump	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		6	Excvator	Owned		24	24	24	24	24	24	24	24	24	24	24	24
		7	Truck	Owned		100	100	100	100	100	100	100	100	100	100	100	100
		8	Mobile Crane	Owned		20	20	20	20	20	20	20	20	20	20	20	20
Total	Number of rental equipment provided (Y)	1	Bulldozer	Rental		10	8	1	0	0	6	7	5	3	2	2	2
		2	loader	Rental		22	23	6	0	1	14	15	10	8	7	7	7
		3	Grader	Rental		9	10	5	8	4	14	14	16	15	12	15	15
		4	Roller	Rental		29	27	9	17	14	31	31	34	33	29	33	33
		5	Concrete pump	Rental		12	16	4	6	12	21	20	17	16	15	14	14
		6	Excvator	Rental		20	22	14	5	6	14	14	13	10	9	8	8
		7	Truck	Rental		25	35	0	0	0	24	25	24	14	8	10	10
		8	Mobile Crane	Rental		0	0	0	0	0	0	0	0	0	0	0	0

Table 5.3 - Equipment demand and supply patterns for both ES and optimal schedules for each jobsite individually and for the portfolio as a whole; case study # 2-1

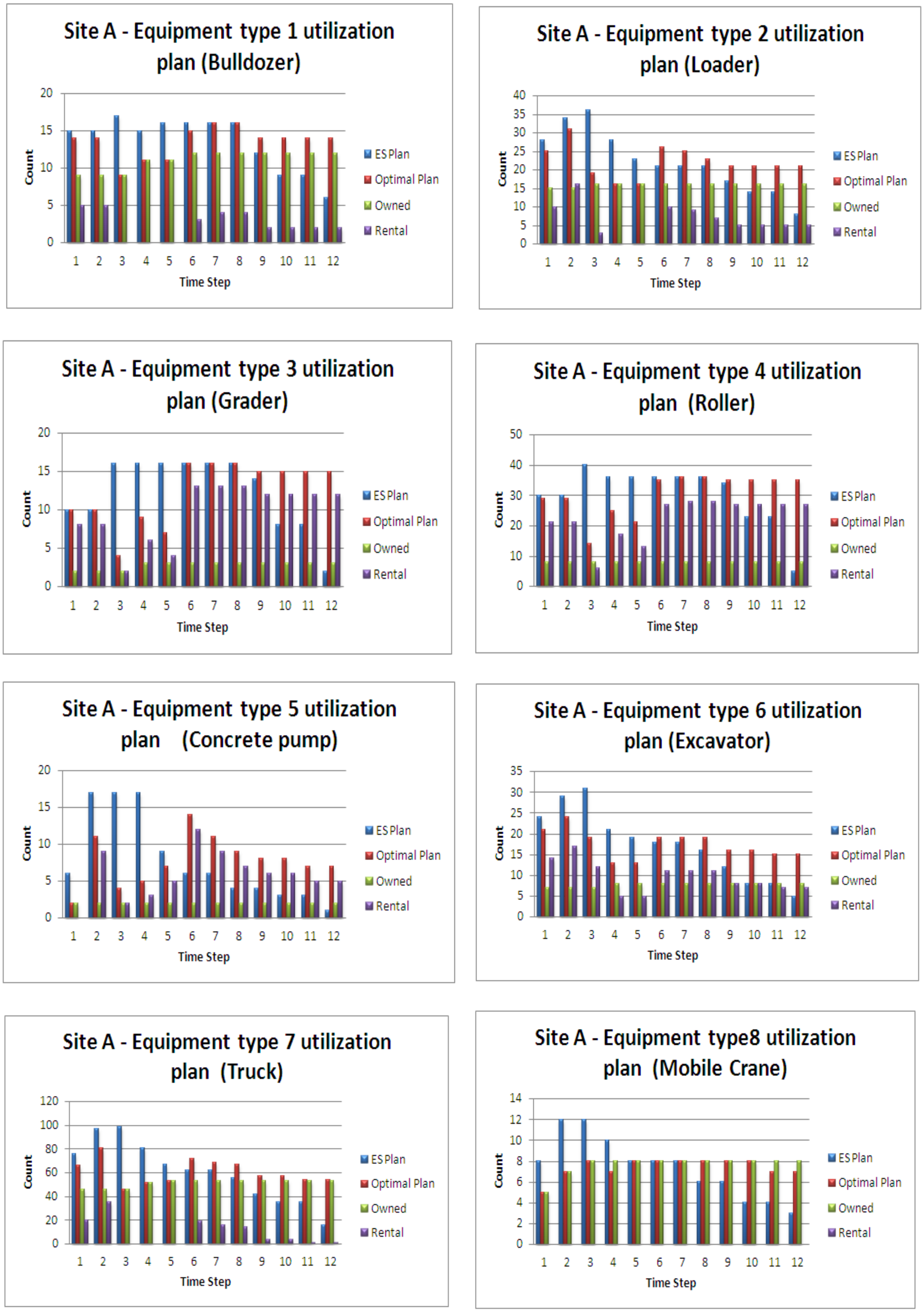


Figure 5.15 - Equipment demand and supply patterns for jobsite A; case study # 2-1

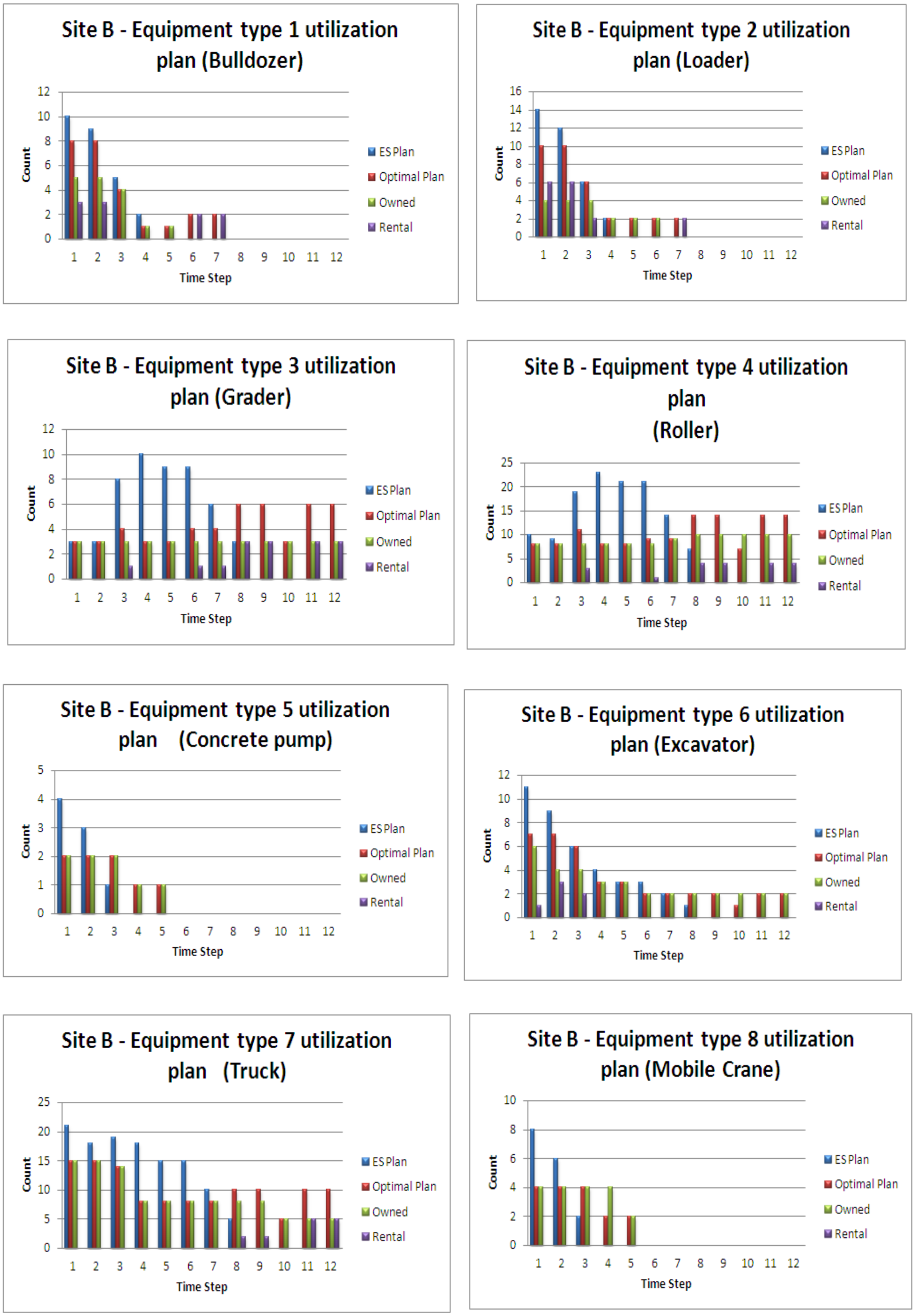


Figure 5.16 - Equipment demand and supply patterns for jobsite B; case study # 2-1

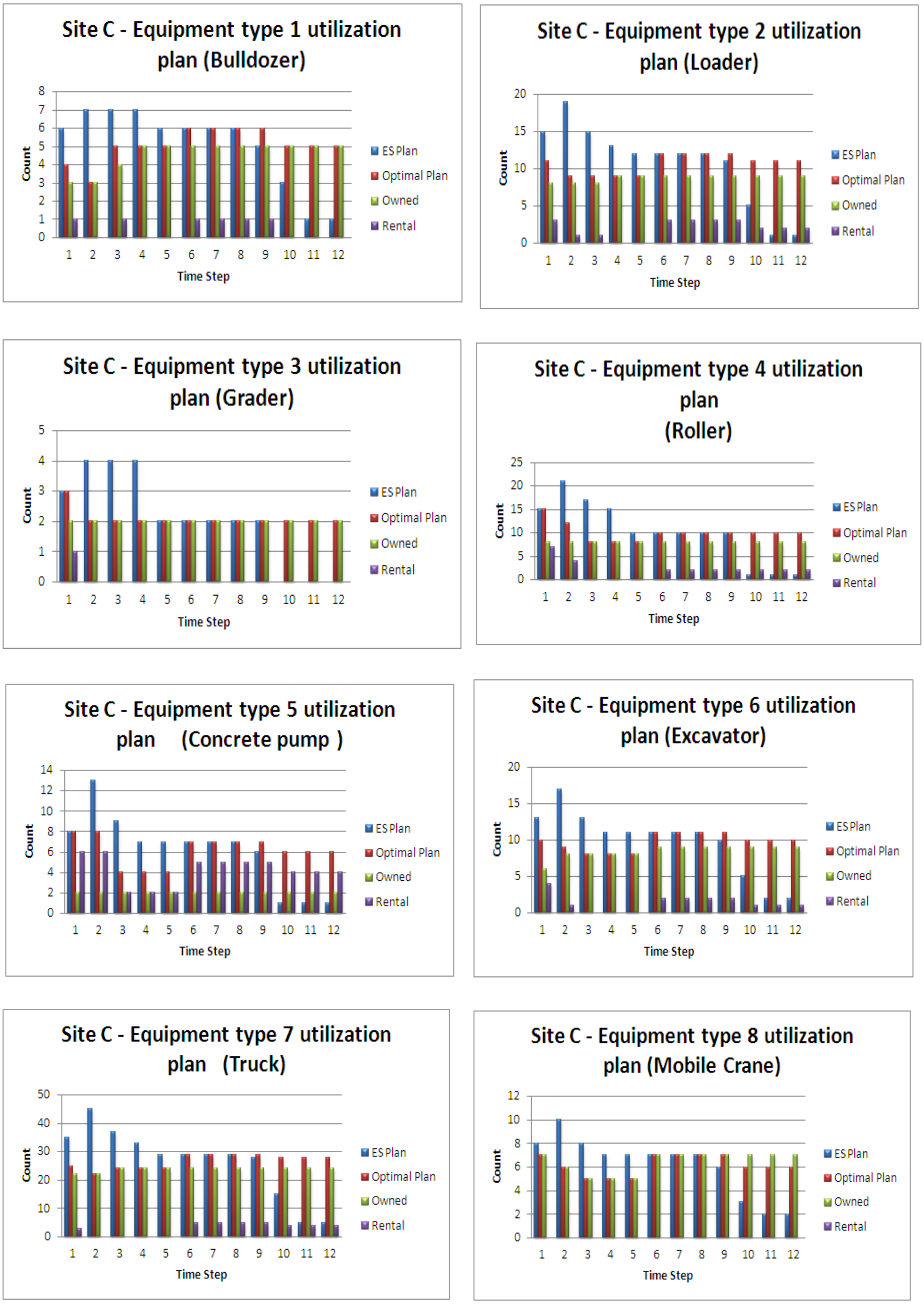
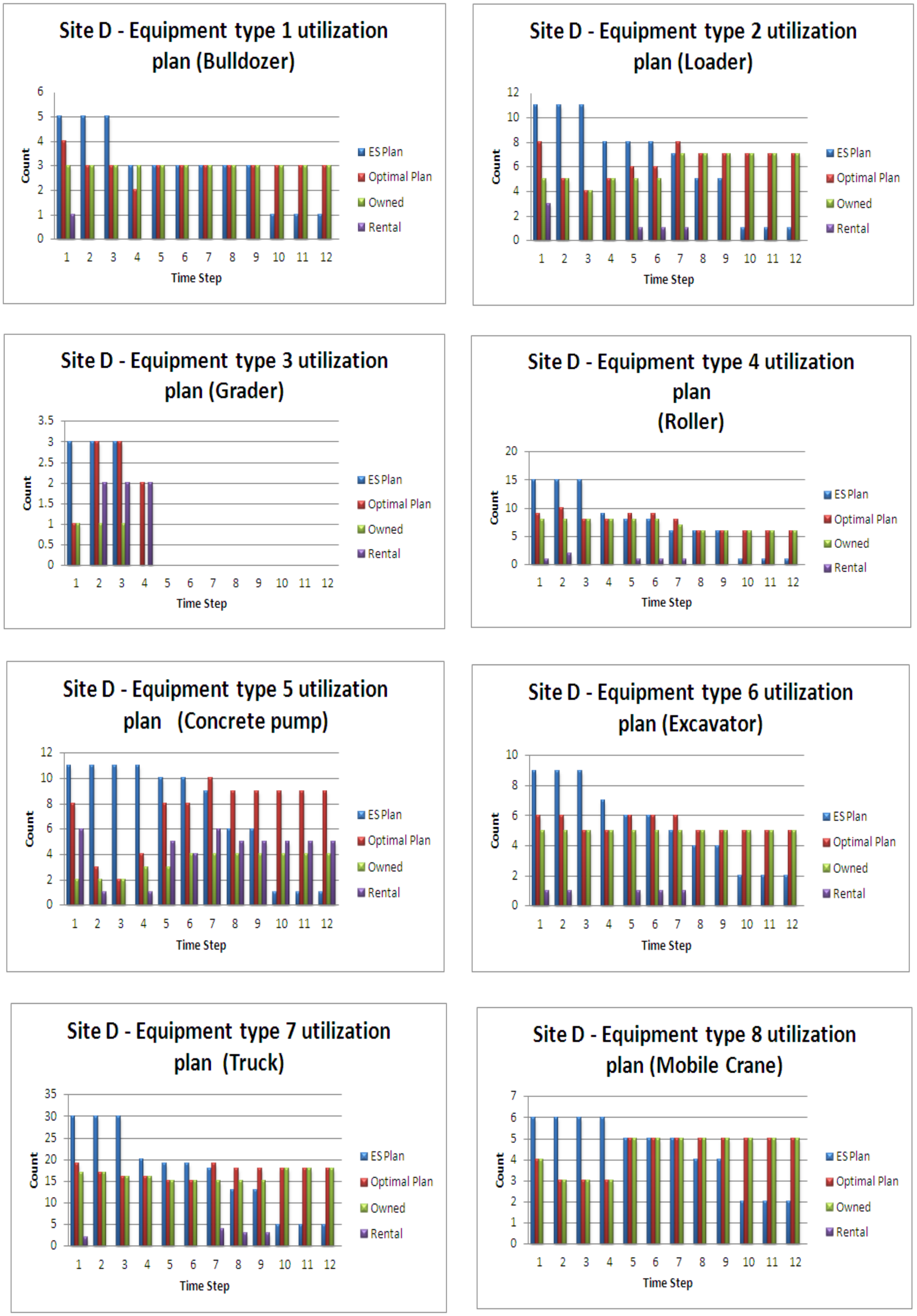


Figure 5.17 - Equipment demand and supply patterns for jobsite C; case study # 2-1



Site D - Equipment type 1 utilization plan (Bulldozer)

Site D - Equipment type 2 utilization plan (Loader)

Site D - Equipment type 3 utilization plan (Grader)

Site D - Equipment type 4 utilization plan (Roller)

Site D - Equipment type 5 utilization plan (Concrete pump)

Site D - Equipment type 6 utilization plan (Excavator)

Site D - Equipment type 7 utilization plan (Truck)

Site D - Equipment type 8 utilization plan (Mobile Crane)

Figure 5.18- Equipment demand and supply patterns for jobsite D; case study # 2-1

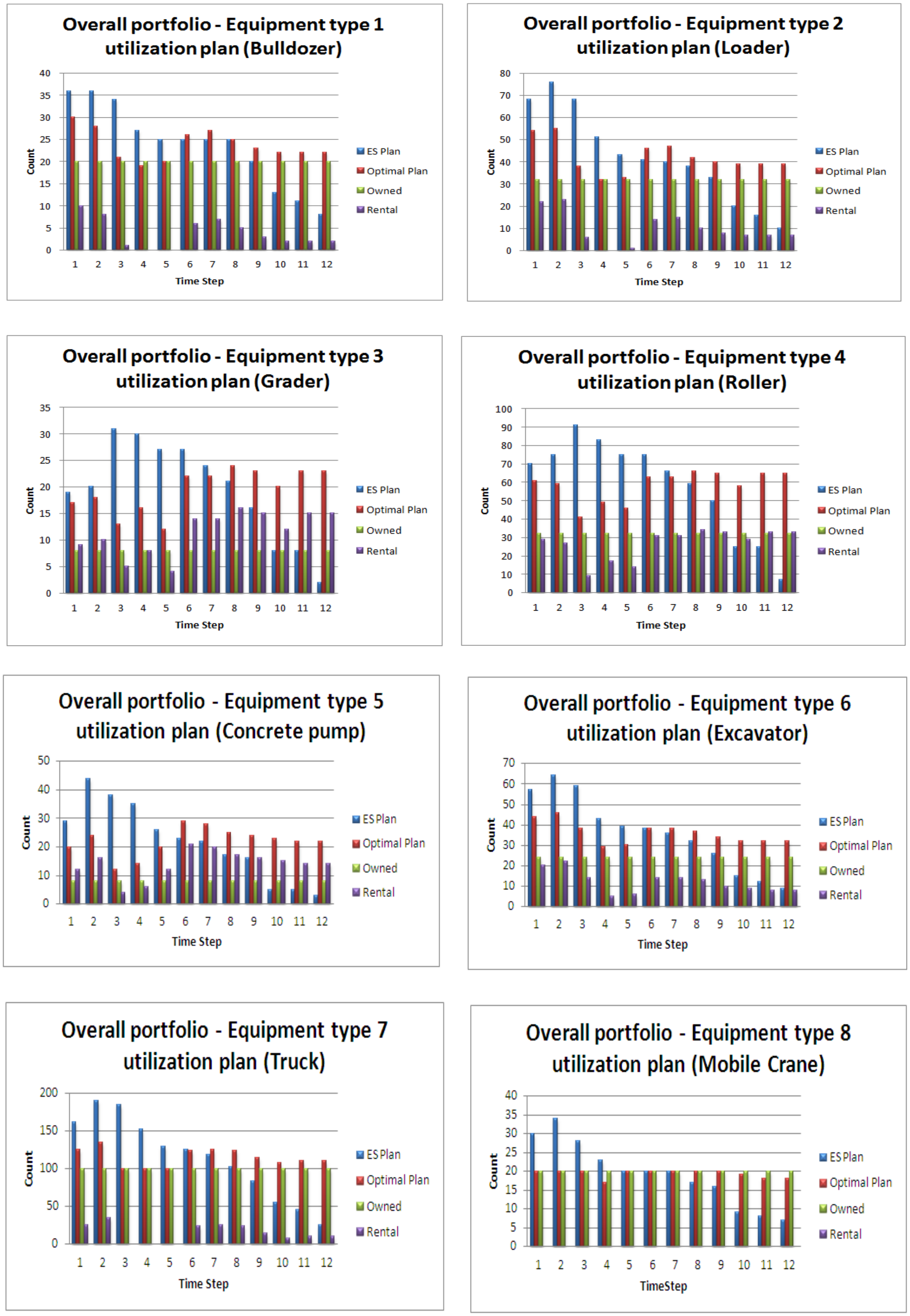


Figure 5.19- Equipment demand and supply patterns for the whole portfolio; case study # 2-1

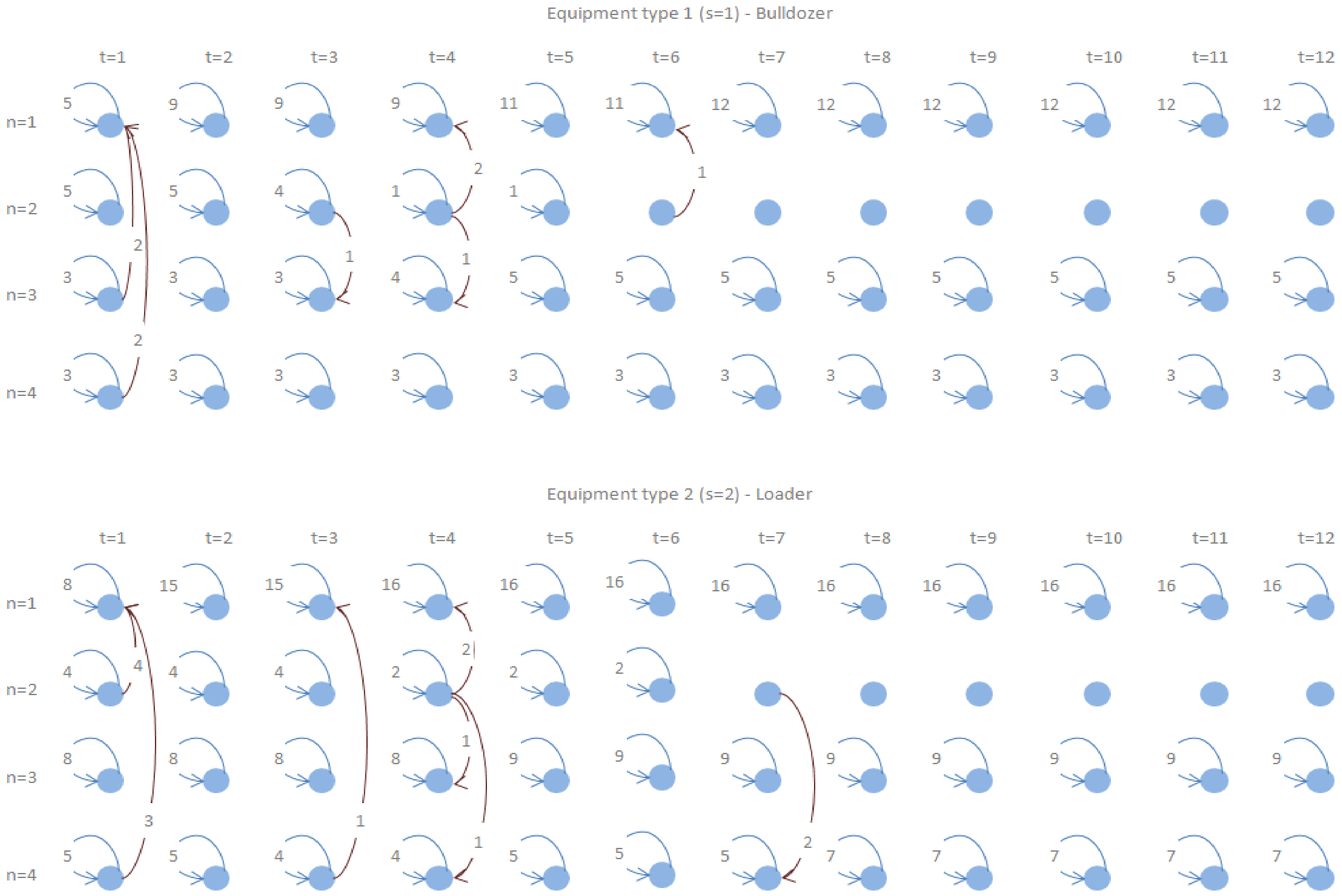
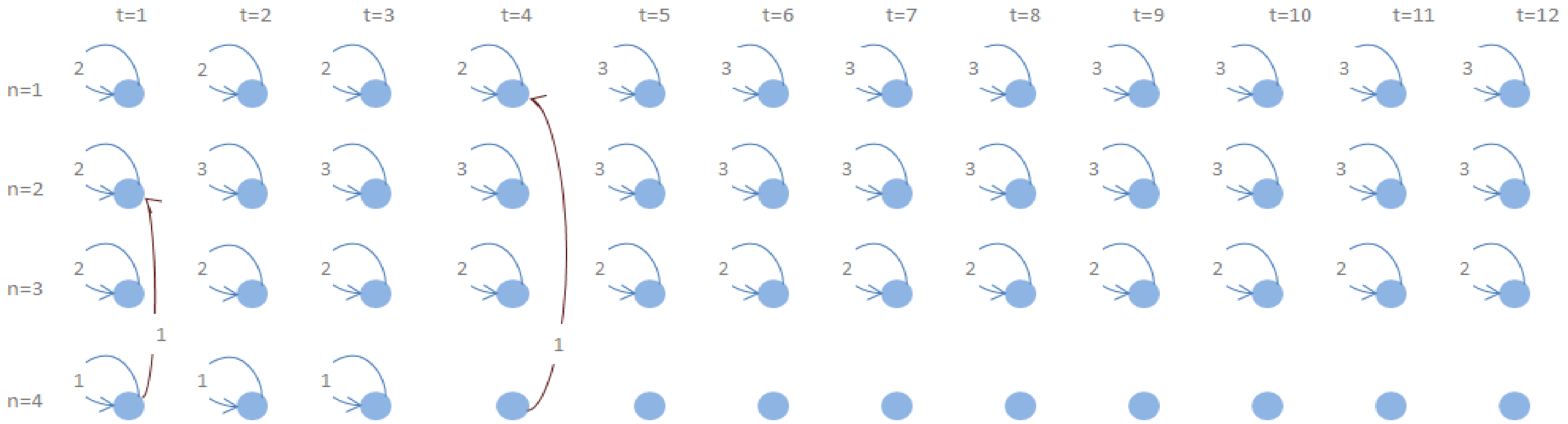


Figure 5.20 - Optimal equipment shipping pattern for each equipment type; case study # 2-1


Equipment type 3 (s=3) - Grader

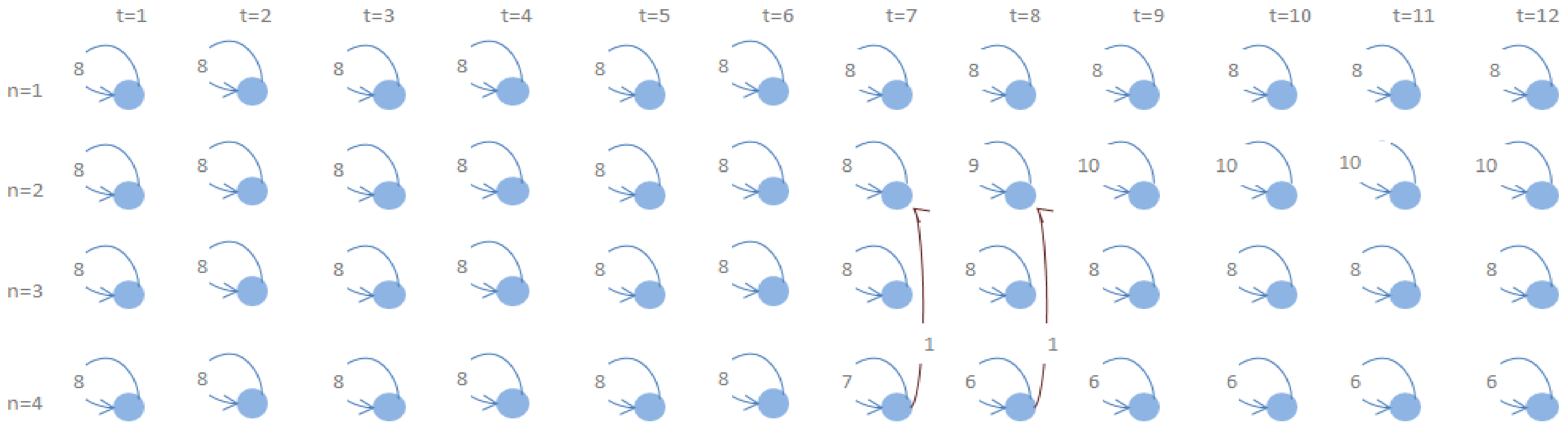
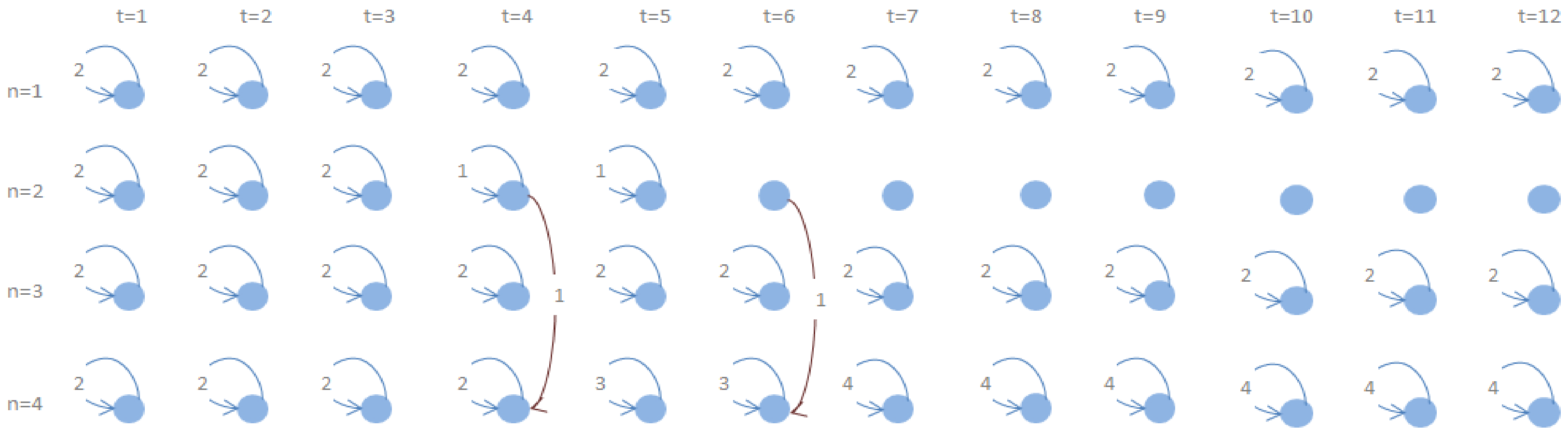

Equipment type 4 (s=4) - Roller

Figure 5.20 - Optimal equipment shipping pattern for each equipment type; case study # 2-1 (Cont’d)

Equipment type 5 (s=5) - Concrete pump



Equipment type 6 (s=6) - Excavator

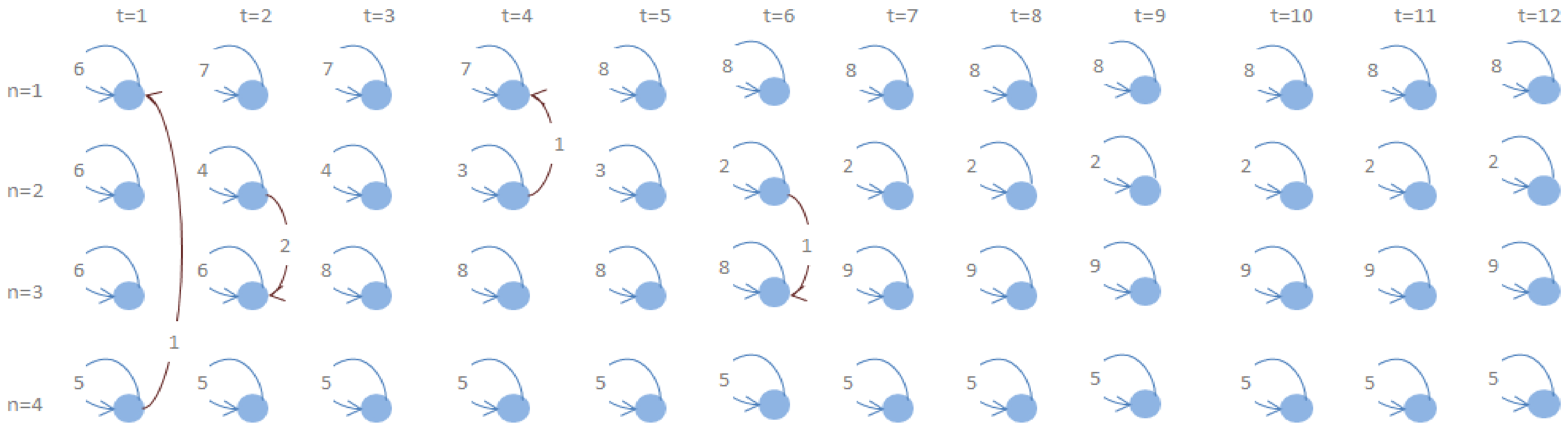


Figure 5.20- Optimal equipment shipping pattern for each equipment type; case study # 2-1 (Cont’d)

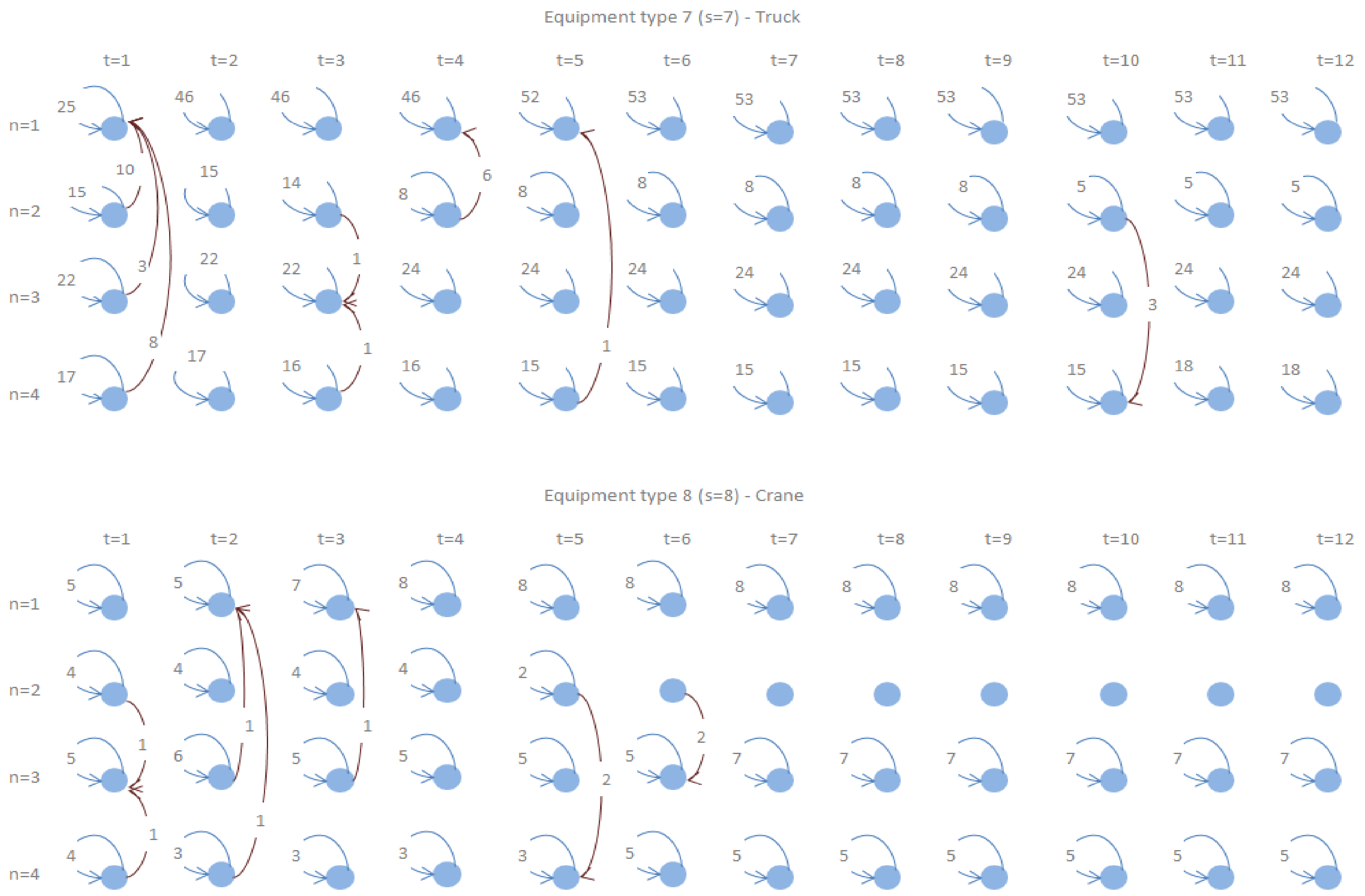


Figure 5.20 - Optimal equipment shipping pattern for each equipment type; case study # 2-1 (Cont'd)

Results:

- In this case study, which has the least constrained setting, the cost of operation (objective function value) is $ 3,854,630 which is significantly lower in comparison to case study #1-4. This significant cut in operation cost reflects economical worthiness of strategies such as simultaneous optimization of both the schedule and the equipment operation plan and equipment sharing among jobsites.
- According to the structure of this case study, at least 4,023 Equipment-week should be provided in order to meet the demand. However, based on the output of the model 4,036 Equipment-week is provided which shows presence of 13 Equipment-week of idle owned equipment in the plan. From 4,036 Equipment-week 2,928 is provided through the owned equipment fleet and 1,108 is provided through the available rental fleet.

Case study #2-2:

This case study is designed to investigate the effects of the addition of resource leveling constraints to the setting of case study #2-1.

Results:

- In this case study the cost of operation (The objective function value) is $ 3,860,410 which is slightly higher than the number in case study #2-1. This increase is due to the application of leveling constraints which translates into more restrictions in solving the problem. So, leveling is considered to be an inappropriate resource allocation strategy and should be avoided if not necessary.

Case study #2-3:

This case study is designed to examine the results of the addition of distance based clustering constraints to the setting of case study #2-1. In this scenario, sites A and C are put in cluster #1 and sites B and D form cluster #2. In this setting while intra-cluster equipment sharing is possible, inter-cluster equipment sharing is not.

Results:

- In this case study the cost of operation (The objective function value) is $ 5,484,370 which is significantly higher than the objective function value of case study #2-1. This case study shows that the clustering strategy has significant adverse effects on the value of the objective function even when both the schedule and equipment operation plan are optimized. So, clustering is considered to be an inappropriate resource allocation strategy and should be avoided, if not necessary.

Case study #2-4:

This case study is designed to examine the results of the simultaneous addition of both distance based clustering and leveling constraints to the setting of case #2-1.

Results:

- In this case study the cost of operation (The objective function value) is $ 5,543,940. This number is significantly higher than the objective function value of case study #2-1 and slightly higher than the objective function value of case study #2-3. These two comparisons show that a large fraction of this increase can be attributed to the addition of clustering constraints where the addition of leveling constraints is not a major contributor to the increase.

Case study #2-5:

This case study is designed to examine the results of total isolation of jobsites while other settings remain unchanged from case study #2-1.

Results:

- In this case study the cost of operation (The objective function value) is $ 5,655,530. This number is significantly higher than the objective function value of case study # 2-1 which shows total isolation of jobsites, even when the operation plan is optimized, has significant adverse effects on the objective function value. The increase in the value of the objective function as the result of jobsite isolation strategy is even more than the increase resulting from the addition of clustering and leveling constraints combined. Thus, isolation of jobsites, which is a current industry practice, is an extremely inefficient managerial strategy and should be avoided, unless necessary.

5.2.3. Set#3 case studies

Set #3 case studies (#3-1 and #3-2) are designed to examine the effects of presence of time price function in the model. More specifically, these examples are designed to show the effects of adopting exponential time price function as the time slot pricing mechanism on different components of the projects including the bottom- line operation cost.

Case study #3-1:

This case study is designed to study the effects of the presence of an exponential time price function on the model's performance. This problem has the exact setting of case study #2-1 except for the fact that instead of PH5, PH16 has been considered which means higher prices have been assigned to time slots.

Results:

- In this case study the cost of operation is $ 5,728,710 which shows a significant increase in comparison to case study #2-1. A large fraction of this increase is due to an increase in rental and shipment costs in order to perform tasks as early as it is economically possible thereby avoiding extremely high costs of incurring delay by using later time slots of PH16.

Case study #3-2:

This case study is also designed to examine the effects of presence of an exponential time price function on the model's performance. This problem has the exact setting of case study # 3-1 except for the fact that instead of allowing the model to optimize the schedule, the activities are moved to their LS.

Results:

- Cost of operation in this scenario is \$ 34,605,100 which is much higher than the cost of the operation in other case studies. Examination of the breakdown of this number reveals that the changes in shipping and rental costs are not a significant portion of the total operation cost while the schedule delay cost is \$ 29,402,800. Comparison of this case study with case study #1-2 shows that there is a large difference between the schedule delay costs in PH5 (\$ 650,168) and PH16 (\$ 29,402,800) resulting from adoption of an exponential time slot pricing function which provides the linkage between the price of timeslots and liquidated damages of projects. In practice, adoption of this pricing model translates into higher costs of delay as the finish milestone of projects is approached. This pattern matches reality since later time slots have higher levels of contribution to overall financial damages.

5.2.4. Set#4 case studies

Set #4 case studies (#4-1 and #4-2) are designed to demonstrate the capabilities of the proposed model in performing analysis regarding long term decisions such as purchasing heavy equipment. More specifically, these examples are designed to determine the optimum size of a company's owned equipment fleet for performing activities of the given portfolio and to examine the effects of optimizing the size of the owned fleet on different components of projects including the bottom-line operation cost.

Case study #4-1:

This case study is designed to investigate the results of adding heavy equipment purchase decision to the scope of the problem. Actual purchase prices of equipment, shipment costs, rental costs and price assigned to time slots form the input of the problem. Also, no leveling and no clustering constraints are in place. Although the number of owned pieces of equipment is a decision variable in set #4 case studies, in this particular case study, the value of this decision variable is set to constant values which represent the number of equipment currently owned by the company.

Results:

- The objective function value for this case study is $ 116,941,120 which represents the equipment ownership and operation cost over the course of all 16 PHs. This scenario also establishes a base case for investigating results of adding equipment purchase decisions to the initial problem statement.

Case study #4-2:

This case study, which is designed to find the optimum size of the owned heavy equipment fleet, has the exact setting of case study #4-1 except for the fact that numbers of owned pieces of equipment are decision variables for which values are yet to be determined.

Results:

- In case study #4-1 the objective function value is \$ 116,941,120 of which \$ 51,160,000 is the cost of purchasing equipment and \$ 56,744,000 is the cost of renting equipment. However, in case study #4-2 the objective function value is reduced to \$ 84,945,120 of which \$ 72,220,000 is the equipment purchase cost and \$ 2,980,800 belongs to the rental cost. The significant reduction in the cost of equipment ownership and operation in comparison to case study #4-1 is the result of the addition of the equipment purchasing option. Having this option, enables managers to make long term investment decisions regarding the purchase of heavy equipment as an integrated part of their operational level decisions. This strategy pays off in long term and reduces the overall cost by significantly cutting the rental expenses.

5.2.5. Set#5 case studies

Set #5 case studies (5-1, 5-2 and 5-3) are designed to analyze the effects of rental equipment availability on different components of projects including the bottom-line operation cost.

Case study #5-1:

This case study is designed to study the effects of rental equipment availability cap on the solution provided by the model. More specifically, in this case study finding the maximum cap value for which the problem becomes infeasible is the target. The case study has exactly the same structure as case study #4-1 with the only difference being that the cap of the rental equipment availability is changed in order to find the specified target.

Results:

- If the rental equipment availability cap is set to 6 units, the problem becomes infeasible. This means not even a single owned equipment sharing and activity shifting /splitting pattern can be found to supplement this level of rental equipment availability (6 units) to meet the demand.

Case study #5-2:

This case study is also designed to study the effects of rental equipment availability cap on the solution provided by the model. More specifically, in this case study finding the minimum cap value for which the problem is still feasible is the target. The case study has exactly the same structure as case study #4-1 with the only difference being that in this case study the cap of the rental equipment availability is changed in order to find the specified target.

Results:

- The rental equipment availability of 7 units is the lowest cap which makes the problem feasible. This means that at least one owned equipment sharing and activity shifting/splitting pattern can be found to supplement this level of rental equipment availability (7 units) in order to meet the demand. The objective function value in this case study is $ 121,561,920 which is significantly higher than the objective function of case study #4-1 being $ 116,941,120. Since costs of equipment ownership are equal in both case studies ($ 51,160,000), the cost increase can be attributed to an increase in shipment, rental and schedule delay costs. Technically, the resulting increase in shipping expenses is directly linked to applying more restrictions on the availability of rental equipment while the increase in rental and schedule delay costs is an indirect result of the presence of such restrictions.

Case study #5-3:

This case study is also designed to study the effects of rental equipment availability cap on the solution. More specifically, in this case study no cap has been assigned to rental equipment and the objective is to investigate the effects of this change on the model's output. The case study has exactly the same structure as the case study #4-1 with the only difference being that in this case study rental equipment availability is not limited.

Results:

- The unlimited rental equipment availability decreases the value of the objective function ($ 116,941,120) in comparison to case study #5-2 ($ 121,561,920). This decrease in cost is the result of higher availability of rental equipment which translates into a less constrained problem in mathematical terms. This in practice means more and cheaper owned equipment sharing and activity shifting/splitting patterns can be found and supplemented by available rental equipment to meet the demand.
- When the cap for rental equipment availability is relaxed to be a decision variable, the maximum value it assumes is 56 units. This value is significantly higher than

7 which is forced in case study #5-2. This means case study #5-3 is less constrained in comparison to 5-2, and thus has a significantly better (lower) objective function value.

5.3. Conclusions and discussion on results

In this chapter, a number of practical case studies were introduced and solved by using the exact approach to demonstrate the functionality and examine various features of the proposed mathematical model. Table 5.4 provides detailed information about 16 case studies which are studied in five subsections of section 5.2 in a consolidated manner. Cross comparison of all these case studies, drawing practically useful conclusions and sensitivity analysis for the length of the PH are subjects of discussion in this section.

Case studies solution report

Case study #	Comparison base case #	Case description	LP relaxation value ($)	Objective function value ($)	Best Lower bound value ($)	Gap (%)	Solution time (Sec)	Delay cost ($)	Shipping cost ($)	Rental cost ($)	Ownership cost ($)	Saving in comparison to base case (%)
1-1	-	ES plan/ Actual shipment and rental costs/ Exponential time price function/ No leveling constraint/ Jobsites totally isolated and no equipment sharing	7,016,000	7,016,000	-	0	0.1	0	0	7,016,000	0	-
1-2	1-1	LS plan/ Actual shipment and rental costs/ Exponential time price function/ No leveling constraint/ Jobsites totally isolated and no equipment sharing	7,057,770	7,057,770	-	0	0.1	650,168	0	6,407,600	0	-0.595%
1-3	1-1	ES plan/ Actual shipment and rental costs/ Exponential time price function/ No leveling constraint/ Distance base clustering (Cluster #1 : sites A&C and Cluster #2: sites B & D)	6,715,280	6,715,280	-	0	0.1	0	64,880	6,650,400	0	4.286%
1-4	1-1	ES plan/ Actual shipment and rental costs/ Exponential time price function/ No leveling constraint/ No clustering	5,767,300	5,767,300	-	0	0.1	0	268,700	5,498,600	0	17.798%
2-1	1-4	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/No Leveling constraint/ No clustering	3,661,330	3,854,630	3,809,740	1.17	12,000	189,228	232,605	3,432,800	0	33.164%
2-2	2-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/Leveling constraint in place/No clustering	3,662,130	3,860,410	3,819,180	1.07	44,200	196,506	224,805	3,439,100	0	-0.150%
2-3	2-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ No Leveling constraint / Distance base clustering (Cluster #1 : sites A&C and Cluster #2: sites B & D)	5,331,610	5,484,370	5,468,600	0.287	4,000	179,524	49,945	5,254,900	0	-42.280%
2-4	2-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/Leveling constraint in place/ Distance base clustering (Cluster #1 : sites A&C and Cluster #2: sites B & D)	5,343,800	5,543,940	5,504,210	0.72	2,400	230,470	68,170	5,245,300	0	-43.825%
2-5	2-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/No Leveling constraint / Jobsites totally isolated and no equipment sharing	5,495,710	5,655,530	-	0	4	198,932	0	5,456,600	0	-46.720%

Case studies solution report (cont'd)

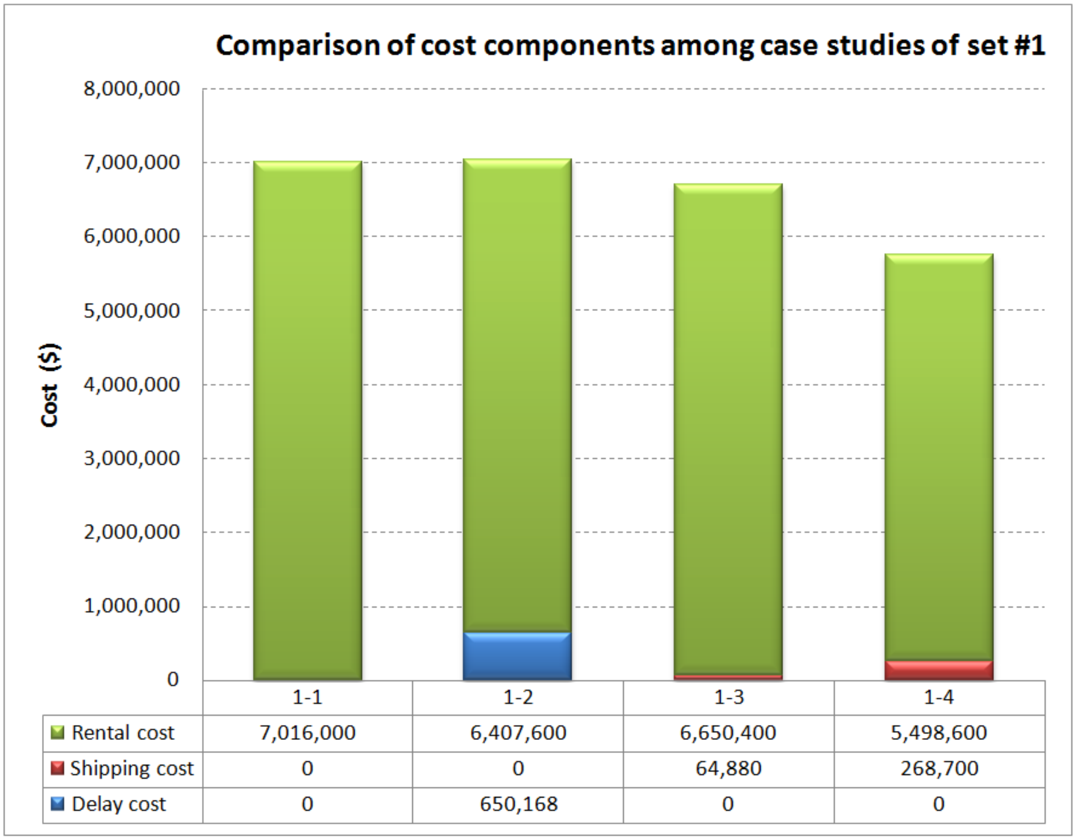
Case study #	Comparison base case #	Case description	LP relaxation value ($)	Objective function value ($)	Best Lower bound value ($)	Gap (%)	Solution time (Sec)	Delay cost ($)	Shipping cost ($)	Rental cost ($)	Ownership cost ($)	Saving in comparison to base case (%)
3-1	2-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function /No Leveling constraint /No clustering/ Shifting the schedule activities from current PH 5 to PH16	4,896,350	5,728,710	-	0	1.4	109,712	265,200	5,353,800	0	-48.619%
3-2	3-1	LS plan/ Actual shipment and rental costs/ Exponential time price function /No Leveling constraint /No clustering/ Shifting the schedule of activities from PH5 to PH16	34,605,100	34,605,100	-	0	0.1	29,402,800	270,900	4,931,400	0	-504.064%
4-1	-	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Actual market price for equipment /No Leveling constraint /No clustering/ Fix (given) number of owned pieces of equipment	111,416,960	116,941,120	116,437,600	0.43	757	4,938,480	4,098,560	56,744,000	51,160,000	-
4-2	4-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Actual market price for equipment /No Leveling constraint /No clustering/ Variable number of owned pieces of equipment	75,968,480	84,945,120	82,908,800	2.4	62,753	7,901,568	1,842,800	2,980,800	72,220,000	27.361%
5-1	-	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Actual market price for equipment / No Leveling constraint /No clustering/ Fix (given) number of owned pieces of equipment/ Maximum cap value for availability of rental equipment such that the problem is infeasible	0	0	0	0	0	0	0	0	0	-
5-2	4-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Actual market price for equipment /No Leveling constraint /No clustering/ Fix (given) number of owned pieces of equipment/ Minimum cap value for availability of rental equipment such that the problem is feasible	113,078,720	121,561,920	119,084,160	2.04	70,121	7,352,848	6,010,640	57,038,400	51,160,000	-
5-3	5-2	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Actual market price for equipment /No Leveling constraint /No clustering/ Fix (given) number of owned pieces of equipment/ No cap value for availability of rental equipment	111,416,960	116,941,120	116,437,600	0.43	757	4,938,480	4,098,560	56,744,000	51,160,000	3.801%

Note 1) : The configuration of the system that was used in performing sensitivity analysis is as follows : CPU: Intel (R) Core (TM)2 Duo E8200@2.67 GHz , RAM: 4GB , OS: Windows7; 64bit.

Note 2) : The basis for saving calculations in each case is the objective function value (overall cost of operation) of the comparison base scenario which is assigned to that particular case.

Table 5.4 - Detailed information about 16 cases studied in five subsections of section 5.2

In case studies in set #1, activity schedules are fixed to either ES or LS and in this setting various managerial strategies regarding equipment sharing among jobsites were examined and their effects on different cost components and overall cost efficiency of operation were assessed. These strategies ranged from absolutely no equipment sharing to equipment sharing among geographically close jobsites to equipment sharing among all jobsites regardless of distance. Figure 5.21 illustrates the effects of different scheduling and equipment sharing strategies on components of the operation cost in case studies of set #1.



	1-1	1-2	1-3	1-4
🟩 Rental cost	7,016,000	6,407,600	6,650,400	5,498,600
🟥 Shipping cost	0	0	64,880	268,700
🟦 Delay cost	0	650,168	0	0

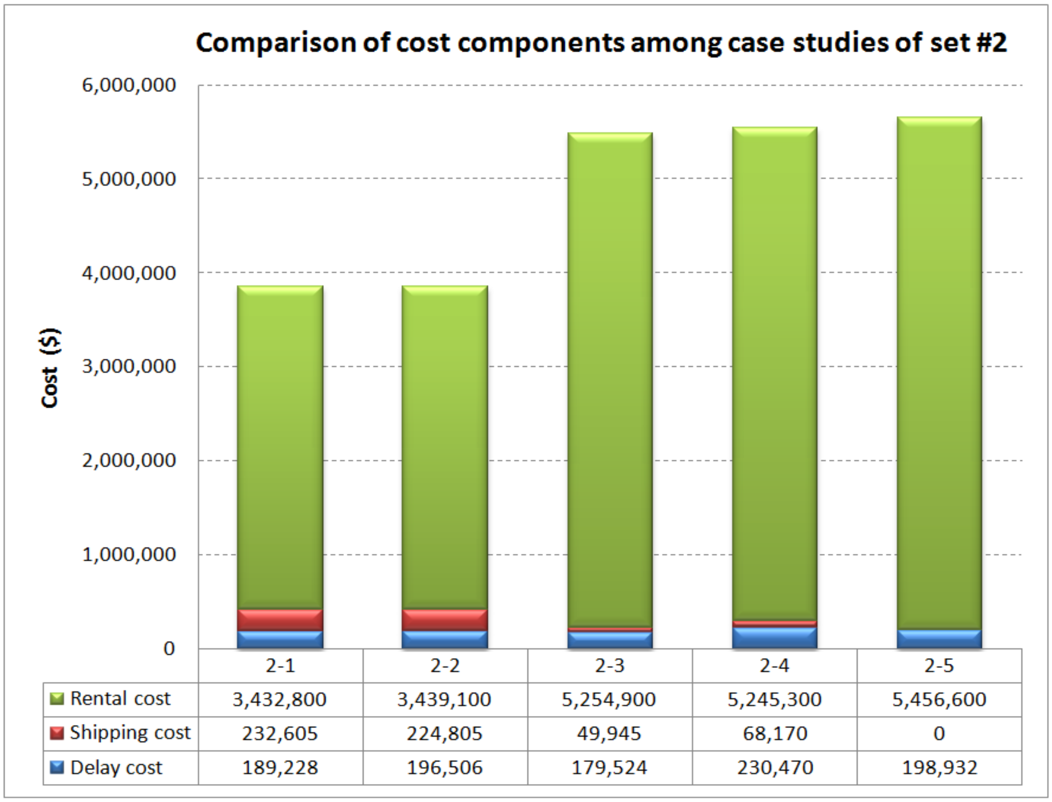
Figure 5.21 - Effects of different scheduling and equipment sharing strategies on components of the operation cost in case studies of set #1

Conclusions that are derived from cross comparison of set #1case studies are as follows.

- Case study #1-1vs.case study #1-4: Optimizing the equipment operation even under a fixed schedule setting significantly reduces the overall operation cost.
- Case study #1-1 vs. case study #1-2: By shifting the schedule from ES to LS significant delay cost is incurred due to the presence of time slot pricing. This comparison shows that incurring higher delay cost does not directly translate into higher operation cost since other components of the operation cost can change by changing the schedule. For instance in this particular case, a significant decrease in rental cost has almost compensated the increase in delay cost and the overall operation cost has slightly increased in the LS situation.
- Case studies #1-1, #1-3, #1-4: Comparison of these case studies reveals that shifting the equipment sharing strategy, from absolute jobsite isolation to distance based clustering to free equipment sharing, results in higher utilization of owned equipment fleet and more savings in the operation cost. Thus, it can be concluded that optimal equipment sharing, which is not the current practice in the construction industry, increases the cost efficiency of the operation.
- Case study #1-4: Results of this case study show that given this portfolio of projects and the current status of owned equipment fleet there is a severe shortage of owned equipment and a heavy dependence on rental equipment even when free equipment sharing is allowed. This conclusion implies that an increase in size and changes in composition of the owned fleet might be beneficial cost wise. The option of changing properties of the owned equipment fleet is exercised in case studies of set #4.

In case studies in set #2, both activity schedules and equipment operation plans are optimized simultaneously. This practice significantly increases the cost efficiency of the operation. Also, under new circumstances effects of equipment sharing and resource leveling strategies are examined. Generally, obtained results support the presence of the same pattern of effects among outputs as it was tracked in case studies of set #1.

Additionally as a new finding, it is shown that resource leveling strategies have slight adverse effects on the cost efficiency of the operation. Hence, if deemed necessary to apply, adverse effects of such strategies should be considered in related cost-benefit analyses. Figure 5.22 illustrates the effects of different scheduling and equipment sharing strategies on components of the operation cost in case studies of set #2.



	2-1	2-2	2-3	2-4	2-5
🟩 Rental cost	3,432,800	3,439,100	5,254,900	5,245,300	5,456,600
🟥 Shipping cost	232,605	224,805	49,945	68,170	0
🟦 Delay cost	189,228	196,506	179,524	230,470	198,932

Figure 5.22 - Effects of different scheduling and equipment sharing strategies on components of the operation cost in case studies of set #2

Conclusions that are derived from a cross comparison of set #1 and 2 case studies are as follows.

- Case study #2-1 vs. case study #1-4: Optimizing the activity schedule adds significant reduction in comparison to the situation in which only the equipment operation plan is optimized.
- Case study #2-1 vs. case study #2-2: The presence of leveling constraints results in a slight increase in the total cost. The operation cost increase is due to lower utilization of the owned fleet and higher utilization of rental equipment in order to respond to the left out sections of volatile demand. Emergence of higher volatility in some parts of the demand structure is the result of pushing for an overall smoother demand curve by leveling constraints.
- Case study #2-1 vs. case study #2-3: Even when the activity schedule is optimized, the cost difference between distance based clustering and free equipment sharing strategies are significant. However, the cost difference between case study #2-3 and case study # 2-5 is relatively small. A combination of these two results shows that in this particular setting major cost saver shipments are inter cluster (long distance) shipments and their elimination results in significant rise in the operation cost.
- Case studies #1-1, #1-4 vs. case studies #2-1, #2-5: Assuming that the activity schedule is optimized (case studies of set #2) the potential loss resulting from not sharing equipment is more significant in comparison to the situation in which the activity schedule is not optimized.

- Case studies #1-1, #1-4 vs. case studies #1-1, #2-5: Activity schedule optimization or equipment operation optimization have roughly the same effect on cost efficiency if applied separately (not simultaneously).

Comparing the value of idle Equipment-week among a number of case studies shows that the highest utilization of owned equipment fleet happens in the setting of case study # 2-1 when the schedule is optimized and full equipment sharing is in place. This value for case study # 2-1 is equal to13 Equipment-week which is significantly lower than the number reported for other case studies.

Figure 5.23 illustrates the situation of idle owned equipment in different settings.

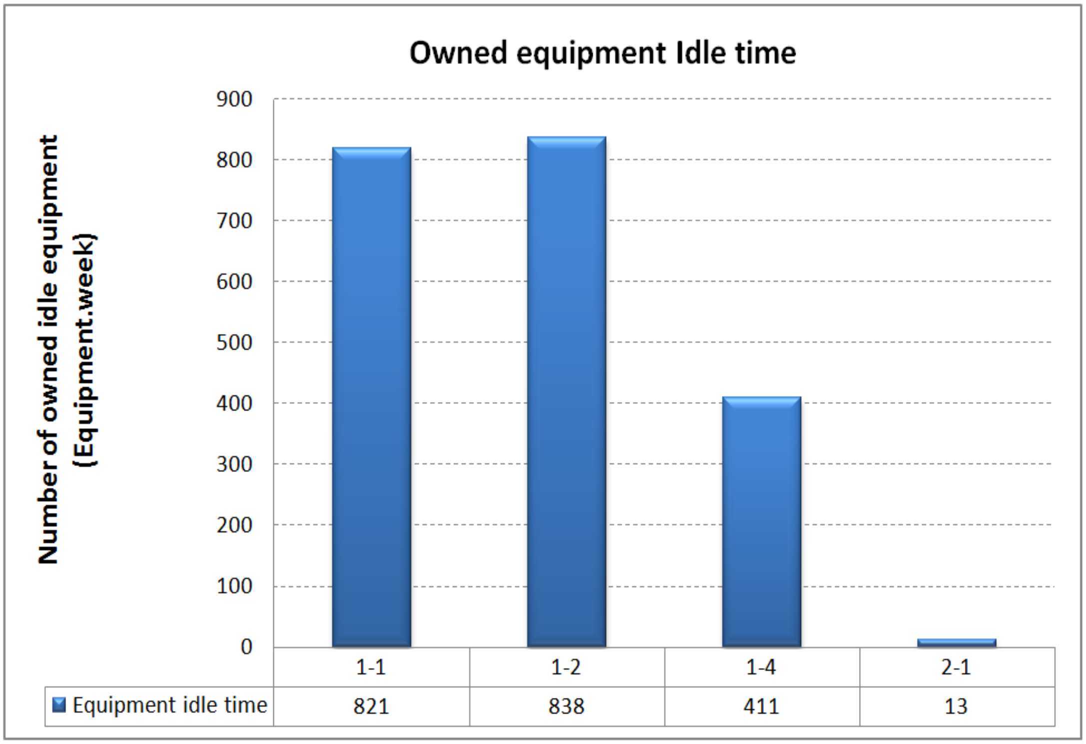


Figure 5.23 - Idle owned equipment in the setting of various case studies

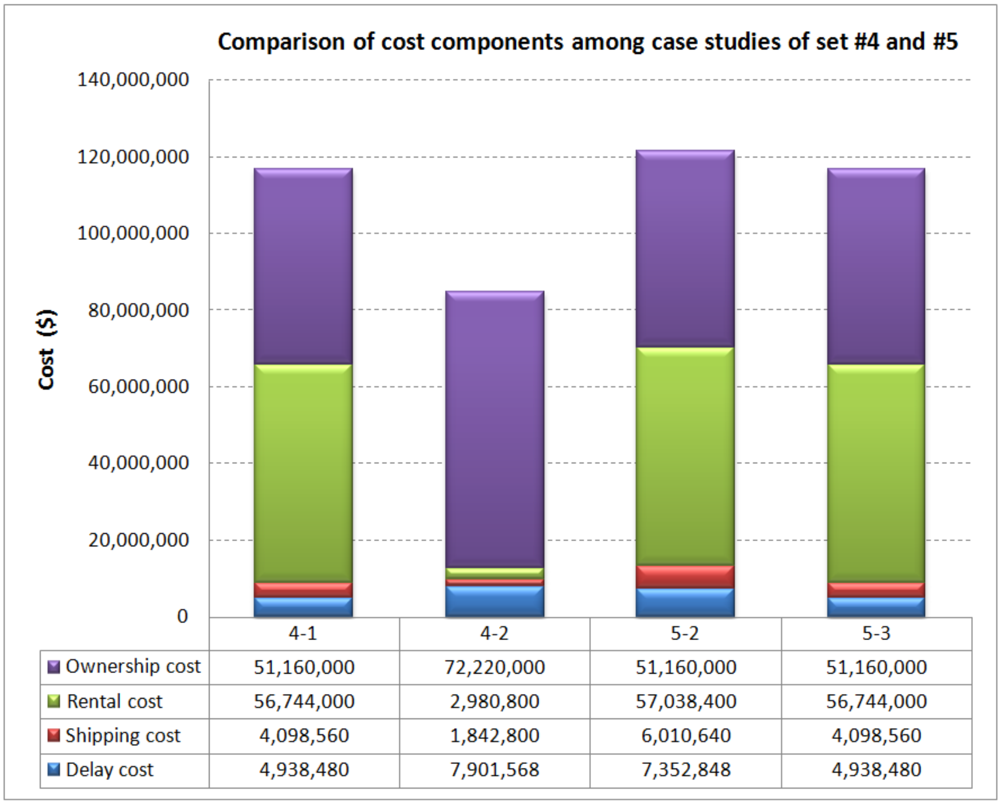
Based on figure 5.23 it can be stated that a result of using the proposed model in preparing the operation plan is a significant drop in the level of owned equipment idle time. For the residual idle time since the model provides project managers with the availability schedule of idle equipment in advance, they have the opportunity of renting these pieces of equipment at spot market. This will be an additional source of revenue for company.

In case studies in set#3, PH5 time slots have been replaced with PH16 time slots which are much more expensive. Then effects of this price difference on the operation pattern (pattern of shipping and renting equipment in jobsites), the operation cost components and the operation cost are fully examined. This evaluation reveals that in the presence of extremely expensive time slots the model will apply all necessary changes in the operation pattern to avoid using those time slots.

Also, it is observed that the delay which results in activities using the time slots close to the finish mile-stone of the project (i.e. PH16) is acutely avoided when the operation pattern is being set by the model. This means that the model correctly considers the linkage between occurrence of delay in activities which are assigned to time slots and incurrence of financial damages. These linkages are introduced to the model through the time slot pricing function.

In case studies in set #4, problems are designed to help high level management to make long term investment decisions regarding purchase of heavy equipment. In these case studies the strategy of operating with a fixed (initially given) owned equipment fleet is compared against the strategy of optimizing the size of the fleet based on the requirements of the given portfolio. This comparison reveals that optimizing the size of the equipment fleet can be associated with high initial investment costs. However, the resulting reduction in the overall operation cost is rewarding enough to encourage high level managers to make such investments.

It is worth mentioning that typically two approaches are available for incorporating such lump sum investment decisions in the decision making process. In theory, the situation can be treated by considering a simple budget constraint. However, in practice generally front end loaded payments by projects' owner and/or long term loans by financial institutions (i.e. specialty banks) are available to contractors for purchasing durable goods such as construction heavy equipment. The proposed model is capable of incorporating both of these mechanisms. Figure 5.24 illustrates the effects of various long term equipment acquisition strategies on components of the operation cost.



	4-1	4-2	5-2	5-3
🟪 Ownership cost	51,160,000	72,220,000	51,160,000	51,160,000
🟩 Rental cost	56,744,000	2,980,800	57,038,400	56,744,000
🟥 Shipping cost	4,098,560	1,842,800	6,010,640	4,098,560
🟦 Delay cost	4,938,480	7,901,568	7,352,848	4,938,480

Figure 5.24 - Effects of various equipment acquisition strategies on components of the operation cost

Case study #4-1 vs. case study #4-2: Comparison of the operation cost components in these two case studies shows that the currently owned fleet is not appropriate for the demand of the given portfolio of projects and it should be exchanged for another fleet. The cost of this exchange will be \$ 72,220,000 from which \$ 51,160,000 is the market value of the current fleet. This means that an additional long term investment of \$ 21,060,000 in the company's owned equipment fleet is needed. However, the reduction in the overall operation cost of the given portfolio which is \$ 31,996,000 not only compensates for this investment but also results in \$ 10,936,000 more profit.

Ultimately, in case studies in set #5 effects of the rental equipment availability on the operation pattern, operation cost components and the overall operation cost are explored. In the first two case studies of this set the threshold of rental equipment availability which changes the feasibility status of the given problem is examined. Results show that when the value of this cap falls below seven units the problem becomes infeasible. Also, in the last case study of set #5the effects of presence of equipment availability cap on the operation are investigated. This investigation reveals that the presence and the value assigned to such cap changes the pattern of operation in comparison to the situation of unlimited equipment availability. It also shows that a decrease in the value of such a cap can have significant adverse effects on the operation cost.

Case study #5-2 vs. case study #5-3: Given the fixed number of owned equipment in case study # 5-2, availability of a minimum number of pieces of rental equipment, which is seven units in this setting, is critical for feasibility of the operation. However, as this threshold is met the excess amount of available rental equipment only marginally decreases the operation cost. This pattern can be seen in results obtained from case study # 5-3.

In this case study, the rental equipment availability cap is set as a decision variable and it assumes the maximum value of 56 units which is significantly higher than seven units that is the minimum value that renders the problem feasible. This additional degree of freedom results in a $ 4,620,800 savings which is the result of the reduction in all three components of the operation cost; delay, shipping and rental costs. It should be noted that the cost of equipment ownership is equal ($ 51,160,000) in both case study # 5-2 and case study # 5-3 since the owned equipment fleet remains unchanged.

Last analysis in this chapter targets the effects of variation of length of the planning horizon (value of PH) on the operation cost. According to the literature the value of PH is assigned based on empirical criteria. Typical values for this parameter in the context of construction and mining industry are between 6 and 12 weeks. PH values below 6 weeks are considered too small. By assigning such values to PH the available flexibility in the activity schedule and resource availability plan will be underutilized. Technically speaking in this setting the option of utilizing available flexibility while introducing acceptable level of uncertainty to the model will be undermined.

On the contrary, by assigning values higher than 12 weeks to PH, unrealistic amount of flexibility will be utilized and at the same time unacceptably high amount of uncertainty will be introduced to the model. Therefore, although in theory the cost of operation will be reduced, the actual cost of operation will eventually be higher than the planned cost. This happens as a consequence of several changes and updates that are realized as time unfolds.

Standard practice in industry is to assign values to PH within the range of 6 to12 weeks based on analysis of historical data and structure of the activity schedule. The key point in this assignment is to maintain the balance between the operation cost reduction and the amount of uncertainty which is being introduced to the model.

To perform sensitivity analysis case study #2-1 in which all model features are functional and the problem is optimized to the fullest possible extent has been selected. According to this analysis, the proposed model demonstrated high level of sensitivity to the value of PH as one of its inputs. Figure 5.25 shows the variation of the operation cost (objective function value of the model) with changes in value of PH. As expected, the operation cost is a decreasing function of PH and the rate of this decrease is dependent on structure of the activity schedule.

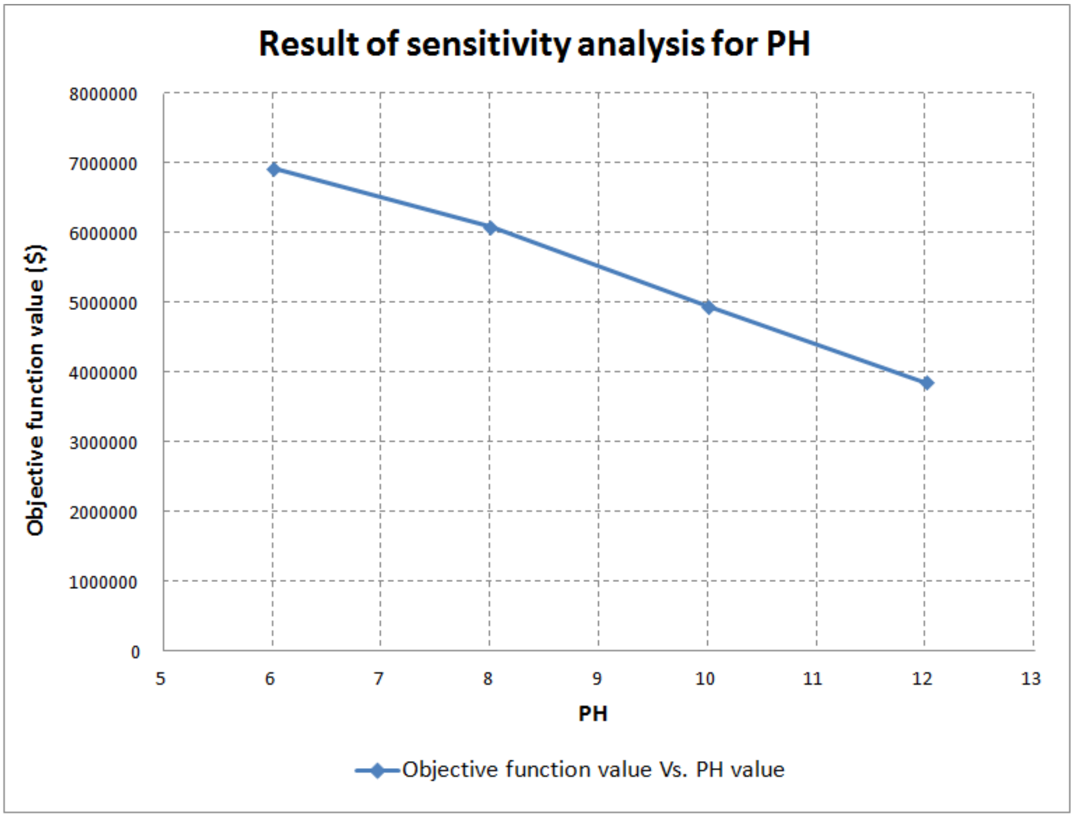


Figure 5.25 – Result of sensitivity analysis for parameter PH

Chapter 6: Heuristic Approach and Computational Efficiency

This chapter is mainly dedicated to development and validation of an efficient heuristic which significantly enhances the model's performance in dealing with numerically burdensome problems.

Although the problem stated in this research being a planning problem is not generally sensitive to solution time and due to high efficiency the proposed model is proved to be capable of handling practical size problems in a reasonable amount of time, still having a fast and efficient heuristic ensures the practicality of the proposed model when extremely large problems are encountered.

In the last section of this chapter a brief discussion on tips that were used to increase the computational efficiency of the proposed formulation is provided.

6.1. Heuristic approach

According to the literature, heuristics are approaches which approximate non-exact solutions with acceptable error instead of providing the exact solution, in exchange for a meaningful reduction in the solution time.

Since the problem stated in this research falls in the category of planning problems due to its nature, solving such problems in practical scale and for commercial purposes is not subject to time constrains. Also, assessing solution times reported for case studies that are discussed in section 5.2 reveals the fact that for large cases, even with a mediocre computer system such as the one which is used in this research, the solution time is not a factor that impedes the model’s effectiveness and practicality. All these being granted, development of a heuristic solution method is not considered to be a crucial part of this study. However, this section is devoted to development of a heuristic approach to further enhance the model for solving extremely large problems within relatively short time spans.

The integrated optimization problem which is dealt with in this research is a combination of a scheduling problem as the upper level problem, and the resource allocation problem as the lower level problem. Having this in mind, and through examination of various case studies previously discussed in chapter 5, the author concluded that the upper level problem is a combinatorial problem which is larger by orders of magnitude in comparison to the lower level problem. Therefore, cutting the feasible region of this problem would significantly reduce the size of the problem and consequently the solution time.

In order to find the proper heuristic (efficient cuts in feasible region of the overall problem) which would result in negligible changes in the objective function value, several fixing schemes were examined. Some of these schemes are different patterns of activity locking, jobsites clustering and resource leveling. These assessments showed that from a solution time reduction point of view, locking constraints ranked first, clustering constraints ranked second and resource leveling constraints ranked third. This ranking pattern can be attributed to the fact that jobsite clustering and resource leveling constraints cut the feasible region of the resource allocation problem (lower level problem) which is significantly smaller than the scheduling problem (upper level problem), while locking constraints cut the feasible region of the scheduling problem. With regard to worsening (increasing) the objective function value, clustering constraints ranked first, locking constraints ranked second and leveling constraints ranked third. By considering these rankings, application of a variation of locking constraints became the candidate platform for developing appropriate heuristic approach.

Hence, the proposed heuristic method would be a smart way of applying locking constraints (cuts) to the scheduling (upper level) problem. These cuts, while effectively reducing the solution time of the problem, should not alter the feasible region in a way that the objective function value of the overall problem is shifted outside the acceptable vicinity of the optimal solution (or the best solution) found through application of an exact approach.

Considering this criterion, it was decided to apply such cuts to the feasible region by enforcing certain locking patterns to a subset of schedule activities which allows them to shift within their available float but prevents them from being split. The effects of the application of this scheme on the solution time and the objective function value of the problem (operating cost) are probed in case studies that are discussed in section 6.3.

6.2. Dynamics of the heuristic approach

For any given problem, initially the exact solution approach will be applied. If the solution with optimality gap ≤1% is not reached within 3600 sec during the first attempt (i=0), then the exact solution approach will be terminated and the heuristic module will come into play. To apply the above-described heuristic approach (locking/fixing heuristic), the structure of the proposed model has been modified to incorporate the following steps.

i. Calculate the ratio of total float over duration (TF/D) for all activities and set i=1.
ii. Read L(i) from the input file. This parameter is the TF/D threshold for activity selection in the ith cycle of applying the heuristic.
iii. In the ith cycle, select activities for which the ratio of TF/D is greater than or equal to L(i) ; (TF/D≥ L(i)).These activities are then stored in subset(i) to be locked.
iv. In ith cycle apply locking (fixing) constraint to activities in subset(i). Typically, activities of subset(i) will be locked so that they can only move within their float span as a single continuous activity. The typical constraint which is used in this step is shown as equation 6.1.

$$\sum_{t=1}^{tf} t\ TE_{jat} - \sum_{t=1}^{tf} t\ TS_{jat} = \mathrm{d}(j,a) \qquad [6.1]$$

v. Run subroutine A to optimize the restructured problem.

vi. Check two conditions of optimality gap ≤1% and solution time ≤ 3600 sec. If both of these conditions are met then stop and provide output, otherwise move to step vii.

vii. In step vii set i=i+1, and initiate a new cycle of locking (fixing). As the value of (i) increases the activity threshold of L(i) decreases and thus, the size of subset(i) increases. Also, as mentioned previously, the amount of the reduction in each cycle is an input value.

Repeat steps ii through vii until the gap of ≤1% is reached in 3600 sec. Dynamics of the model and the proposed heuristic approach are both shown in the flowchart of figure 6.1.

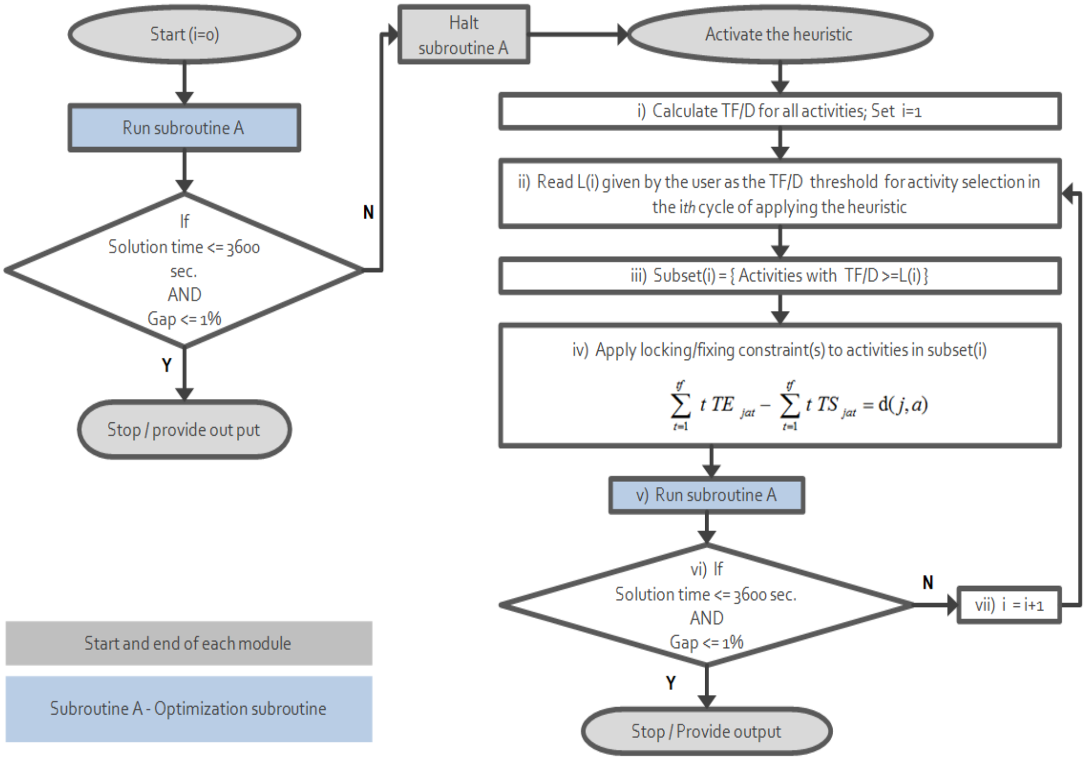


Figure 6.1- Model dynamics including the dynamics of the proposed heuristic

6.3. Application of the heuristic approach and discussion of results

In this section, a locking heuristic will be applied to case studies #2-1, # 2-2, #4-2 and #5-2 to reduce their solution times. These case studies are selected because an acceptable solution (solution with an optimality gap of around 1%) for them could not be reached within an acceptable time (around 3,600 seconds).

Case study #2-1(Locked):

Similar to case study #2-1, this case study is also designed to study the results of optimizing both the schedule and the equipment operation plan. So, this case study has the exact structure of case study #2-1 with the only difference being that it has a locking module activated.

Results:

- Originally, case study #2-1 was solved with a 1.17% optimality gap in 12,000 sec. By applying the locking heuristic, case study #2-1 (Locked) is solved to optimality in 255 sec.

Case study #2-2(Locked):

Similar to case study #2-2, this case study is also designed to study the effects of the addition of resource leveling constraints to the setting of case study #2-2. So, this case study has the exact structure of case study #2-2 with the only difference being that it has a locking module activated.

Results:

- Originally case study #2-2 was solved with a 1.07% optimality gap in 44,200 sec. By applying the locking heuristic, case study #2-2 (Locked) is solved to a 0.46% optimality gap in 385 sec.

Case study #4-2(Locked):

This case study is also designed to find the optimum size of the owned heavy equipment fleet. So, this case study has the exact structure of case study #4-2 with the only difference being that it has a locking module activated.

Results:

- Originally, case study #4-2 was solved with a 2.4% optimality gap in 62,753 sec. By applying the locking heuristic case study #4-2 (Locked) is solved to a 1.04% optimality gap in 3,852 sec.

Case study #5-2(Locked):

Similar to case study #5-2, this case study is designed to study the effects of a rental equipment availability cap on the solution. More specifically, in this case study the cap value is set to 7 units. This number represents the minimum value of the cap for which the problem is still feasible. So, this case study has the exact structure of case study #5-2 with the only difference being that it has a locking module activated.

Results:

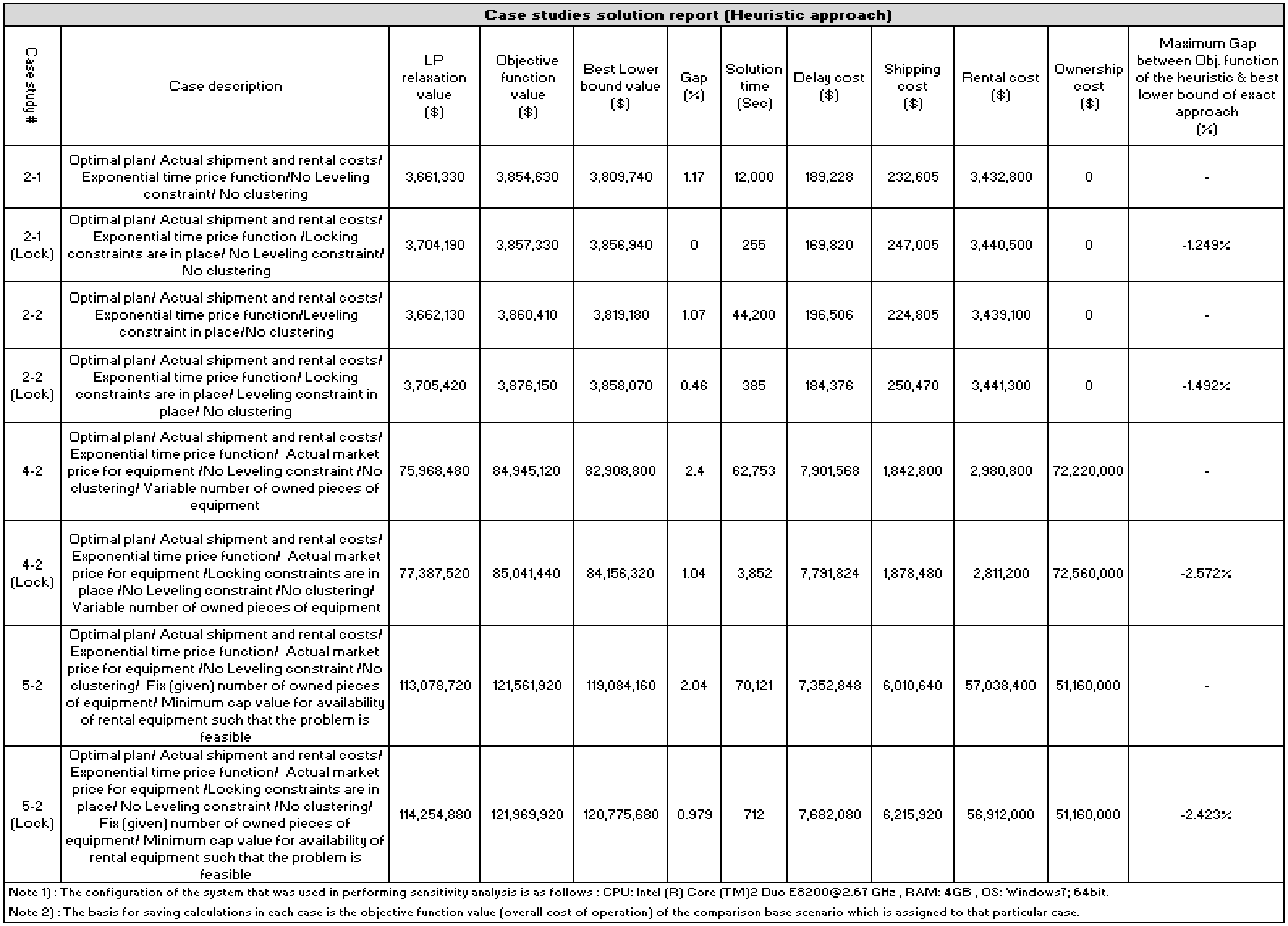
- Originally, case study #5-2 was solved with a 2.04 % optimality gap in 70,121 sec. By applying the locking heuristic case study #5-2 (Locked) is solved to a 0.97% optimality gap in 712 sec.

6.4. Conclusions and discussion on results

In this chapter, numerically burdensome case studies of chapter 5 were selected and solved with application of the proposed heuristic. Table 6.1 provides detailed information about four case studies which are solved through application of the proposed heuristic in a consolidated manner. For the sake of simpler comparison, results of solving these problems both with and without application of the heuristic are reported in the same table.

Results obtained from performed analysis confirm the capability of the heuristic in effectively reducing the solution time and validate its output. Cross comparisons among case studies and drawing conclusions regarding effects of applying the heuristic approach are subject of discussion in this section.

In general, by evaluating results presented in table 6.1 it can be observed that through application of the proposed locking heuristic, solutions within a reasonable optimality gap are obtainable within a reasonable time. A reasonable gap (approximately 1%) is determined based on the accepted norm in the optimization community and a reasonable time (approximately 3,600 seconds) based on the nature of the problem and constraints that are imposed on the solution time due to practicality issues.



Case studies solution report (Heuristic approach)

Case study #	Case description	LP relaxation value ($)	Objective function value ($)	Best Lower bound value ($)	Gap (%)	Solution time (Sec)	Delay cost ($)	Shipping cost ($)	Rental cost ($)	Ownership cost ($)	Maximum Gap between Obj. function of the heuristic & best lower bound of exact approach (%)
2-1	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/No Leveling constraint/ No clustering	3,661,330	3,854,630	3,809,740	1.17	12,000	189,228	232,605	3,432,800	0	-
2-1 (Lock)	Optimal plan/ Actual shipment and rental costs/ Exponential time price function /Locking constraints are in place/ No Leveling constraint/ No clustering	3,704,190	3,857,330	3,856,940	0	255	169,820	247,005	3,440,500	0	-1.249%
2-2	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/Leveling constraint in place/No clustering	3,662,130	3,860,410	3,819,180	1.07	44,200	196,506	224,805	3,439,100	0	-
2-2 (Lock)	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Locking constraints are in place/ Leveling constraint in place/ No clustering	3,705,420	3,876,150	3,858,070	0.46	385	184,376	250,470	3,441,300	0	-1.492%
4-2	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Actual market price for equipment /No Leveling constraint /No clustering/ Variable number of owned pieces of equipment	75,968,480	84,945,120	82,908,800	2.4	62,753	7,901,568	1,842,800	2,980,800	72,220,000	-
4-2 (Lock)	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Actual market price for equipment /Locking constraints are in place /No Leveling constraint /No clustering/ Variable number of owned pieces of equipment	77,387,520	85,041,440	84,156,320	1.04	3,852	7,791,824	1,878,480	2,811,200	72,560,000	-2.572%
5-2	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Actual market price for equipment /No Leveling constraint /No clustering/ Fix (given) number of owned pieces of equipment/ Minimum cap value for availability of rental equipment such that the problem is feasible	113,078,720	121,561,920	119,084,160	2.04	70,121	7,352,848	6,010,640	57,038,400	51,160,000	-
5-2 (Lock)	Optimal plan/ Actual shipment and rental costs/ Exponential time price function/ Actual market price for equipment /Locking constraints are in place/ No Leveling constraint /No clustering/ Fix (given) number of owned pieces of equipment/ Minimum cap value for availability of rental equipment such that the problem is feasible	114,254,880	121,969,920	120,775,680	0.979	712	7,682,080	6,215,920	56,912,000	51,160,000	-2.423%

Note 1) : The configuration of the system that was used in performing sensitivity analysis is as follows : CPU: Intel (R) Core (TM)2 Duo E8200@2.67 GHz , RAM: 4GB , OS: Windows7; 64bit.

Note 2) : The basis for saving calculations in each case is the objective function value (overall cost of operation) of the comparison base scenario which is assigned to that particular case.

Table 6.1- Detailed information about the application of the proposed heuristic approach to four case studies in section 6.3

Additionally, lower bounds for minimization problems establish bench marks for quality control of solutions provided through application of heuristics. This being said, the difference between the best lower bound of the exact solution approach and the objective function value resulting from application of the proposed heuristic is considered to be the quality bench mark which is reported in table 6.1. Since the value of this indicator is small enough in all cases, it can be stated that solutions obtained through application of the heuristic approach have a tight lower bound. This simply means that the proposed heuristic provides solutions with acceptable degree of precision. Figure 6.2 illustrates this difference for all four pairs of case studies.

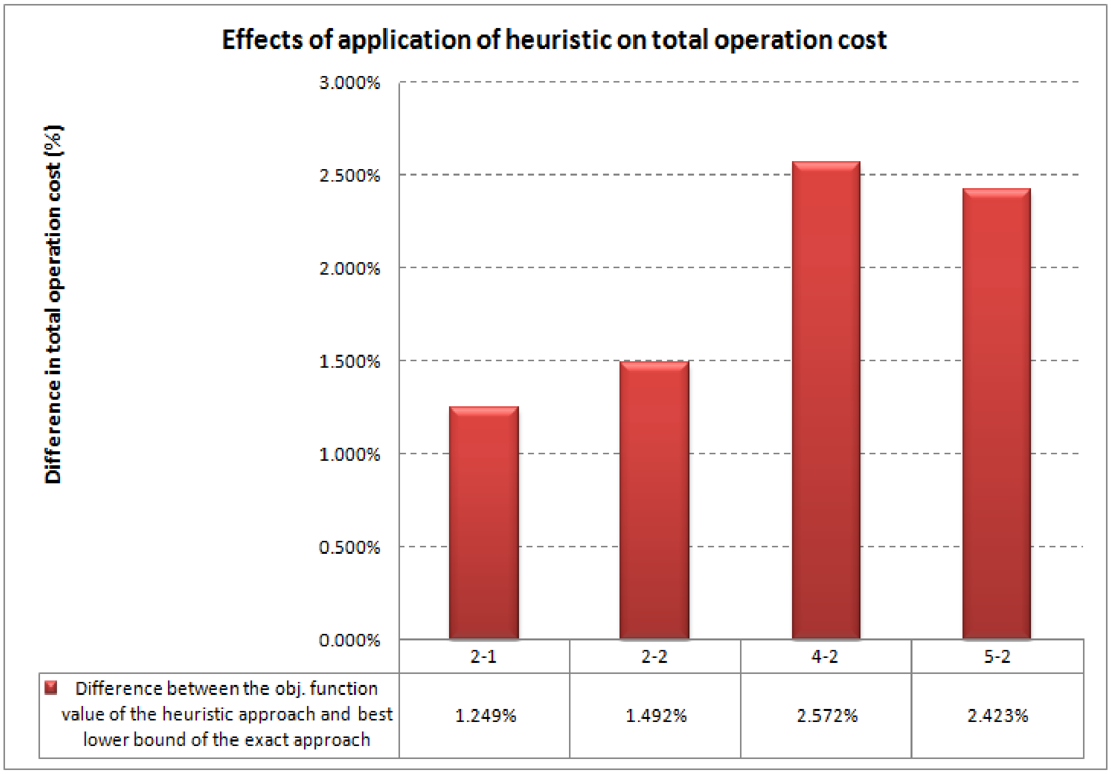
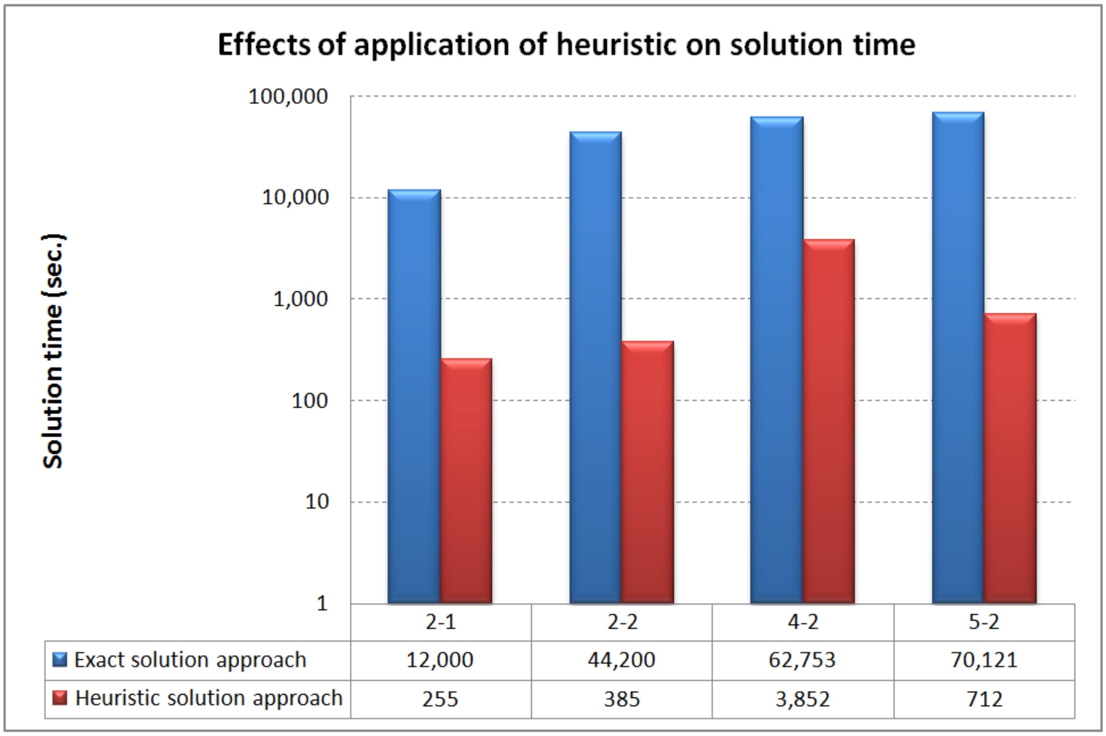


Figure 6.2 – Difference between the best lower bound value of the exact approach and the objective function value of the heuristic approach

Also, solution time differences for case studies that are solved through application of exact and heuristic approaches are shown in figure 6.3.



	2-1	2-2	4-2	5-2
🟦 Exact solution approach	12,000	44,200	62,753	70,121
🟥 Heuristic solution approach	255	385	3,852	712

Figure 6.3- Solution time difference for case studies which are solved through application of exact and heuristic approaches

Considering tables 5.4, 6.1 and figure 6.3, three combinations of circumstances are identified as the primary cause of the heavy computational burden in the discussed case studies. These settings are sorted in order of decreasing impact on computational burden.

- Circumstances which result in increase in the size of the upper level problem (scheduling problem) such as an increase in the number of possible choices of TW in combination with a higher degree of freedom for equipment sharing. The increase in the number of choices of TW is a consequence of the increase in the number of nodes, activities, time steps and/or increase in value of TF/D of activities.

- Circumstances which result in higher utilization of the owned equipment fleet such as an increase in equipment demand and rental cost in combination with a decrease in transportation cost or abundance of owned pieces of equipment with low prices.
- Circumstances which result in a lower level of access to rental equipment such as higher rental costs, lower rental equipment availability in combination with a fixed size of the owned equipment fleet.

Since locking heuristic targets the most important cause of excessive computational burden according to the above list, it has been successful in increasing the efficiency of the solution procedure.

6.5. Remarks on computational efficiency considerations

The last section of this chapter is devoted to a thorough discussion on efficiency of the proposed mathematical formulation and specifically guidelines that were followed during model development process in order to increase computational efficiency of the formulation.

Since the early stages of this study, it was recognized that the problem which is embarked on in its practical size will be a large combinatorial problem. Therefore, careful thoughts were given to development of an efficient formulation in conjunction with implementation of a compatible solution algorithm. In doing so, properties of the problem were evaluated through solving series of small examples. For instance, important combinations of characteristics which intensify the size hardening properties of the problem as listed in section 6.4 were spotted in the very same stage. The final mathematical formulation is the result of several rounds of reformulation during which following guidelines were carefully followed to lower the complexity level of the proposed formulation (Williams, 1990).

As the first step in developing the formulation, the simplest and most straightforward thought process was put into action to avoid unnecessary complexity and establish a feasible region which is the closest possible to the convex hull of the problem.

Moreover, unlike the common practice of formulating scheduling problems in which continuous and/or general integer decision variables are used, binary integer variables are widely used in the proposed formulation. This choice made the formulation a perfect candidate for adoption of branch and bound solution algorithm. Additionally, although replacing continuous and general integer variables with binary variables increases the number of decision variables, on the contrary to general presumptions, it leads to a computationally more efficient formulation in the case of IP problems.

Another step would be increasing the efficiency of existing constraints. An example for this action would be changing the range of time index (t) in the formulation. Although the formulation works perfectly when the range for t is set to $1 \ldots t_f$, incorporation of activity time windows (ES, EF, LS and LF) in defining the range of this index significantly reduces the computational burden and increases its efficiency.

In addition to above mentioned points, some other formulation tricks are also applied to further increase the efficiency of the problem. For instance, to the possible extent large constraints are broken into number of simpler constraints (i.e. constraint set 5).

Finally, the author made an informed decision in choosing the solver package. According to the literature Xpress 7.0 is among the best commercial packages available for solving IP problems. This statement makes more sense by considering the fact that commercial optimization software packages (i.e. CPLEX, Xpress, GAMS and MATLAB) are not equally efficient in solving different classes of optimization problems. An inappropriate choice of a solver causes the problem to seem extremely difficult or even impossible to solve which might not be the case otherwise.

Based on detailed results of solving various case studies reported in tables 5.4 and 6.1, it can be concluded that considering all above-mentioned guidelines in formulating and solving the problem has paid off since acceptable solution(s) of the practical size problems are reached within an acceptable amount of time.

Chapter 7: Summary of Conclusions and Recommendations for Future Research

Chapter 7 includes three sections. In the first section a summary of conclusions regarding enhanced managerial capabilities and savings that can be achieved as a result of implementing the proposed decision support system in project planning and control process is provided. In the second section, qualitative conclusions which are generalized form of the quantitative results of chapter 5 are summarized in the format of practically useful rules of thumb. By use of these rules the manager will be able to refine the outcome of the decision making process to some extent without directly using the proposed optimization framework. Ultimately, in the third section recommendations for continuation of this line of research or its variations are presented.

7.1. Summary of Conclusions

Following is a summary of general conclusions that are derived from this study.

- According to the results presented in chapter 5 it can be concluded that equipment and float sharing among projects are two cost saving strategies even if implemented in a sub-optimal fashion. Obviously, simultaneous implementation of these two strategies in combination with optimization of the operation plan reduces the operation cost even further. However, due to mathematically complex nature of the problem optimizing the integrated activity schedule and equipment operation plan, it has been left out of scope in the construction industry. In this research, this problem has been efficiently modeled and solved using the mathematical programming approach.
- In current scheduling and resource allocation practice in the construction industry several simplifying assumptions are in place. Some of these assumptions are considering a fixed baseline schedule (i.e. ES schedule), considering minimum or no equipment sharing among jobsites, considering the resource leveling as the only constraint which governs the resource allocation process and accepting any feasible solution (if any can be found through manual approaches!) instead of the cost optimal solution(s). On the contrary, by using the proposed model, cost optimal solution(s) can be found with minimum manual computational effort, in reasonable amount of time and without implementation of oversimplifying assumptions. Therefore, it can be concluded that using the proposed model and consequently adopting the optimal operation approach can significantly improve the efficiency of the construction operation.

- Based on results of set #4 case studies it can be concluded that the size and composition of the owned equipment fleet should be compatible with the demand structure of company's portfolio of projects. Otherwise, the operation will become extremely inefficient. In other words, size and composition of the owned equipment fleet should be updated based on the demand structure of the projects at hand. This is an important responsibility of the equipment management sector of construction companies which is typically neglected in the current industry practice. This negligence has led to financial inefficiency in managing the owned fleet, consequent reduction in companies' margin of profit and increase in final cost of projects. Managing owned equipment fleet more efficiently is the way out of this problem for which the proposed decision support system is essential.
- Additionally, this decision support system enables managers to identify rental equipment bottlenecks before they are encountered and find remedies for them. Also, given the option, project managers will be able to perform benefit/cost analysis for availability of extra rental equipment.
- By using the proposed model not only all initial critical paths of the activity schedule will be identified, respected and will remain intact but also additional critical chains which might emerge due to lack of resource availability will be identified and respected as well. It is also important to emphasize that the model, through its time slot pricing mechanism, avoids creating parallel critical chains which is an instance of poor scheduling practice.
- Considering the numerical results reported in table 6.1, it also can be concluded that the proposed heuristic approach meets all initially defined criteria for an

acceptable heuristic. Thus, it is highly recommended for solving large problems which are either impossible or extremely difficult to solve via the exact approach.

As closing remarks, the author believes that this model provides the construction industry with an effective scheduling/resource allocation optimization package which can be used as a supplementary module along with common scheduling software packages to optimize their output.

7.2. Qualitative practical guidelines derived based on quantitative analyses

Based on the extensive quantitative analyses performed in chapter 5, a number of generalized qualitative rules are derived and listed below. Prudent application of this set of rules can to some extent improve the optimality level of the solution obtained through use of conventional planning approaches.

- Presence of critical and/or near critical chains and instances of emergence of parallel critical chains should be closely inspected. As a general rule, addition of critical or near critical chains is undesirable and should be avoided. This study confirmed the validity of this point by showing that in an optimal solution above-mentioned structures are avoided to the possible extent.
- In order to increase the optimality level of a resource loaded schedule, float which is available on each path of the activity network should be allocated to activities on that path proportional to their resource utilization. Resource utilization of an activity in this context is defined as the cumulative cost of all resources which are used by that activity over the course of its duration. In the current scheduling

practice each activity is allowed to consume as much float as is available to it in each snap shot of time.

- Demand stack over even when the resulting plan is feasible is an undesirable and typically far from optimal situation which should be avoided. Visual inspection of demand curves produced by commercial scheduling software packages can be used to spot demand stack over instances. When found, manual shifting and splitting of activities which are contributing to the situation can be used to improve the demand curve.
- Cost efficiency of resource loaded schedules which are developed by using conventional scheduling and resource allocation approaches for a given portfolio can be significantly improved by adopting inter project resource sharing instead of project isolation strategy which is the current industry practice. However, if the model proposed in this research is not to be used, means of exercising this option will be curtailed to manual benefit-cost analyses and conventional portfolio coordination systems which should be utilized by the portfolio manager in order to develop a more cost efficient operation plan. Even this inferior approach yields savings in comparison to project isolation approach.
- Contrary to the typical scheduling practice, resource leveling is a cost increasing strategy which should be cautiously applied based on detailed benefit-cost analysis and only when it is unavoidable.

7.3. Recommendations for future research

The problem statement and the model that is developed for solving this problem are both novel. The author has built upon a rough idea and taken it to the stage of a well-established and validated model with extensive practical applications. Therefore, this study offers several opportunities for researchers to enhance the proposed model or to modify it for making it applicable to a broader range of scheduling and resource allocation problems. Following is a list of such future research topics which are logically preceded by the current study in this line of research.

- The proposed model is structured in a way that it can be fed with several equivalent demand patterns in a loop. However, it is not designed to find the cost optimum demand pattern among several equivalent demand structure possibilities. Thus, adding an interactive resource exchange feature to find the cost optimal demand pattern can be considered a valuable extension of this research.
- The scheduling module of this model is designed to be flexible and compatible with various categories of resource allocations. Therefore, with some modifications it can accommodate other resource allocation problems such as material or labor allocation. Figure 7.1 shows major categories of resources which are required for execution of construction projects.

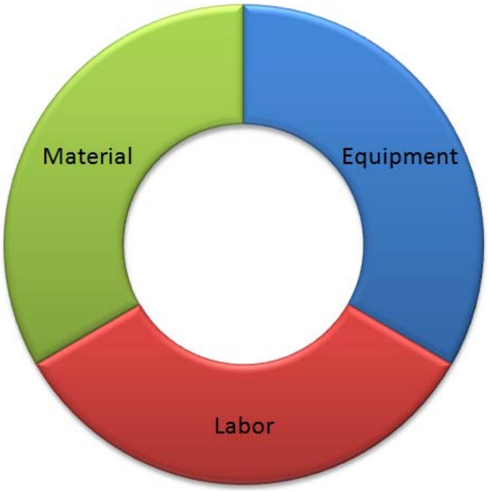


Figure 7.1- Major categories of resources required for execution of construction projects

- Another valuable extension of this study would be developing the robust or stochastic version of the proposed model.

  In the case of development of a robust optimization model, a new deterministic mathematical framework with considerations of robust optimization techniques should be built. In the case of developing a stochastic model, the main conceptual difference from the deterministic model would be the replacement of deterministic parameters such as task duration, demand and owned/rental equipment availability with their equivalent random variables.

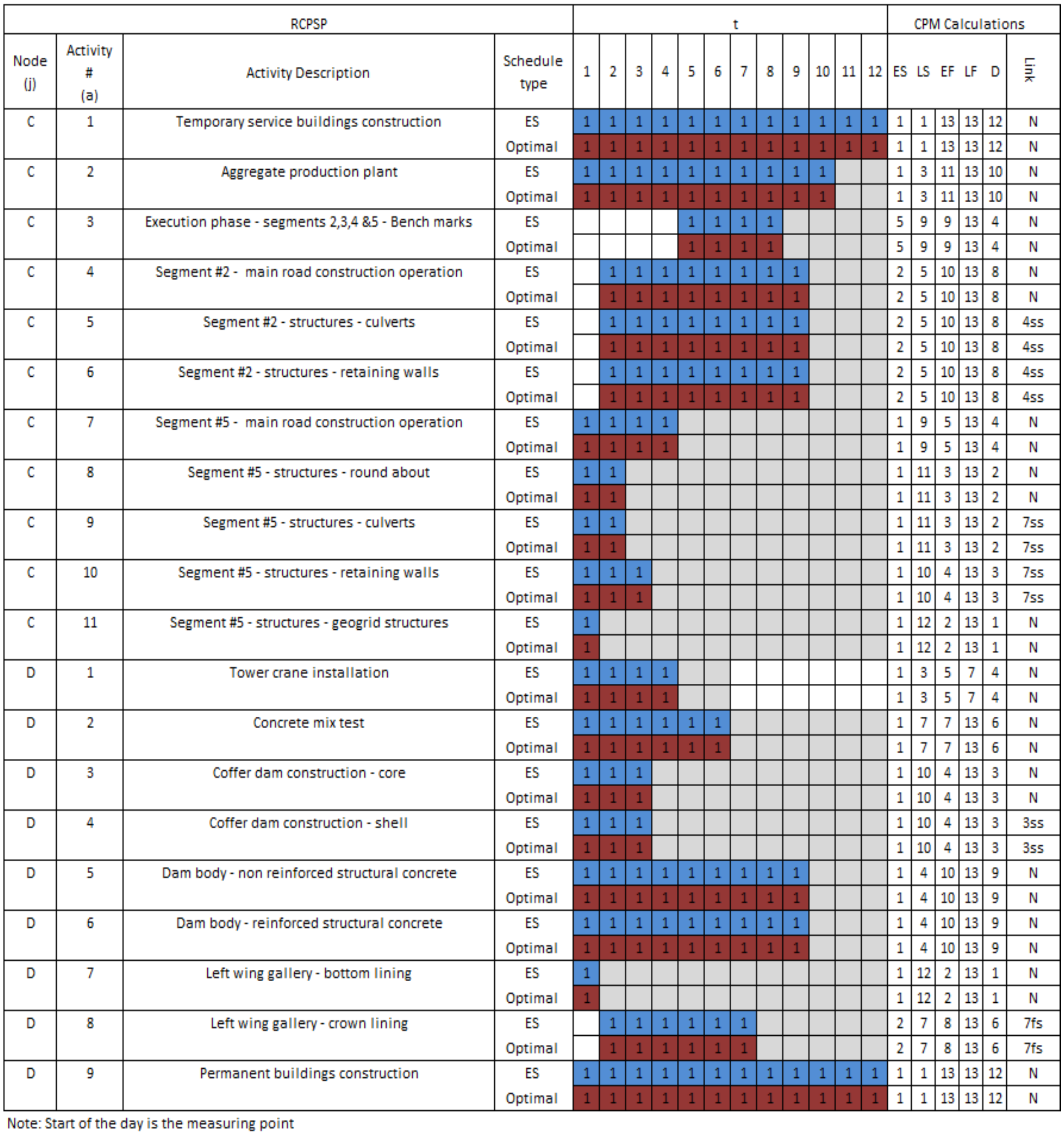
  Either of these changes increases the complexity level of the problem drastically. Ultimately, it should be mentioned that although building stochastic models for such problems constitutes a valid line of research, the practicality of implementation of these models in industries like construction might be questionable.

Appendices

Appendix I (Case studies detail output)

Case study # 1-1:

RCPSP				t												CPM Calculations					
Node (j)	Activity # (a)	Activity Description	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12	ES	LS	EF	LF	D	Link
A	1	Temporary service roads construction	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
A	2	Temporary service buildings construction	ES	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
			Optimal	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
A	3	Temporary site work	ES	1	1	1	1	1	1	1	1	1	1	1		1	2	12	13	11	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1		1	2	12	13	11	N
A	4	Aggregate production plant	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
A	5	Dam body construction-Bench marks	ES					1	1	1	1	1	1	1	1	5	5	13	13	8	N
			Optimal					1	1	1	1	1	1	1	1	5	5	13	13	8	N
A	6	Dam body - left wing - excavation - level 1	ES	1	1	1	1	1	1	1	1					1	5	9	13	8	N
			Optimal	1	1	1	1	1	1	1	1					1	5	9	13	8	N
A	7	Dam body - left wing -leveling	ES			1	1	1	1	1	1	1				3	6	10	13	7	6ss+2
			Optimal			1	1	1	1	1	1	1				3	6	10	13	7	6ss+2
A	8	Dam body - left wing -trench temporary protection	ES		1	1	1	1	1	1						2	7	8	13	6	6ss+1
			Optimal		1	1	1	1	1	1						2	7	8	13	6	6ss+1
A	9	Dam body - right wing - excavation - level 1	ES	1	1	1	1	1	1	1	1					1	5	9	13	8	N
			Optimal	1	1	1	1	1	1	1	1					1	5	9	13	8	N
A	10	Dam body - right wing -leveling	ES			1	1	1	1	1	1	1				3	6	10	13	7	9ss+2
			Optimal			1	1	1	1	1	1	1				3	6	10	13	7	9ss+2
A	11	Dam body - right wing -trench temporary protection	ES		1	1	1	1	1	1						2	7	8	13	6	9ss+1
			Optimal		1	1	1	1	1	1						2	7	8	13	6	9ss+1
A	12	Dam body - rockfill	ES	1	1	1	1	1	1	1	1	1	1	1		1	2	12	13	11	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1		1	2	12	13	11	N
A	13	Dam body - concrete face	ES		1	1	1	1								2	7	6	11	4	12ss+1
			Optimal		1	1	1	1								2	7	6	11	4	12ss+1
A	14	Gallery construction - middle section - concrete lining	ES	1	1	1	1									1	9	5	13	4	N
			Optimal	1	1	1	1									1	9	5	13	4	N
A	15	Gallery construction - left wing - excavation	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
A	16	Gallery construction - left wing - leveling	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
A	17	Gallery construction - left wing - concrete lining	ES		1	1	1									2	10	5	13	3	16ss+1
			Optimal		1	1	1									2	10	5	13	3	16ss+1
A	18	Gallery construction - right wing - excavation	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
A	19	Gallery construction - right wing - leveling	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
A	20	Gallery construction - right wing - concrete lining	ES		1	1	1									2	10	5	13	3	19ss+1
			Optimal		1	1	1									2	10	5	13	3	19ss+1
B	1	Segment #1 - water pipeline relocation	ES	1	1											1	4	3	6	2	N
			Optimal	1	1											1	4	3	6	2	N
B	2	Segment #1 - structures - canal - derivation	ES	1	1	1										1	5	4	8	3	N
			Optimal	1	1	1										1	5	4	8	3	N
B	3	Segment #2 - water pipeline relocation	ES	1	1											1	4	3	6	2	N
			Optimal	1	1											1	4	3	6	2	N
B	4	Segment #3 - water pipeline relocation	ES	1												1	12	2	13	1	N
			Optimal	1												1	12	2	13	1	N
B	5	Segment #4 - water pipeline relocation	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
B	6	Segment #4 - structures - bridges - derivation	ES	1	1											1	11	3	13	2	N
			Optimal	1	1											1	11	3	13	2	N
B	7	Segment #5 - structures - bridges - derivation	ES	1	1	1	1									1	9	5	13	4	N
			Optimal	1	1	1	1									1	9	5	13	4	N
B	8	Segment #1 - pavement - base construction	ES			1	1	1	1	1						3	8	8	13	5	2fs-1
			Optimal			1	1	1	1	1						3	8	8	13	5	2fs-1
B	9	Segment #2 - pavement - sub base construction	ES			1	1	1	1							3	9	7	13	4	3fs
			Optimal			1	1	1	1							3	9	7	13	4	3fs
B	10	Segment #2 - pavement - base construction	ES				1	1	1	1	1					4	8	9	13	5	9ss+1
			Optimal				1	1	1	1	1					4	8	9	13	5	9ss+1



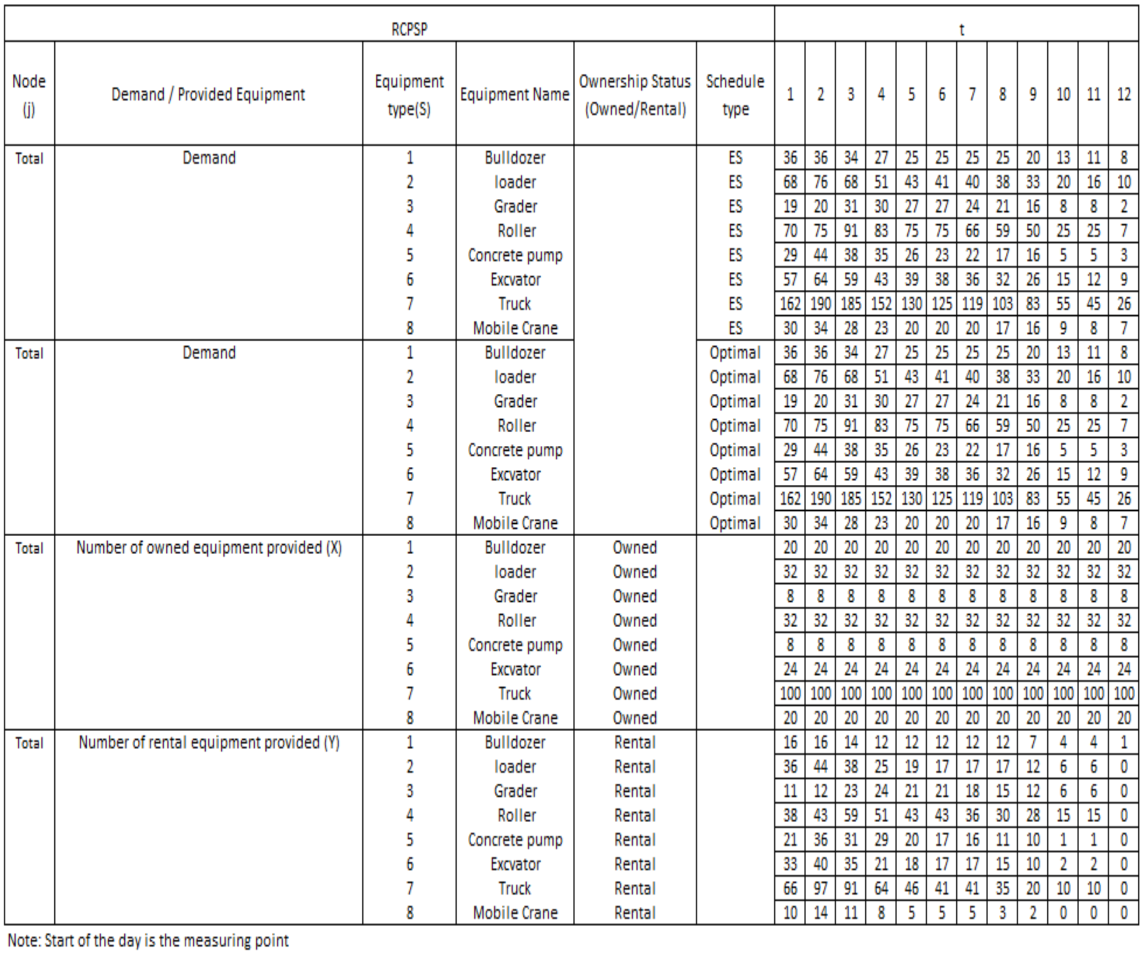
RCPSP				t												CPM Calculations					
Node (j)	Activity # (a)	Activity Description	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12	ES	LS	EF	LF	D	Link
C	1	Temporary service buildings construction	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
C	2	Aggregate production plant	ES	1	1	1	1	1	1	1	1	1	1			1	3	11	13	10	N
			Optimal	1	1	1	1	1	1	1	1	1	1			1	3	11	13	10	N
C	3	Execution phase - segments 2,3,4 &5 - Bench marks	ES					1	1	1	1					5	9	9	13	4	N
			Optimal					1	1	1	1					5	9	9	13	4	N
C	4	Segment #2 - main road construction operation	ES		1	1	1	1	1	1	1	1				2	5	10	13	8	N
			Optimal		1	1	1	1	1	1	1	1				2	5	10	13	8	N
C	5	Segment #2 - structures - culverts	ES		1	1	1	1	1	1	1	1				2	5	10	13	8	4ss
			Optimal		1	1	1	1	1	1	1	1				2	5	10	13	8	4ss
C	6	Segment #2 - structures - retaining walls	ES		1	1	1	1	1	1	1	1				2	5	10	13	8	4ss
			Optimal		1	1	1	1	1	1	1	1				2	5	10	13	8	4ss
C	7	Segment #5 - main road construction operation	ES	1	1	1	1									1	9	5	13	4	N
			Optimal	1	1	1	1									1	9	5	13	4	N
C	8	Segment #5 - structures - round about	ES	1	1											1	11	3	13	2	N
			Optimal	1	1											1	11	3	13	2	N
C	9	Segment #5 - structures - culverts	ES	1	1											1	11	3	13	2	7ss
			Optimal	1	1											1	11	3	13	2	7ss
C	10	Segment #5 - structures - retaining walls	ES	1	1	1										1	10	4	13	3	7ss
			Optimal	1	1	1										1	10	4	13	3	7ss
C	11	Segment #5 - structures - geogrid structures	ES	1												1	12	2	13	1	N
			Optimal	1												1	12	2	13	1	N
D	1	Tower crane installation	ES	1	1	1	1									1	3	5	7	4	N
			Optimal	1	1	1	1									1	3	5	7	4	N
D	2	Concrete mix test	ES	1	1	1	1	1	1							1	7	7	13	6	N
			Optimal	1	1	1	1	1	1							1	7	7	13	6	N
D	3	Coffer dam construction - core	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
D	4	Coffer dam construction - shell	ES	1	1	1										1	10	4	13	3	3ss
			Optimal	1	1	1										1	10	4	13	3	3ss
D	5	Dam body - non reinforced structural concrete	ES	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
			Optimal	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
D	6	Dam body - reinforced structural concrete	ES	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
			Optimal	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
D	7	Left wing gallery - bottom lining	ES	1												1	12	2	13	1	N
			Optimal	1												1	12	2	13	1	N
D	8	Left wing gallery - crown lining	ES		1	1	1	1	1	1						2	7	8	13	6	7fs
			Optimal		1	1	1	1	1	1						2	7	8	13	6	7fs
D	9	Permanent buildings construction	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N

Note: Start of the day is the measuring point

Appendix I. Figure 1- ES and optimal master schedule of the portfolio; case study # 1-1

RCPSP						t											
Node (j)	Demand / Provided Equipment	Equipment type(S)	Equipment Name	Ownership Status (Owned/Rental)	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12
A	Demand	1	Bulldozer		ES	15	15	17	15	16	16	16	16	12	9	9	6
		2	loader		ES	28	34	36	28	23	21	21	21	17	14	14	8
		3	Grader		ES	10	10	16	16	16	16	16	16	14	8	8	2
		4	Roller		ES	30	30	40	36	36	36	36	36	34	23	23	5
		5	Concrete pump		ES	6	17	17	17	9	6	6	4	4	3	3	1
		6	Excvator		ES	24	29	31	21	19	18	18	16	12	8	8	5
		7	Truck		ES	76	97	99	81	67	62	62	56	42	35	35	16
		8	Mobile Crane		ES	8	12	12	10	8	8	8	6	6	4	4	3
A	Demand	1	Bulldozer		Optimal	15	15	17	15	16	16	16	16	12	9	9	6
		2	loader		Optimal	28	34	36	28	23	21	21	21	17	14	14	8
		3	Grader		Optimal	10	10	16	16	16	16	16	16	14	8	8	2
		4	Roller		Optimal	30	30	40	36	36	36	36	36	34	23	23	5
		5	Concrete pump		Optimal	6	17	17	17	9	6	6	4	4	3	3	1
		6	Excvator		Optimal	24	29	31	21	19	18	18	16	12	8	8	5
		7	Truck		Optimal	76	97	99	81	67	62	62	56	42	35	35	16
		8	Mobile Crane		Optimal	8	12	12	10	8	8	8	6	6	4	4	3
A	Number of owned equipment provided (X)	1	Bulldozer	Owned		5	5	5	5	5	5	5	5	5	5	5	5
		2	loader	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		3	Grader	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		4	Roller	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		5	Concrete pump	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		6	Excvator	Owned		6	6	6	6	6	6	6	6	6	6	6	6
		7	Truck	Owned		25	25	25	25	25	25	25	25	25	25	25	25
		8	Mobile Crane	Owned		5	5	5	5	5	5	5	5	5	5	5	5
A	Number of rental equipment provided (Y)	1	Bulldozer	Rental		10	10	12	10	11	11	11	11	7	4	4	1
		2	loader	Rental		20	26	28	20	15	13	13	13	9	6	6	0
		3	Grader	Rental		8	8	14	14	14	14	14	14	12	6	6	0
		4	Roller	Rental		22	22	32	28	28	28	28	28	26	15	15	0
		5	Concrete pump	Rental		4	15	15	15	7	4	4	2	2	1	1	0
		6	Excvator	Rental		18	23	25	15	13	12	12	10	6	2	2	0
		7	Truck	Rental		51	72	74	56	42	37	37	31	17	10	10	0
		8	Mobile Crane	Rental		3	7	7	5	3	3	3	1	1	0	0	0
B	Demand	1	Bulldozer		ES	10	9	5	2	0	0	0	0	0	0	0	0
		2	loader		ES	14	12	6	2	0	0	0	0	0	0	0	0
		3	Grader		ES	3	3	8	10	9	9	6	3	0	0	0	0
		4	Roller		ES	10	9	19	23	21	21	14	7	0	0	0	0
		5	Concrete pump		ES	4	3	1	0	0	0	0	0	0	0	0	0
		6	Excvator		ES	11	9	6	4	3	3	2	1	0	0	0	0
		7	Truck		ES	21	18	19	18	15	15	10	5	0	0	0	0
		8	Mobile Crane		ES	8	6	2	0	0	0	0	0	0	0	0	0
B	Demand	1	Bulldozer		Optimal	10	9	5	2	0	0	0	0	0	0	0	0
		2	loader		Optimal	14	12	6	2	0	0	0	0	0	0	0	0
		3	Grader		Optimal	3	3	8	10	9	9	6	3	0	0	0	0
		4	Roller		Optimal	10	9	19	23	21	21	14	7	0	0	0	0
		5	Concrete pump		Optimal	4	3	1	0	0	0	0	0	0	0	0	0
		6	Excvator		Optimal	11	9	6	4	3	3	2	1	0	0	0	0
		7	Truck		Optimal	21	18	19	18	15	15	10	5	0	0	0	0
		8	Mobile Crane		Optimal	8	6	2	0	0	0	0	0	0	0	0	0
B	Number of owned equipment provided (X)	1	Bulldozer	Owned		5	5	5	5	5	5	5	5	5	5	5	5
		2	loader	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		3	Grader	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		4	Roller	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		5	Concrete pump	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		6	Excvator	Owned		6	6	6	6	6	6	6	6	6	6	6	6
		7	Truck	Owned		25	25	25	25	25	25	25	25	25	25	25	25
		8	Mobile Crane	Owned		5	5	5	5	5	5	5	5	5	5	5	5
B	Number of rental equipment provided (Y)	1	Bulldozer	Rental		5	4	0	0	0	0	0	0	0	0	0	0
		2	loader	Rental		6	4	0	0	0	0	0	0	0	0	0	0
		3	Grader	Rental		1	1	6	8	7	7	4	1	0	0	0	0
		4	Roller	Rental		2	1	11	15	13	13	6	0	0	0	0	0
		5	Concrete pump	Rental		2	1	0	0	0	0	0	0	0	0	0	0
		6	Excvator	Rental		5	3	0	0	0	0	0	0	0	0	0	0
		7	Truck	Rental		0	0	0	0	0	0	0	0	0	0	0	0
		8	Mobile Crane	Rental		3	1	0	0	0	0	0	0	0	0	0	0

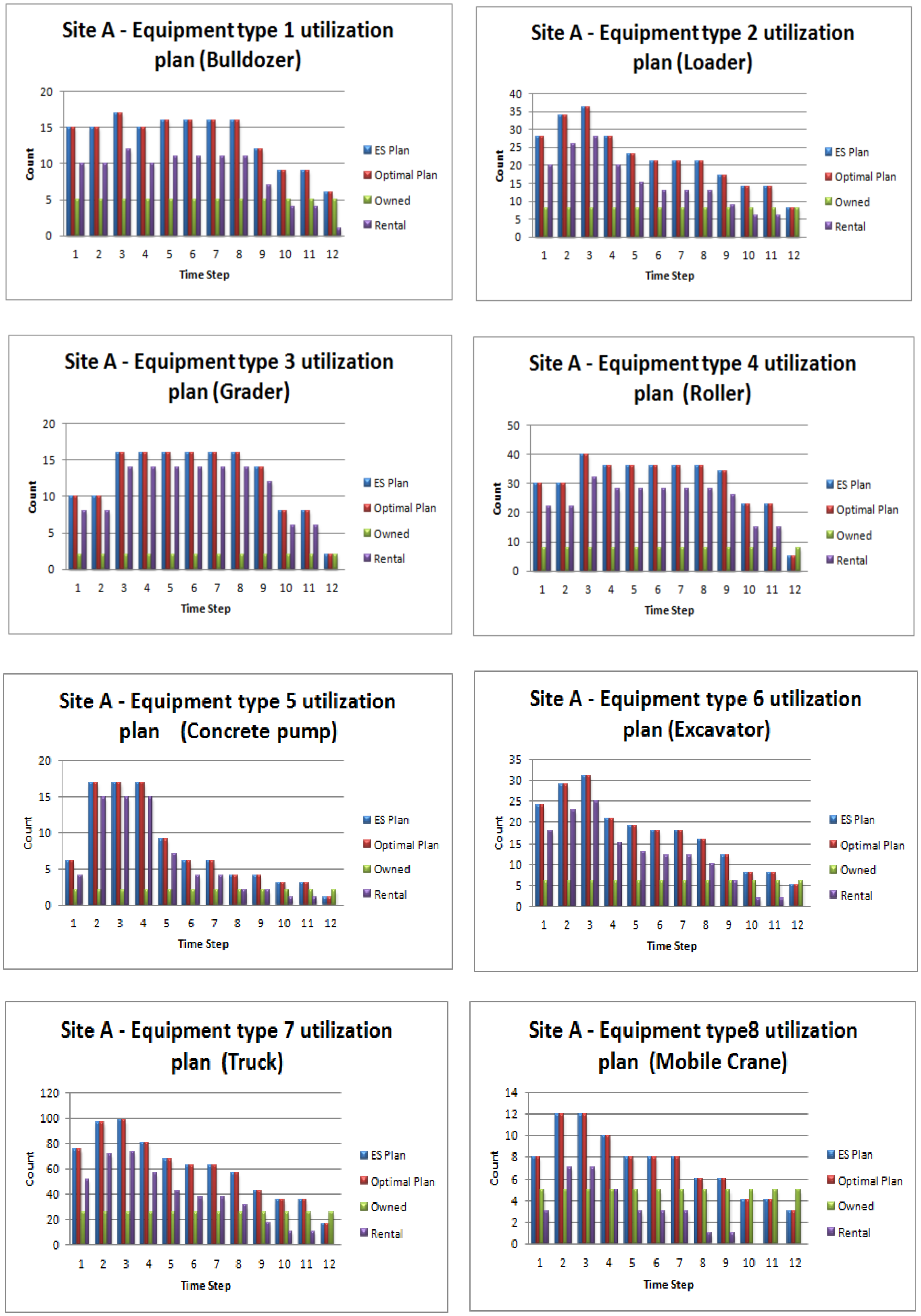
RCPSP						t											
Node (j)	Demand / Provided Equipment	Equipment type(S)	Equipment Name	Ownership Status (Owned/Rental)	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12
C	Demand	1	Bulldozer		ES	6	7	7	7	6	6	6	6	5	3	1	1
		2	loader		ES	15	19	15	13	12	12	12	12	11	5	1	1
		3	Grader		ES	3	4	4	4	2	2	2	2	2	0	0	0
		4	Roller		ES	15	21	17	15	10	10	10	10	10	1	1	1
		5	Concrete pump		ES	8	13	9	7	7	7	7	7	6	1	1	1
		6	Excvator		ES	13	17	13	11	11	11	11	11	10	5	2	2
		7	Truck		ES	35	45	37	33	29	29	29	29	28	15	5	5
		8	Mobile Crane		ES	8	10	8	7	7	7	7	7	6	3	2	2
C	Demand	1	Bulldozer		Optimal	6	7	7	7	6	6	6	6	5	3	1	1
		2	loader		Optimal	15	19	15	13	12	12	12	12	11	5	1	1
		3	Grader		Optimal	3	4	4	4	2	2	2	2	2	0	0	0
		4	Roller		Optimal	15	21	17	15	10	10	10	10	10	1	1	1
		5	Concrete pump		Optimal	8	13	9	7	7	7	7	7	6	1	1	1
		6	Excvator		Optimal	13	17	13	11	11	11	11	11	10	5	2	2
		7	Truck		Optimal	35	45	37	33	29	29	29	29	28	15	5	5
		8	Mobile Crane		Optimal	8	10	8	7	7	7	7	7	6	3	2	2
C	Number of owned equipment provided (X)	1	Bulldozer	Owned		5	5	5	5	5	5	5	5	5	5	5	5
		2	loader	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		3	Grader	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		4	Roller	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		5	Concrete pump	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		6	Excvator	Owned		6	6	6	6	6	6	6	6	6	6	6	6
		7	Truck	Owned		25	25	25	25	25	25	25	25	25	25	25	25
		8	Mobile Crane	Owned		5	5	5	5	5	5	5	5	5	5	5	5
C	Number of rental equipment provided (Y)	1	Bulldozer	Rental		1	2	2	2	1	1	1	1	0	0	0	0
		2	loader	Rental		7	11	7	5	4	4	4	4	3	0	0	0
		3	Grader	Rental		1	2	2	2	0	0	0	0	0	0	0	0
		4	Roller	Rental		7	13	9	7	2	2	2	2	2	0	0	0
		5	Concrete pump	Rental		6	11	7	5	5	5	5	5	4	0	0	0
		6	Excvator	Rental		7	11	7	5	5	5	5	5	4	0	0	0
		7	Truck	Rental		10	20	12	8	4	4	4	4	3	0	0	0
		8	Mobile Crane	Rental		3	5	3	2	2	2	2	2	1	0	0	0
D	Demand	1	Bulldozer		ES	5	5	5	3	3	3	3	3	3	1	1	1
		2	loader		ES	11	11	11	8	8	8	7	5	5	1	1	1
		3	Grader		ES	3	3	3	0	0	0	0	0	0	0	0	0
		4	Roller		ES	15	15	15	9	8	8	6	6	6	1	1	1
		5	Concrete pump		ES	11	11	11	11	10	10	9	6	6	1	1	1
		6	Excvator		ES	9	9	9	7	6	6	5	4	4	2	2	2
		7	Truck		ES	30	30	30	20	19	19	18	13	13	5	5	5
		8	Mobile Crane		ES	6	6	6	6	5	5	5	4	4	2	2	2
D	Demand	1	Bulldozer		Optimal	5	5	5	3	3	3	3	3	3	1	1	1
		2	loader		Optimal	11	11	11	8	8	8	7	5	5	1	1	1
		3	Grader		Optimal	3	3	3	0	0	0	0	0	0	0	0	0
		4	Roller		Optimal	15	15	15	9	8	8	6	6	6	1	1	1
		5	Concrete pump		Optimal	11	11	11	11	10	10	9	6	6	1	1	1
		6	Excvator		Optimal	9	9	9	7	6	6	5	4	4	2	2	2
		7	Truck		Optimal	30	30	30	20	19	19	18	13	13	5	5	5
		8	Mobile Crane		Optimal	6	6	6	6	5	5	5	4	4	2	2	2
D	Number of owned equipment provided (X)	1	Bulldozer	Owned		5	5	5	5	5	5	5	5	5	5	5	5
		2	loader	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		3	Grader	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		4	Roller	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		5	Concrete pump	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		6	Excvator	Owned		6	6	6	6	6	6	6	6	6	6	6	6
		7	Truck	Owned		25	25	25	25	25	25	25	25	25	25	25	25
		8	Mobile Crane	Owned		5	5	5	5	5	5	5	5	5	5	5	5
D	Number of rental equipment provided (Y)	1	Bulldozer	Rental		0	0	0	0	0	0	0	0	0	0	0	0
		2	loader	Rental		3	3	3	0	0	0	0	0	0	0	0	0
		3	Grader	Rental		1	1	1	0	0	0	0	0	0	0	0	0
		4	Roller	Rental		7	7	7	1	0	0	0	0	0	0	0	0
		5	Concrete pump	Rental		9	9	9	9	8	8	7	4	4	0	0	0
		6	Excvator	Rental		3	3	3	1	0	0	0	0	0	0	0	0
		7	Truck	Rental		5	5	5	0	0	0	0	0	0	0	0	0
		8	Mobile Crane	Rental		1	1	1	1	0	0	0	0	0	0	0	0



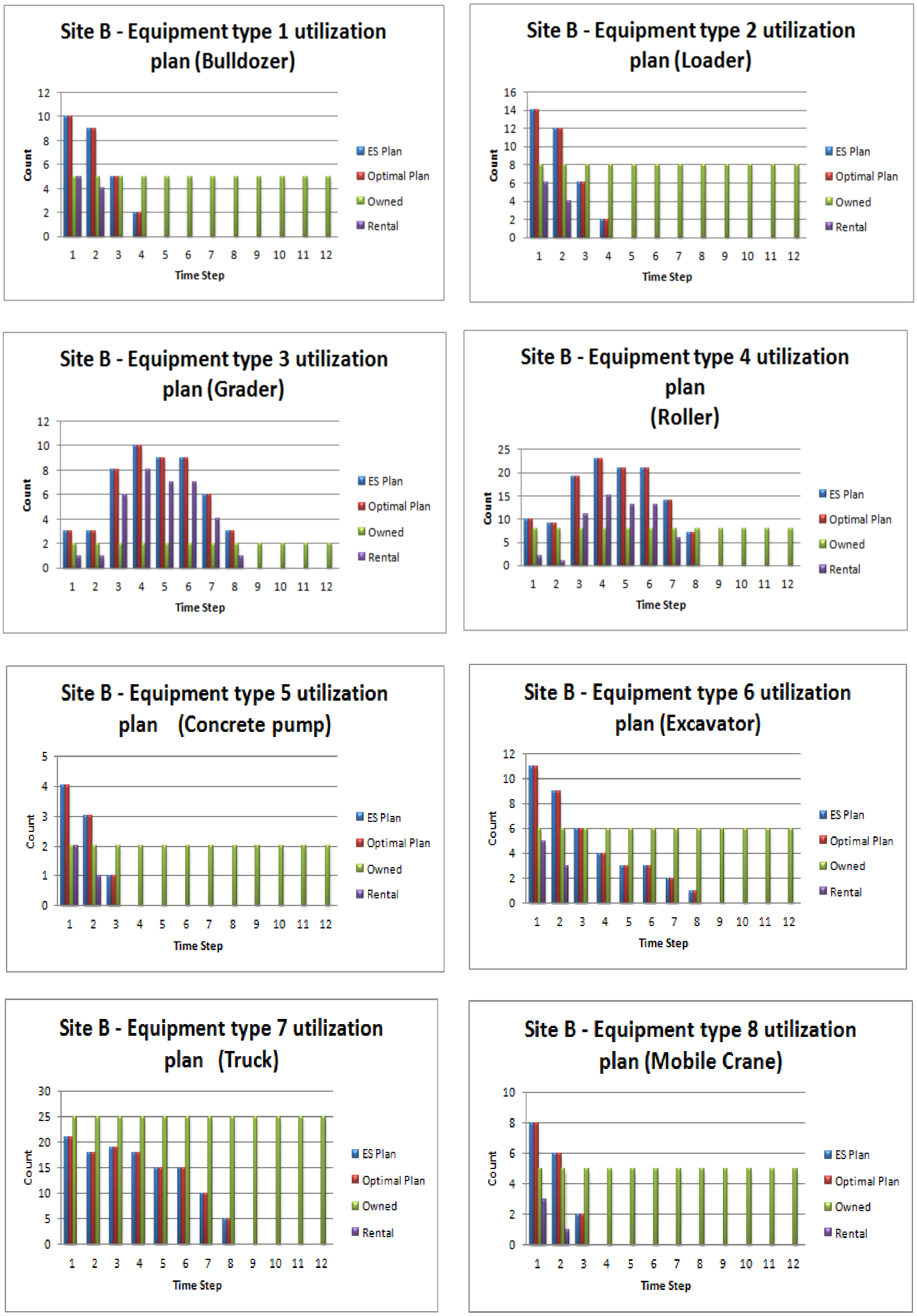
RCPSP						t											
Node (j)	Demand / Provided Equipment	Equipment type(S)	Equipment Name	Ownership Status (Owned/Rental)	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12
Total	Demand	1	Bulldozer		ES	36	36	34	27	25	25	25	25	20	13	11	8
		2	loader		ES	68	76	68	51	43	41	40	38	33	20	16	10
		3	Grader		ES	19	20	31	30	27	27	24	21	16	8	8	2
		4	Roller		ES	70	75	91	83	75	75	66	59	50	25	25	7
		5	Concrete pump		ES	29	44	38	35	26	23	22	17	16	5	5	3
		6	Excvator		ES	57	64	59	43	39	38	36	32	26	15	12	9
		7	Truck		ES	162	190	185	152	130	125	119	103	83	55	45	26
		8	Mobile Crane		ES	30	34	28	23	20	20	20	17	16	9	8	7
Total	Demand	1	Bulldozer		Optimal	36	36	34	27	25	25	25	25	20	13	11	8
		2	loader		Optimal	68	76	68	51	43	41	40	38	33	20	16	10
		3	Grader		Optimal	19	20	31	30	27	27	24	21	16	8	8	2
		4	Roller		Optimal	70	75	91	83	75	75	66	59	50	25	25	7
		5	Concrete pump		Optimal	29	44	38	35	26	23	22	17	16	5	5	3
		6	Excvator		Optimal	57	64	59	43	39	38	36	32	26	15	12	9
		7	Truck		Optimal	162	190	185	152	130	125	119	103	83	55	45	26
		8	Mobile Crane		Optimal	30	34	28	23	20	20	20	17	16	9	8	7
Total	Number of owned equipment provided (X)	1	Bulldozer	Owned		20	20	20	20	20	20	20	20	20	20	20	20
		2	loader	Owned		32	32	32	32	32	32	32	32	32	32	32	32
		3	Grader	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		4	Roller	Owned		32	32	32	32	32	32	32	32	32	32	32	32
		5	Concrete pump	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		6	Excvator	Owned		24	24	24	24	24	24	24	24	24	24	24	24
		7	Truck	Owned		100	100	100	100	100	100	100	100	100	100	100	100
		8	Mobile Crane	Owned		20	20	20	20	20	20	20	20	20	20	20	20
Total	Number of rental equipment provided (Y)	1	Bulldozer	Rental		16	16	14	12	12	12	12	12	7	4	4	1
		2	loader	Rental		36	44	38	25	19	17	17	17	12	6	6	0
		3	Grader	Rental		11	12	23	24	21	21	18	15	12	6	6	0
		4	Roller	Rental		38	43	59	51	43	43	36	30	28	15	15	0
		5	Concrete pump	Rental		21	36	31	29	20	17	16	11	10	1	1	0
		6	Excvator	Rental		33	40	35	21	18	17	17	15	10	2	2	0
		7	Truck	Rental		66	97	91	64	46	41	41	35	20	10	10	0
		8	Mobile Crane	Rental		10	14	11	8	5	5	5	3	2	0	0	0

Note: Start of the day is the measuring point

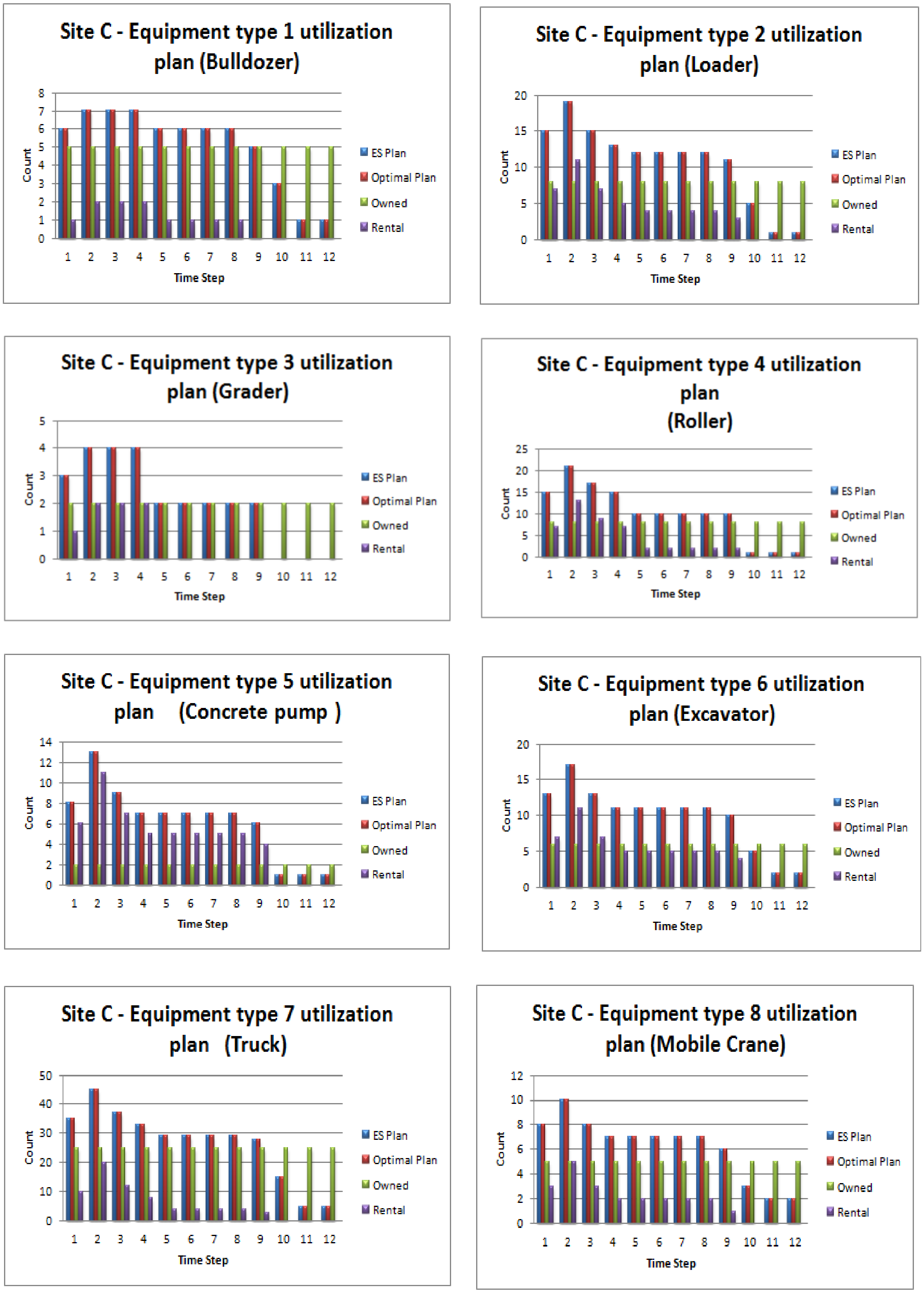
Appendix I. Table 1. - Equipment demand and supply patterns for both ES and optimal schedules for each jobsite individually and for the portfolio as a whole; case study # 1-1



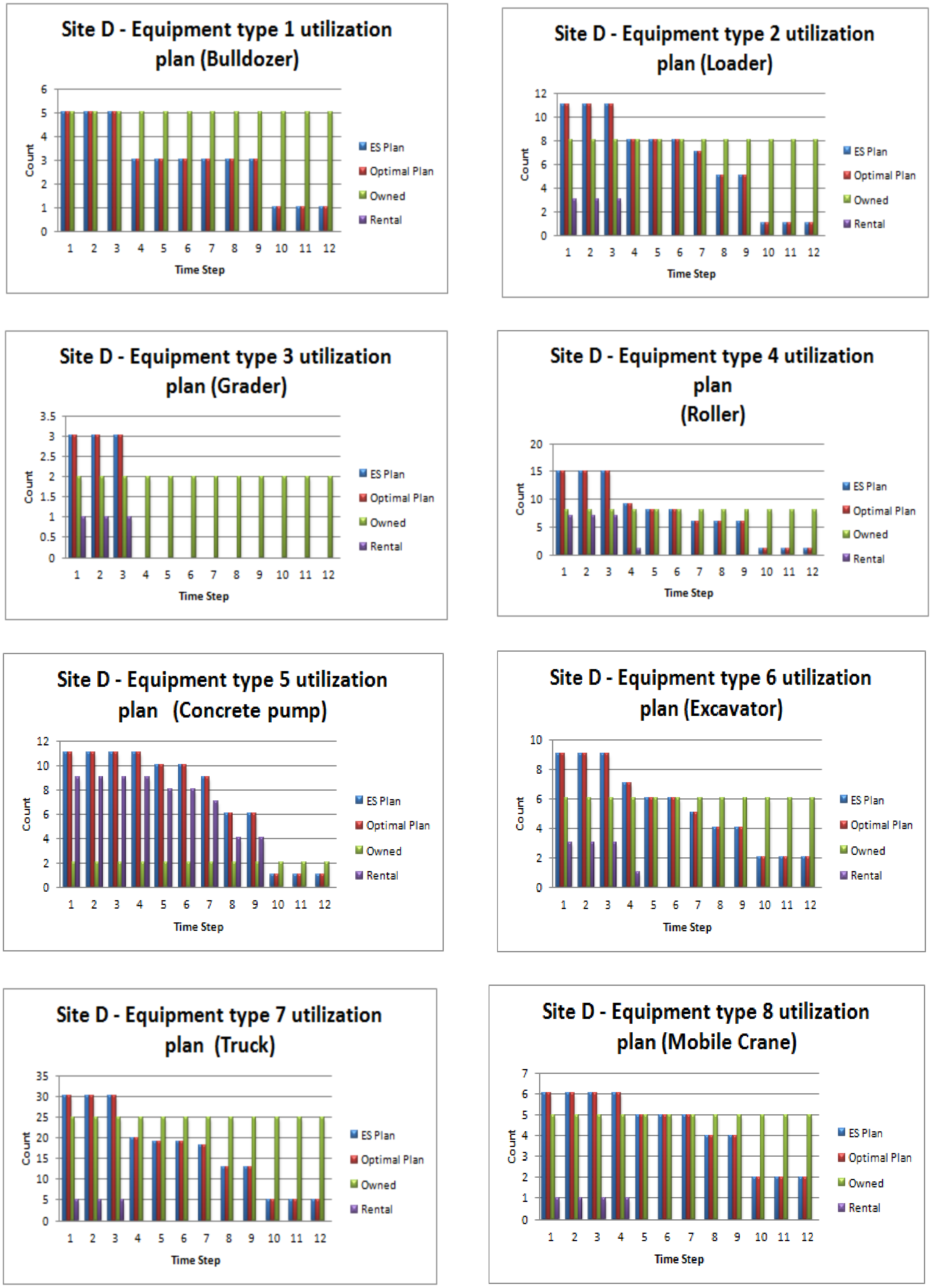
Appendix I. Figure 2- Equipment demand and supply patterns for jobsite A; case study # 1-1



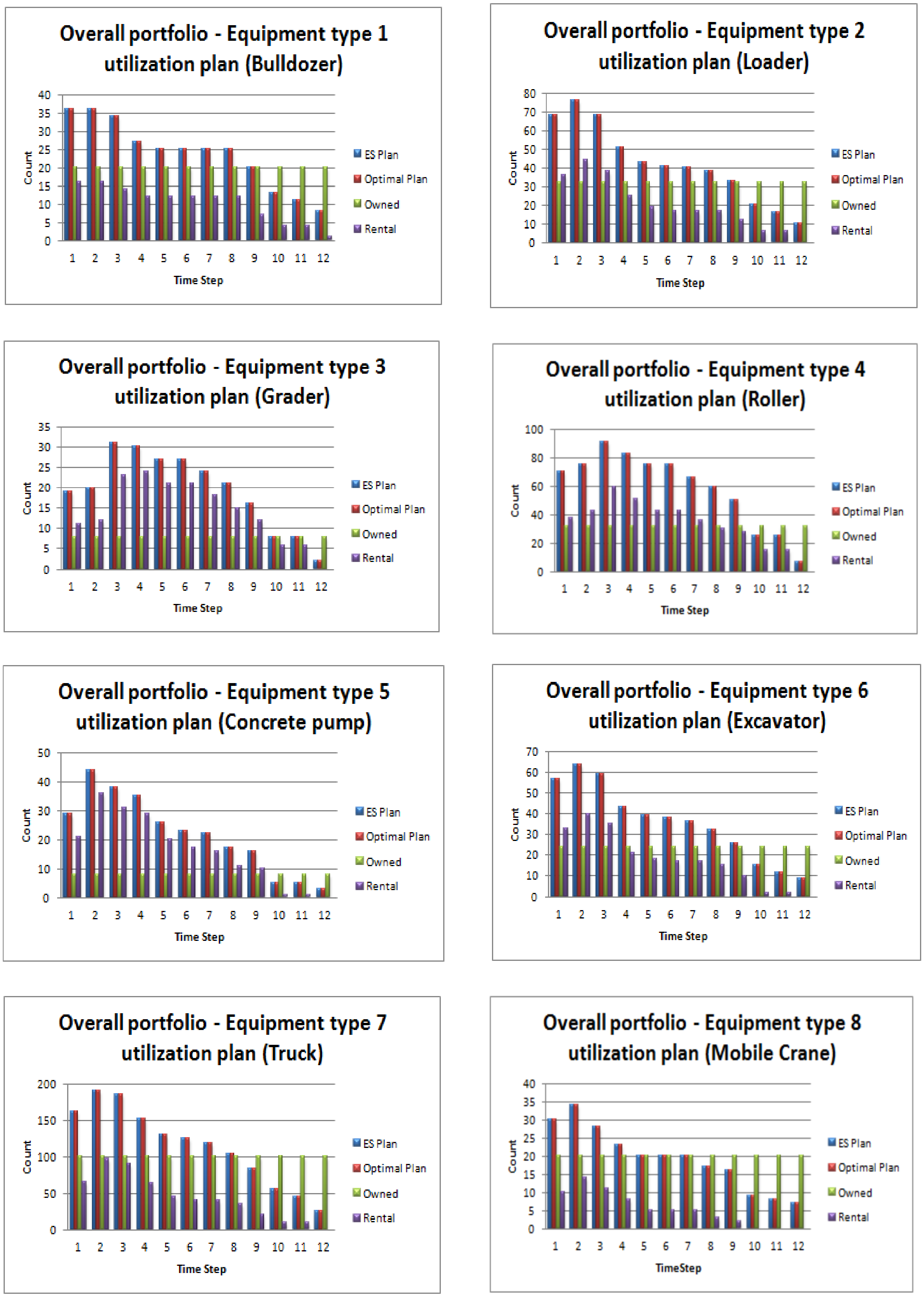
Appendix I. Figure 3- Equipment demand and supply patterns for jobsite B; case study # 1-1



Appendix I. Figure 4- Equipment demand and supply patterns for jobsite C; case study # 1-1



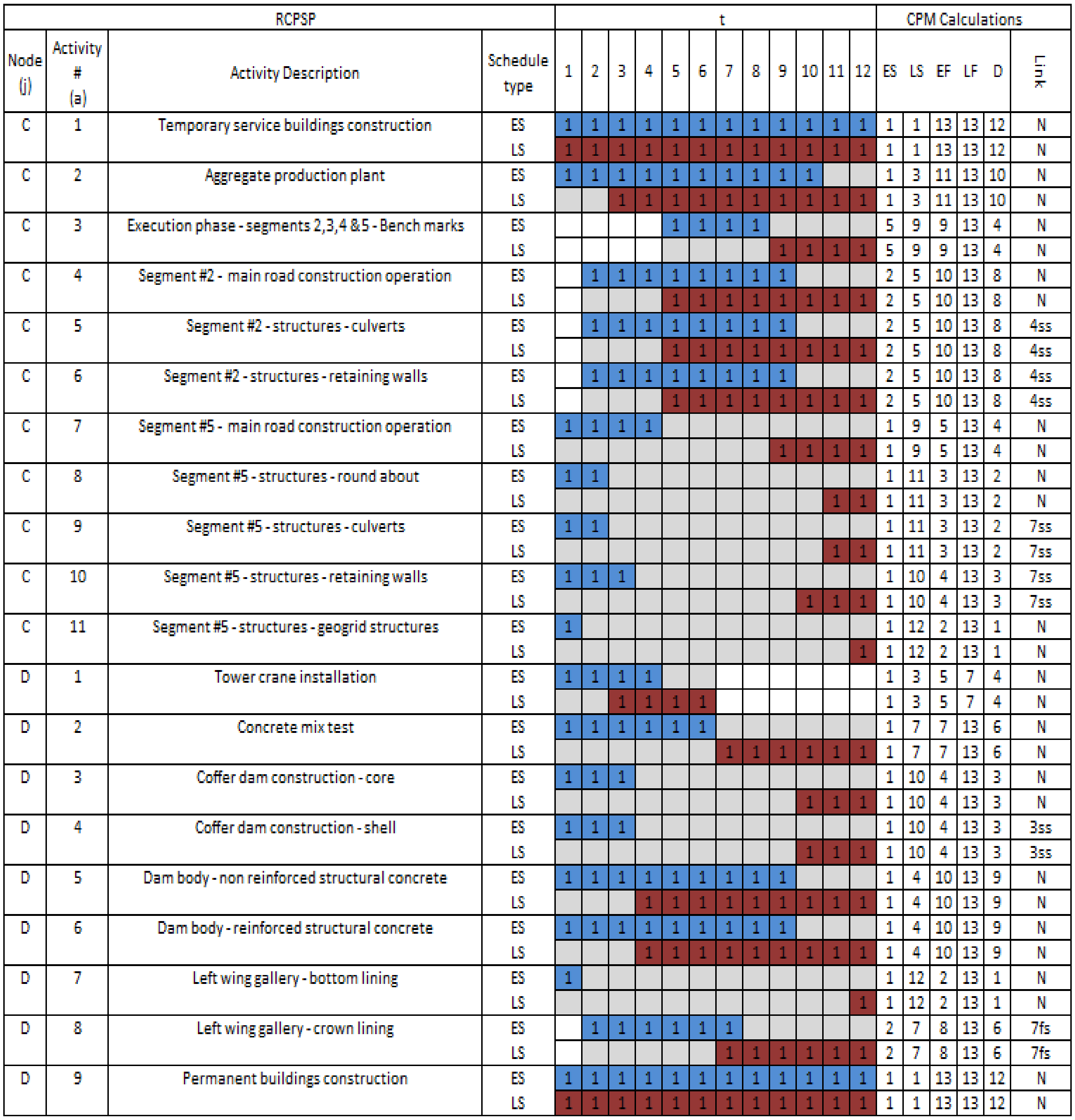
Appendix I. Figure 5- Equipment demand and supply patterns for jobsite D; case study # 1-1



Appendix I. Figure 6- Equipment demand and supply patterns for the whole portfolio; case study # 1-1

Case study #1-2:

RCPSP				t												CPM Calculations					
Node (j)	Activity # (a)	Activity Description	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12	ES	LS	EF	LF	D	Link
A	1	Temporary service roads construction	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			LS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
A	2	Temporary service buildings construction	ES	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
			LS				1	1	1	1	1	1	1	1	1	1	4	10	13	9	N
A	3	Temporary site work	ES	1	1	1	1	1	1	1	1	1	1	1		1	2	12	13	11	N
			LS		1	1	1	1	1	1	1	1	1	1	1	1	2	12	13	11	N
A	4	Aggregate production plant	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			LS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
A	5	Dam body construction-Bench marks	ES					1	1	1	1	1	1	1	1	5	5	13	13	8	N
			LS					1	1	1	1	1	1	1	1	5	5	13	13	8	N
A	6	Dam body - left wing - excavation - level 1	ES	1	1	1	1	1	1	1	1					1	5	9	13	8	N
			LS					1	1	1	1	1	1	1	1	1	5	9	13	8	N
A	7	Dam body - left wing -leveling	ES			1	1	1	1	1	1	1				3	6	10	13	7	6ss+2
			LS						1	1	1	1	1	1	1	3	6	10	13	7	6ss+2
A	8	Dam body - left wing -trench temporary protection	ES		1	1	1	1	1	1						2	7	8	13	6	6ss+1
			LS							1	1	1	1	1	1	2	7	8	13	6	6ss+1
A	9	Dam body - right wing - excavation - level 1	ES	1	1	1	1	1	1	1	1					1	5	9	13	8	N
			LS					1	1	1	1	1	1	1	1	1	5	9	13	8	N
A	10	Dam body - right wing -leveling	ES			1	1	1	1	1	1	1				3	6	10	13	7	9ss+2
			LS						1	1	1	1	1	1	1	3	6	10	13	7	9ss+2
A	11	Dam body - right wing -trench temporary protection	ES		1	1	1	1	1	1						2	7	8	13	6	9ss+1
			LS							1	1	1	1	1	1	2	7	8	13	6	9ss+1
A	12	Dam body - rockfill	ES	1	1	1	1	1	1	1	1	1	1	1		1	2	12	13	11	N
			LS		1	1	1	1	1	1	1	1	1	1	1	1	2	12	13	11	N
A	13	Dam body - concrete face	ES		1	1	1	1								2	7	6	11	4	12ss+1
			LS							1	1	1	1			2	7	6	11	4	12ss+1
A	14	Gallery construction - middle section - concrete lining	ES	1	1	1	1									1	9	5	13	4	N
			LS									1	1	1	1	1	9	5	13	4	N
A	15	Gallery construction - left wing - excavation	ES	1	1	1										1	10	4	13	3	N
			LS										1	1	1	1	10	4	13	3	N
A	16	Gallery construction - left wing - leveling	ES	1	1	1										1	10	4	13	3	N
			LS										1	1	1	1	10	4	13	3	N
A	17	Gallery construction - left wing - concrete lining	ES		1	1	1									2	10	5	13	3	16ss+1
			LS										1	1	1	2	10	5	13	3	16ss+1
A	18	Gallery construction - right wing - excavation	ES	1	1	1										1	10	4	13	3	N
			LS										1	1	1	1	10	4	13	3	N
A	19	Gallery construction - right wing - leveling	ES	1	1	1										1	10	4	13	3	N
			LS										1	1	1	1	10	4	13	3	N
A	20	Gallery construction - right wing - concrete lining	ES		1	1	1									2	10	5	13	3	19ss+1
			LS										1	1	1	2	10	5	13	3	19ss+1
B	1	Segment #1 - water pipeline relocation	ES	1	1											1	4	3	6	2	N
			LS				1	1								1	4	3	6	2	N
B	2	Segment #1 - structures - canal - derivation	ES	1	1	1										1	5	4	8	3	N
			LS					1	1	1						1	5	4	8	3	N
B	3	Segment #2 - water pipeline relocation	ES	1	1											1	4	3	6	2	N
			LS				1	1								1	4	3	6	2	N
B	4	Segment #3 - water pipeline relocation	ES	1												1	12	2	13	1	N
			LS												1	1	12	2	13	1	N
B	5	Segment #4 - water pipeline relocation	ES	1	1	1										1	10	4	13	3	N
			LS										1	1	1	1	10	4	13	3	N
B	6	Segment #4 - structures - bridges - derivation	ES	1	1											1	11	3	13	2	N
			LS											1	1	1	11	3	13	2	N
B	7	Segment #5 - structures - bridges - derivation	ES	1	1	1	1									1	9	5	13	4	N
			LS									1	1	1	1	1	9	5	13	4	N
B	8	Segment #1 - pavement - base construction	ES			1	1	1	1	1						3	8	8	13	5	2fs-1
			LS								1	1	1	1	1	3	8	8	13	5	2fs-1
B	9	Segment #2 - pavement - sub base construction	ES			1	1	1	1							3	9	7	13	4	3fs
			LS									1	1	1	1	3	9	7	13	4	3fs
B	10	Segment #2 - pavement - base construction	ES				1	1	1	1	1					4	8	9	13	5	9ss+1
			LS								1	1	1	1	1	4	8	9	13	5	9ss+1



RCPSP				t												CPM Calculations					
Node (j)	Activity # (a)	Activity Description	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12	ES	LS	EF	LF	D	Link
C	1	Temporary service buildings construction	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			LS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
C	2	Aggregate production plant	ES	1	1	1	1	1	1	1	1	1	1			1	3	11	13	10	N
			LS			1	1	1	1	1	1	1	1	1	1	1	3	11	13	10	N
C	3	Execution phase - segments 2,3,4 &5 - Bench marks	ES					1	1	1	1					5	9	9	13	4	N
			LS									1	1	1	1	5	9	9	13	4	N
C	4	Segment #2 - main road construction operation	ES		1	1	1	1	1	1	1	1				2	5	10	13	8	N
			LS					1	1	1	1	1	1	1	1	2	5	10	13	8	N
C	5	Segment #2 - structures - culverts	ES		1	1	1	1	1	1	1	1				2	5	10	13	8	4ss
			LS					1	1	1	1	1	1	1	1	2	5	10	13	8	4ss
C	6	Segment #2 - structures - retaining walls	ES		1	1	1	1	1	1	1	1				2	5	10	13	8	4ss
			LS					1	1	1	1	1	1	1	1	2	5	10	13	8	4ss
C	7	Segment #5 - main road construction operation	ES	1	1	1	1									1	9	5	13	4	N
			LS									1	1	1	1	1	9	5	13	4	N
C	8	Segment #5 - structures - round about	ES	1	1											1	11	3	13	2	N
			LS											1	1	1	11	3	13	2	N
C	9	Segment #5 - structures - culverts	ES	1	1											1	11	3	13	2	7ss
			LS											1	1	1	11	3	13	2	7ss
C	10	Segment #5 - structures - retaining walls	ES	1	1	1										1	10	4	13	3	7ss
			LS										1	1	1	1	10	4	13	3	7ss
C	11	Segment #5 - structures - geogrid structures	ES	1												1	12	2	13	1	N
			LS												1	1	12	2	13	1	N
D	1	Tower crane installation	ES	1	1	1	1									1	3	5	7	4	N
			LS			1	1	1	1							1	3	5	7	4	N
D	2	Concrete mix test	ES	1	1	1	1	1	1							1	7	7	13	6	N
			LS							1	1	1	1	1	1	1	7	7	13	6	N
D	3	Coffer dam construction - core	ES	1	1	1										1	10	4	13	3	N
			LS										1	1	1	1	10	4	13	3	N
D	4	Coffer dam construction - shell	ES	1	1	1										1	10	4	13	3	3ss
			LS										1	1	1	1	10	4	13	3	3ss
D	5	Dam body - non reinforced structural concrete	ES	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
			LS				1	1	1	1	1	1	1	1	1	1	4	10	13	9	N
D	6	Dam body - reinforced structural concrete	ES	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
			LS				1	1	1	1	1	1	1	1	1	1	4	10	13	9	N
D	7	Left wing gallery - bottom lining	ES	1												1	12	2	13	1	N
			LS												1	1	12	2	13	1	N
D	8	Left wing gallery - crown lining	ES		1	1	1	1	1	1						2	7	8	13	6	7fs
			LS							1	1	1	1	1	1	2	7	8	13	6	7fs
D	9	Permanent buildings construction	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			LS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N

Note: Start of the day is the measuring point

Appendix I. Figure 7- ES and optimal master schedule of the portfolio; case study # 1-2

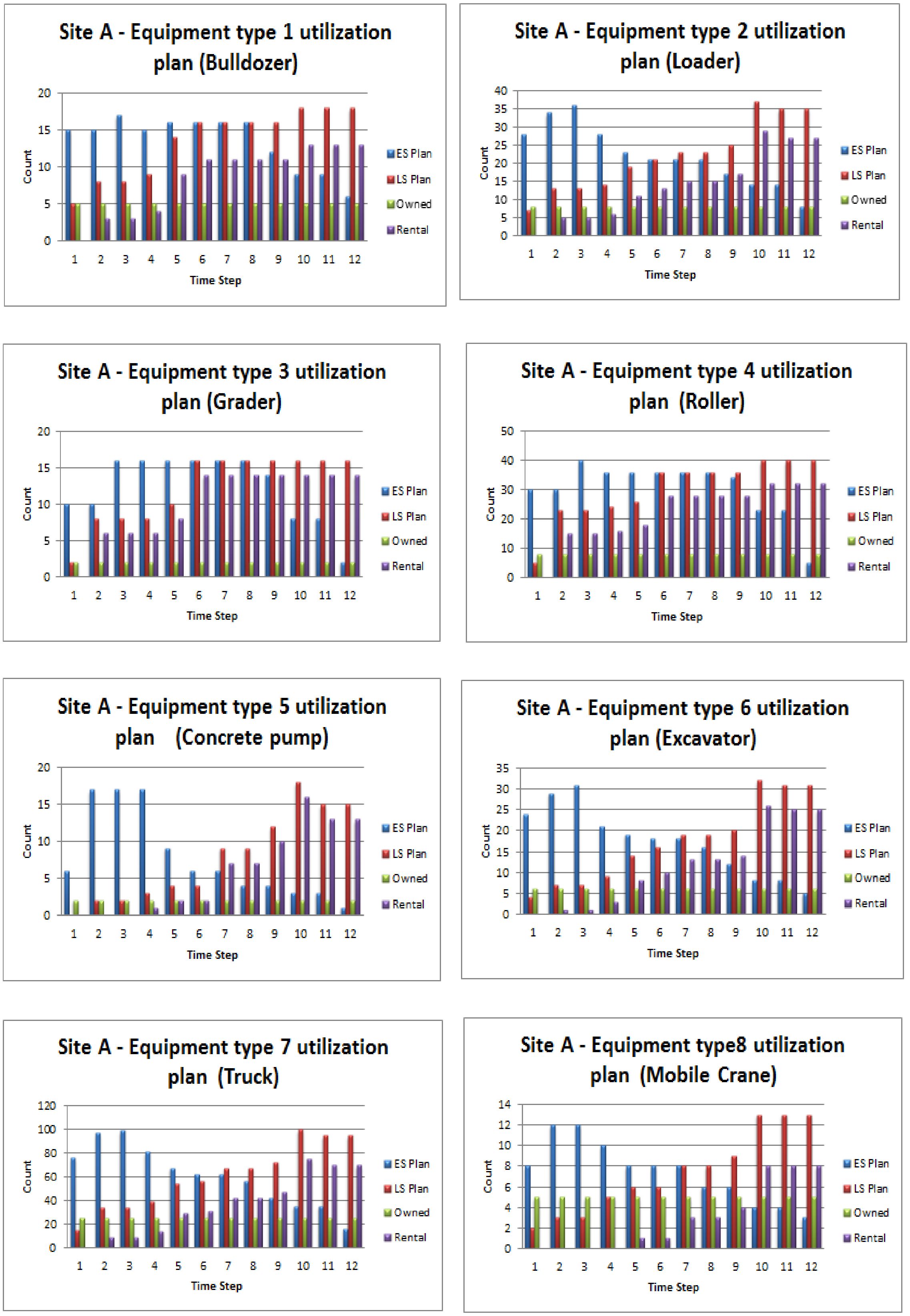
RCPSP						t											
Node (j)	Demand / Provided equipment	Equipment type(S)	Equipment Name	Ownership Status (Owned/Rental)	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12
A	Demand	1	Bulldozer		ES	15	15	17	15	16	16	16	16	12	9	9	6
		2	loader		ES	28	34	36	28	23	21	21	21	17	14	14	8
		3	Grader		ES	10	10	16	16	16	16	16	16	14	8	8	2
		4	Roller		ES	30	30	40	36	36	36	36	36	34	23	23	5
		5	Concrete pump		ES	6	17	17	17	9	6	6	4	4	3	3	1
		6	Excvator		ES	24	29	31	21	19	18	18	16	12	8	8	5
		7	Truck		ES	76	97	99	81	67	62	62	56	42	35	35	16
		8	Mobile Crane		ES	8	12	12	10	8	8	8	6	6	4	4	3
A	Demand	1	Bulldozer		LS	5	8	8	9	14	16	16	16	16	18	18	18
		2	loader		LS	7	13	13	14	19	21	23	23	25	37	35	35
		3	Grader		LS	2	8	8	8	10	16	16	16	16	16	16	16
		4	Roller		LS	5	23	23	24	26	36	36	36	36	40	40	40
		5	Concrete pump		LS	0	2	2	3	4	4	9	9	12	18	15	15
		6	Excvator		LS	4	7	7	9	14	16	19	19	20	32	31	31
		7	Truck		LS	15	34	34	39	54	56	67	67	72	100	95	95
		8	Mobile Crane		LS	2	3	3	5	6	6	8	8	9	13	13	13
A	Number of owned equipment provided (X)	1	Bulldozer	Owned		5	5	5	5	5	5	5	5	5	5	5	5
		2	loader	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		3	Grader	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		4	Roller	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		5	Concrete pump	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		6	Excvator	Owned		6	6	6	6	6	6	6	6	6	6	6	6
		7	Truck	Owned		25	25	25	25	25	25	25	25	25	25	25	25
		8	Mobile Crane	Owned		5	5	5	5	5	5	5	5	5	5	5	5
A	Number of owned equipment provided (Y)	1	Bulldozer	Rental		0	3	3	4	9	11	11	11	11	13	13	13
		2	loader	Rental		0	5	5	6	11	13	15	15	17	29	27	27
		3	Grader	Rental		0	6	6	6	8	14	14	14	14	14	14	14
		4	Roller	Rental		0	15	15	16	18	28	28	28	28	32	32	32
		5	Concrete pump	Rental		0	0	0	1	2	2	7	7	10	16	13	13
		6	Excvator	Rental		0	1	1	3	8	10	13	13	14	26	25	25
		7	Truck	Rental		0	9	9	14	29	31	42	42	47	75	70	70
		8	Mobile Crane	Rental		0	0	0	0	1	1	3	3	4	8	8	8
B	Demand	1	Bulldozer		ES	10	9	5	2	0	0	0	0	0	0	0	0
		2	loader		ES	14	12	6	2	0	0	0	0	0	0	0	0
		3	Grader		ES	3	3	8	10	9	9	6	3	0	0	0	0
		4	Roller		ES	10	9	19	23	21	21	14	7	0	0	0	0
		5	Concrete pump		ES	4	3	1	0	0	0	0	0	0	0	0	0
		6	Excvator		ES	11	9	6	4	3	3	2	1	0	0	0	0
		7	Truck		ES	21	18	19	18	15	15	10	5	0	0	0	0
		8	Mobile Crane		ES	8	6	2	0	0	0	0	0	0	0	0	0
B	Demand	1	Bulldozer		LS	0	0	0	2	4	2	2	0	2	3	5	6
		2	loader		LS	0	0	0	4	6	2	2	0	2	4	6	8
		3	Grader		LS	0	0	0	0	1	1	1	6	10	10	11	11
		4	Roller		LS	0	0	0	2	4	2	2	14	23	24	26	27
		5	Concrete pump		LS	0	0	0	2	2	0	0	0	0	1	1	2
		6	Excvator		LS	0	0	0	4	5	1	1	2	4	6	7	9
		7	Truck		LS	0	0	0	6	9	3	3	10	18	21	24	27
		8	Mobile Crane		LS	0	0	0	4	4	0	0	0	0	2	2	4
B	Number of owned equipment provided (X)	1	Bulldozer	Owned		5	5	5	5	5	5	5	5	5	5	5	5
		2	loader	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		3	Grader	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		4	Roller	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		5	Concrete pump	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		6	Excvator	Owned		6	6	6	6	6	6	6	6	6	6	6	6
		7	Truck	Owned		25	25	25	25	25	25	25	25	25	25	25	25
		8	Mobile Crane	Owned		5	5	5	5	5	5	5	5	5	5	5	5
B	Number of owned equipment provided (Y)	1	Bulldozer	Rental		0	0	0	0	0	0	0	0	0	0	0	1
		2	loader	Rental		0	0	0	0	0	0	0	0	0	0	0	0
		3	Grader	Rental		0	0	0	0	0	0	0	4	8	8	9	9
		4	Roller	Rental		0	0	0	0	0	0	0	6	15	16	18	19
		5	Concrete pump	Rental		0	0	0	0	0	0	0	0	0	0	0	0
		6	Excvator	Rental		0	0	0	0	0	0	0	0	0	0	1	3
		7	Truck	Rental		0	0	0	0	0	0	0	0	0	0	0	2
		8	Mobile Crane	Rental		0	0	0	0	0	0	0	0	0	0	0	0

RCPSP						t											
Node (j)	Demand / Provided equipment	Equipment type(S)	Equipment Name	Ownership Status (Owned/Rental)	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12
C	Demand	1	Bulldozer		ES	6	7	7	7	6	6	6	6	5	3	1	1
		2	loader		ES	15	19	15	13	12	12	12	12	11	5	1	1
		3	Grader		ES	3	4	4	4	2	2	2	2	2	0	0	0
		4	Roller		ES	15	21	17	15	10	10	10	10	10	1	1	1
		5	Concrete pump		ES	8	13	9	7	7	7	7	7	6	1	1	1
		6	Excvator		ES	13	17	13	11	11	11	11	11	10	5	2	2
		7	Truck		ES	35	45	37	33	29	29	29	29	28	15	5	5
		8	Mobile Crane		ES	8	10	8	7	7	7	7	7	6	3	2	2
C	Demand	1	Bulldozer		LS	1	1	3	3	5	5	5	5	8	8	8	9
		2	loader		LS	1	1	5	5	11	11	11	11	14	16	20	22
		3	Grader		LS	0	0	0	0	2	2	2	2	4	4	4	5
		4	Roller		LS	1	1	1	1	10	10	10	10	15	17	21	24
		5	Concrete pump		LS	1	1	1	1	6	6	6	6	8	10	14	14
		6	Excvator		LS	2	2	5	5	10	10	10	10	12	14	18	19
		7	Truck		LS	5	5	15	15	28	28	28	28	34	38	46	49
		8	Mobile Crane		LS	2	2	3	3	6	6	6	6	8	9	11	12
C	Number of owned equipment provided (X)	1	Bulldozer	Owned		5	5	5	5	5	5	5	5	5	5	5	5
		2	loader	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		3	Grader	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		4	Roller	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		5	Concrete pump	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		6	Excvator	Owned		6	6	6	6	6	6	6	6	6	6	6	6
		7	Truck	Owned		25	25	25	25	25	25	25	25	25	25	25	25
		8	Mobile Crane	Owned		5	5	5	5	5	5	5	5	5	5	5	5
C	Number of owned equipment provided (Y)	1	Bulldozer	Rental		0	0	0	0	0	0	0	0	3	3	3	4
		2	loader	Rental		0	0	0	0	3	3	3	3	6	8	12	14
		3	Grader	Rental		0	0	0	0	0	0	0	0	2	2	2	3
		4	Roller	Rental		0	0	0	0	2	2	2	2	7	9	13	16
		5	Concrete pump	Rental		0	0	0	0	4	4	4	4	6	8	12	12
		6	Excvator	Rental		0	0	0	0	4	4	4	4	6	8	12	13
		7	Truck	Rental		0	0	0	0	3	3	3	3	9	13	21	24
		8	Mobile Crane	Rental		0	0	0	0	1	1	1	1	3	4	6	7
D	Demand	1	Bulldozer		ES	5	5	5	3	3	3	3	3	3	1	1	1
		2	loader		ES	11	11	11	8	8	8	7	5	5	1	1	1
		3	Grader		ES	3	3	3	0	0	0	0	0	0	0	0	0
		4	Roller		ES	15	15	15	9	8	8	6	6	6	1	1	1
		5	Concrete pump		ES	11	11	11	11	10	10	9	6	6	1	1	1
		6	Excvator		ES	9	9	9	7	6	6	5	4	4	2	2	2
		7	Truck		ES	30	30	30	20	19	19	18	13	13	5	5	5
		8	Mobile Crane		ES	6	6	6	6	5	5	5	4	4	2	2	2
D	Demand	1	Bulldozer		LS	1	1	1	3	3	3	3	3	3	5	5	5
		2	loader		LS	1	1	1	5	5	5	8	8	8	11	11	13
		3	Grader		LS	0	0	0	0	0	0	0	0	0	3	3	3
		4	Roller		LS	1	1	2	7	7	7	8	8	8	14	14	14
		5	Concrete pump		LS	1	1	2	7	7	7	10	10	10	10	10	13
		6	Excvator		LS	2	2	3	5	5	5	6	6	6	8	8	9
		7	Truck		LS	5	5	6	14	14	14	19	19	19	29	29	34
		8	Mobile Crane		LS	2	2	3	5	5	5	5	5	5	5	5	6
D	Number of owned equipment provided (X)	1	Bulldozer	Owned		5	5	5	5	5	5	5	5	5	5	5	5
		2	loader	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		3	Grader	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		4	Roller	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		5	Concrete pump	Owned		2	2	2	2	2	2	2	2	2	2	2	2
		6	Excvator	Owned		6	6	6	6	6	6	6	6	6	6	6	6
		7	Truck	Owned		25	25	25	25	25	25	25	25	25	25	25	25
		8	Mobile Crane	Owned		5	5	5	5	5	5	5	5	5	5	5	5
D	Number of owned equipment provided (Y)	1	Bulldozer	Rental		0	0	0	0	0	0	0	0	0	0	0	0
		2	loader	Rental		0	0	0	0	0	0	0	0	0	3	3	5
		3	Grader	Rental		0	0	0	0	0	0	0	0	0	1	1	1
		4	Roller	Rental		0	0	0	0	0	0	0	0	0	6	6	6
		5	Concrete pump	Rental		0	0	0	5	5	5	8	8	8	8	8	11
		6	Excvator	Rental		0	0	0	0	0	0	0	0	0	2	2	3
		7	Truck	Rental		0	0	0	0	0	0	0	0	0	4	4	9
		8	Mobile Crane	Rental		0	0	0	0	0	0	0	0	0	0	0	1

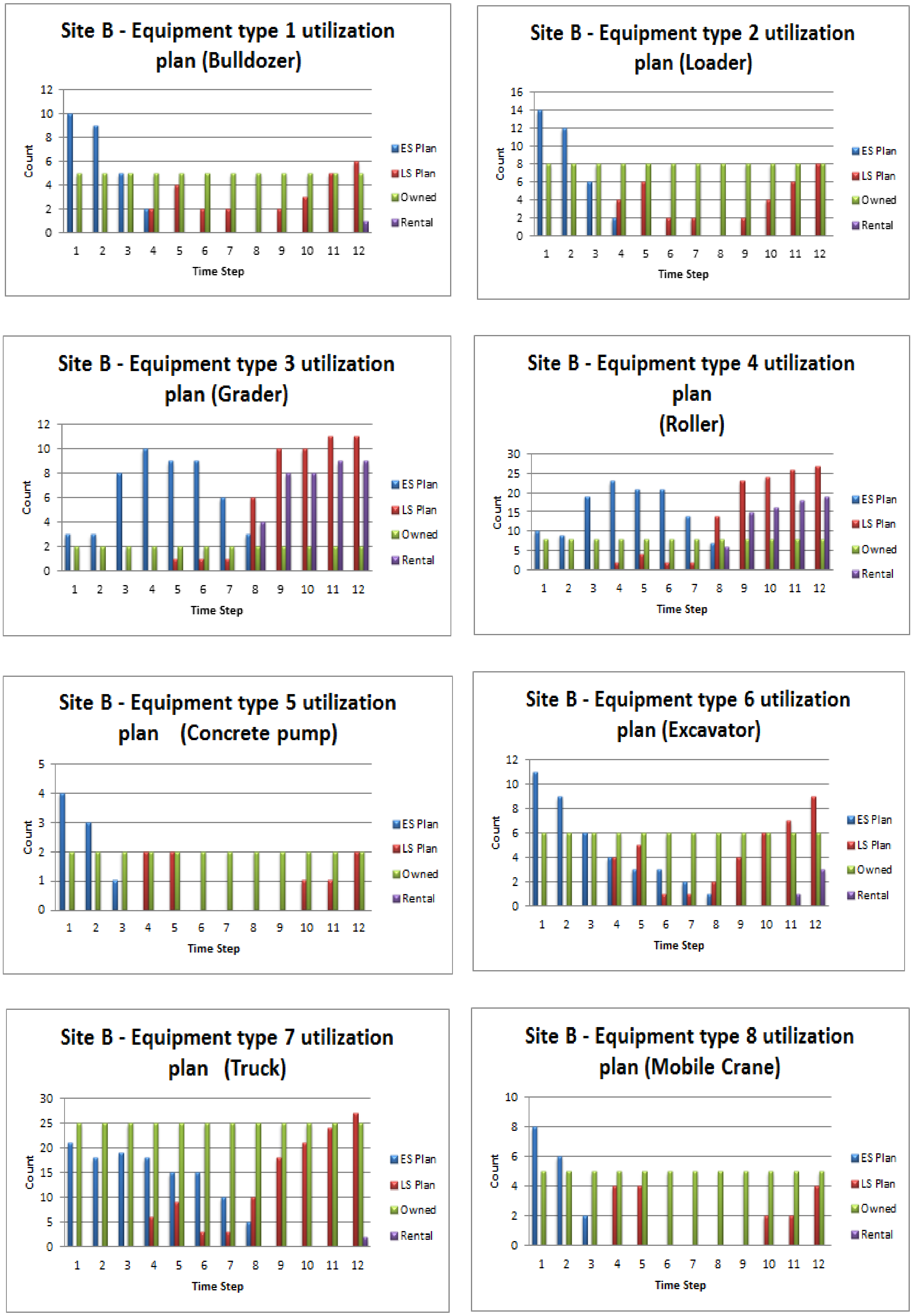
RCPSP						t											
Node (j)	Demand / Provided equipment	Equipment type(S)	Equipment Name	Ownership Status (Owned/Rental)	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12
Total	Demand	1	Bulldozer		ES	36	36	34	27	25	25	25	25	20	13	11	8
		2	loader		ES	68	76	68	51	43	41	40	38	33	20	16	10
		3	Grader		ES	19	20	31	30	27	27	24	21	16	8	8	2
		4	Roller		ES	70	75	91	83	75	75	66	59	50	25	25	7
		5	Concrete pump		ES	29	44	38	35	26	23	22	17	16	5	5	3
		6	Excvator		ES	57	64	59	43	39	38	36	32	26	15	12	9
		7	Truck		ES	162	190	185	152	130	125	119	103	83	55	45	26
		8	Mobile Crane		ES	30	34	28	23	20	20	20	17	16	9	8	7
Total	Demand	1	Bulldozer		LS	7	10	12	17	26	26	26	24	29	34	36	38
		2	loader		LS	9	15	19	28	41	39	44	42	49	68	72	78
		3	Grader		LS	2	8	8	8	13	19	19	24	30	33	34	35
		4	Roller		LS	7	25	26	34	47	55	56	68	82	95	101	105
		5	Concrete pump		LS	2	4	5	13	19	17	25	25	30	39	40	44
		6	Excvator		LS	8	11	15	23	34	32	36	37	42	60	64	68
		7	Truck		LS	25	44	55	74	105	101	117	124	143	188	194	205
		8	Mobile Crane		LS	6	7	9	17	21	17	19	19	22	29	31	35
Total	Number of owned equipment provided (X)	1	Bulldozer	Owned		20	20	20	20	20	20	20	20	20	20	20	20
		2	loader	Owned		32	32	32	32	32	32	32	32	32	32	32	32
		3	Grader	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		4	Roller	Owned		32	32	32	32	32	32	32	32	32	32	32	32
		5	Concrete pump	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		6	Excvator	Owned		24	24	24	24	24	24	24	24	24	24	24	24
		7	Truck	Owned		100	100	100	100	100	100	100	100	100	100	100	100
		8	Mobile Crane	Owned		20	20	20	20	20	20	20	20	20	20	20	20
Total	Number of owned equipment provided (Y)	1	Bulldozer	Rental		0	3	3	4	9	11	11	11	14	16	16	18
		2	loader	Rental		0	5	5	6	14	16	18	18	23	40	42	46
		3	Grader	Rental		0	6	6	6	8	14	14	18	24	25	26	27
		4	Roller	Rental		0	15	15	16	20	30	30	36	50	63	69	73
		5	Concrete pump	Rental		0	0	0	6	11	11	19	19	24	32	33	36
		6	Excvator	Rental		0	1	1	3	12	14	17	17	20	36	40	44
		7	Truck	Rental		0	9	9	14	32	34	45	45	56	92	95	105
		8	Mobile Crane	Rental		0	0	0	0	2	2	4	4	7	12	14	16

Note: Start of the day is the measuring point

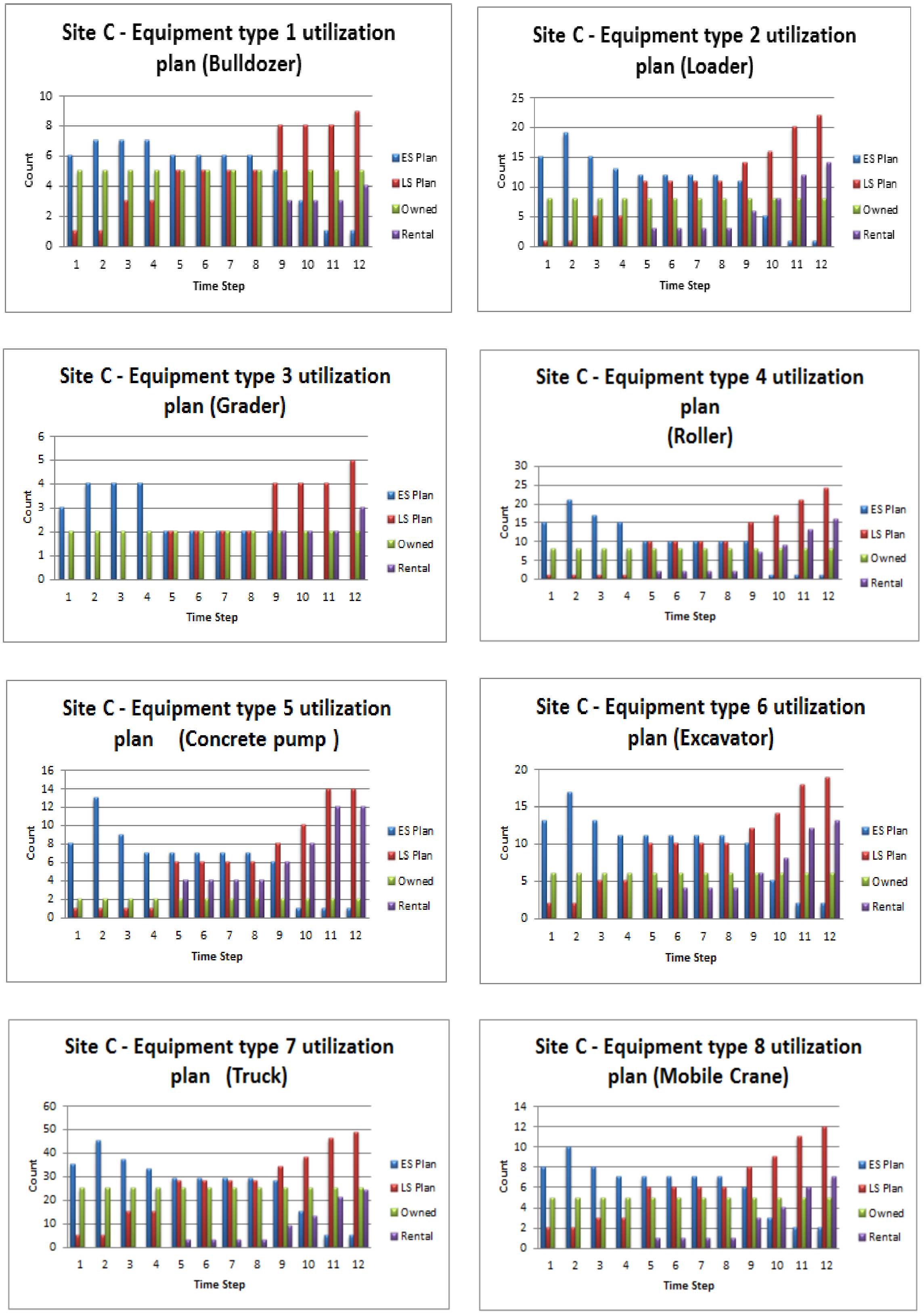
Appendix I. Table 2. - Equipment demand and supply patterns for both ES and optimal schedules for each jobsite individually and for the portfolio as a whole; case study # 1-2



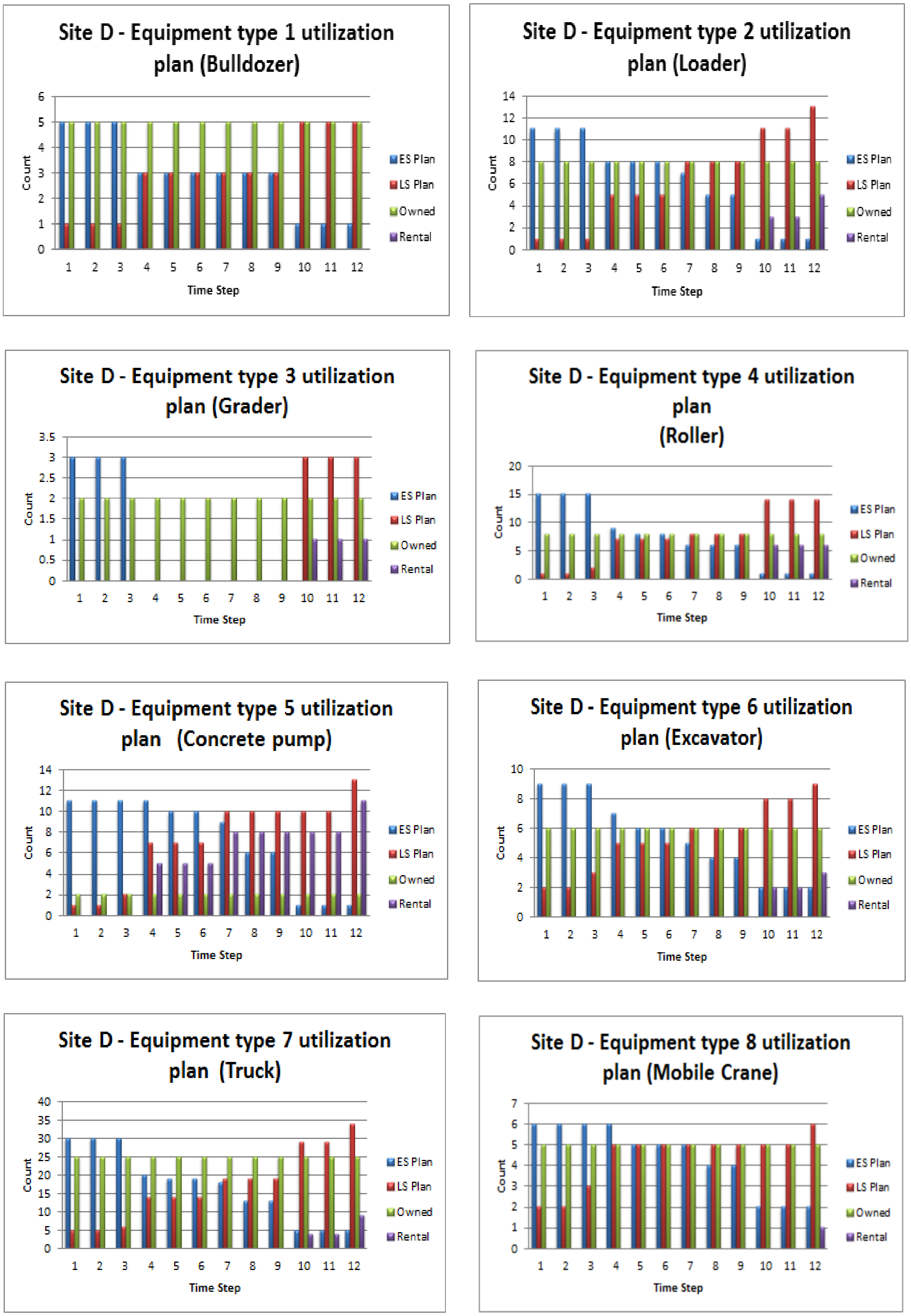
Appendix I. Figure 8- Equipment demand and supply patterns for jobsite A; case study # 1-2



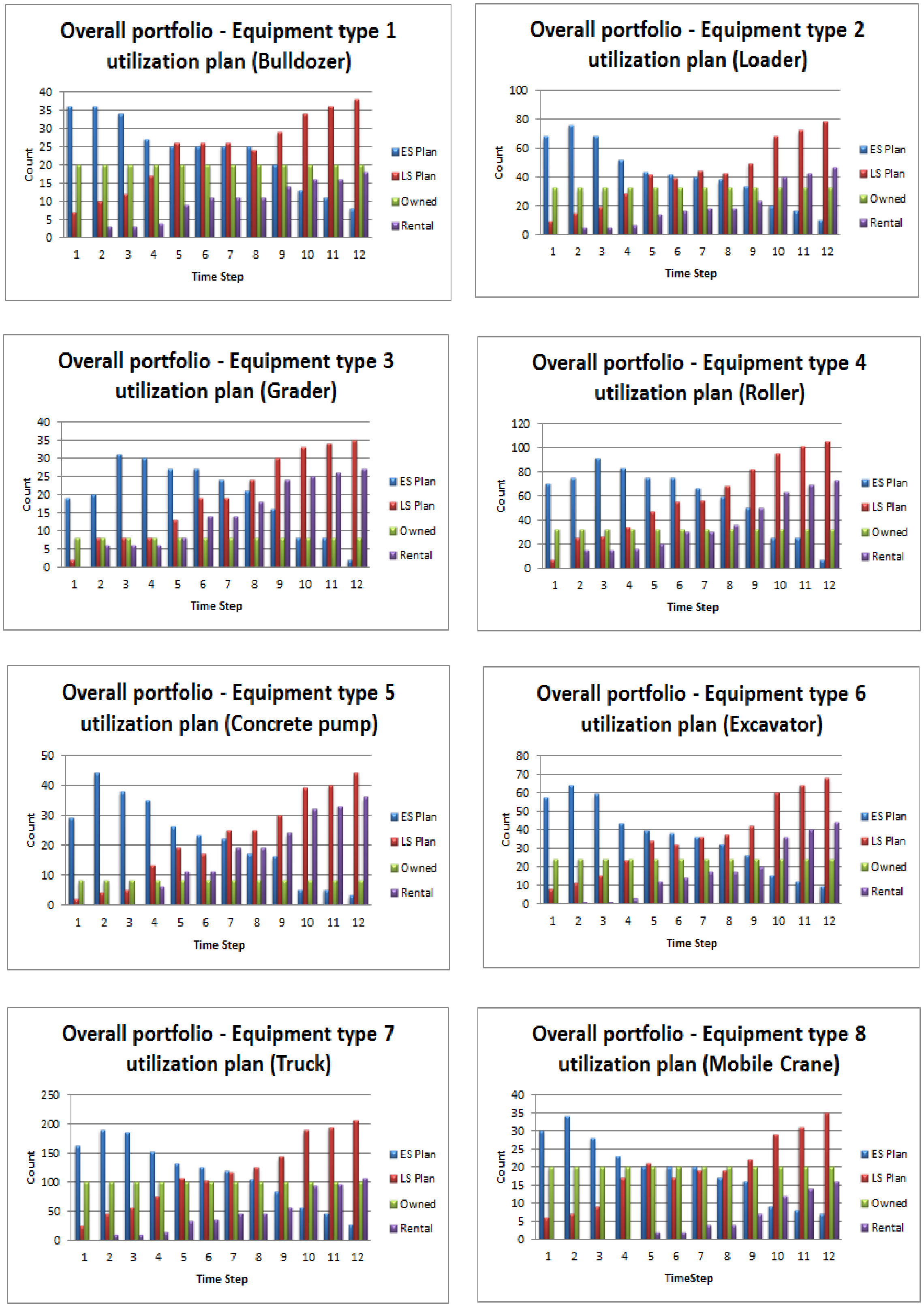
Appendix I. Figure 9- Equipment demand and supply patterns for jobsite B; case study # 1-2



Appendix I. Figure 10- Equipment demand and supply patterns for jobsite C; case study # 1-2



Appendix I. Figure 11- Equipment demand and supply patterns for jobsite D; case study # 1-2



Appendix I. Figure 12- Equipment demand and supply patterns for the whole portfolio; case study # 1-2

Case study # 1-4:

RCPSP				t												CPM Calculations					
Node (j)	Activity # (a)	Activity Description	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12	ES	LS	EF	LF	D	Link
A	1	Temporary service roads construction	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
A	2	Temporary service buildings construction	ES	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
			Optimal	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
A	3	Temporary site work	ES	1	1	1	1	1	1	1	1	1	1	1		1	2	12	13	11	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1		1	2	12	13	11	N
A	4	Aggregate production plant	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
A	5	Dam body construction-Bench marks	ES					1	1	1	1	1	1	1	1	5	5	13	13	8	N
			Optimal					1	1	1	1	1	1	1	1	5	5	13	13	8	N
A	6	Dam body - left wing - excavation - level 1	ES	1	1	1	1	1	1	1	1					1	5	9	13	8	N
			Optimal	1	1	1	1	1	1	1	1					1	5	9	13	8	N
A	7	Dam body - left wing -leveling	ES			1	1	1	1	1	1	1				3	6	10	13	7	6ss+2
			Optimal			1	1	1	1	1	1	1				3	6	10	13	7	6ss+2
A	8	Dam body - left wing -trench temporary protection	ES		1	1	1	1	1	1						2	7	8	13	6	6ss+1
			Optimal		1	1	1	1	1	1						2	7	8	13	6	6ss+1
A	9	Dam body - right wing - excavation - level 1	ES	1	1	1	1	1	1	1	1					1	5	9	13	8	N
			Optimal	1	1	1	1	1	1	1	1					1	5	9	13	8	N
A	10	Dam body - right wing -leveling	ES			1	1	1	1	1	1	1				3	6	10	13	7	9ss+2
			Optimal			1	1	1	1	1	1	1				3	6	10	13	7	9ss+2
A	11	Dam body - right wing -trench temporary protection	ES		1	1	1	1	1	1						2	7	8	13	6	9ss+1
			Optimal		1	1	1	1	1	1						2	7	8	13	6	9ss+1
A	12	Dam body - rockfill	ES	1	1	1	1	1	1	1	1	1	1	1		1	2	12	13	11	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1		1	2	12	13	11	N
A	13	Dam body - concrete face	ES		1	1	1	1								2	7	6	11	4	12ss+1
			Optimal		1	1	1	1								2	7	6	11	4	12ss+1
A	14	Gallery construction - middle section - concrete lining	ES	1	1	1	1									1	9	5	13	4	N
			Optimal	1	1	1	1									1	9	5	13	4	N
A	15	Gallery construction - left wing - excavation	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
A	16	Gallery construction - left wing - leveling	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
A	17	Gallery construction - left wing - concrete lining	ES		1	1	1									2	10	5	13	3	16ss+1
			Optimal		1	1	1									2	10	5	13	3	16ss+1
A	18	Gallery construction - right wing - excavation	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
A	19	Gallery construction - right wing - leveling	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
A	20	Gallery construction - right wing - concrete lining	ES		1	1	1									2	10	5	13	3	19ss+1
			Optimal		1	1	1									2	10	5	13	3	19ss+1
B	1	Segment #1 - water pipeline relocation	ES	1	1											1	4	3	6	2	N
			Optimal	1	1											1	4	3	6	2	N
B	2	Segment #1 - structures - canal - derivation	ES	1	1	1										1	5	4	8	3	N
			Optimal	1	1	1										1	5	4	8	3	N
B	3	Segment #2 - water pipeline relocation	ES	1	1											1	4	3	6	2	N
			Optimal	1	1											1	4	3	6	2	N
B	4	Segment #3 - water pipeline relocation	ES	1												1	12	2	13	1	N
			Optimal	1												1	12	2	13	1	N
B	5	Segment #4 - water pipeline relocation	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
B	6	Segment #4 - structures - bridges - derivation	ES	1	1											1	11	3	13	2	N
			Optimal	1	1											1	11	3	13	2	N
B	7	Segment #5 - structures - bridges - derivation	ES	1	1	1	1									1	9	5	13	4	N
			Optimal	1	1	1	1									1	9	5	13	4	N
B	8	Segment #1 - pavement - base construction	ES			1	1	1	1	1						3	8	8	13	5	2fs-1
			Optimal			1	1	1	1	1						3	8	8	13	5	2fs-1
B	9	Segment #2 - pavement - sub base construction	ES			1	1	1	1							3	9	7	13	4	3fs
			Optimal			1	1	1	1							3	9	7	13	4	3fs
B	10	Segment #2 - pavement - base construction	ES				1	1	1	1	1					4	8	9	13	5	9ss+1
			Optimal				1	1	1	1	1					4	8	9	13	5	9ss+1

RCPSP				t												CPM Calculations					
Node (j)	Activity # (a)	Activity Description	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12	ES	LS	EF	LF	D	Link
C	1	Temporary service buildings construction	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
C	2	Aggregate production plant	ES	1	1	1	1	1	1	1	1	1	1			1	3	11	13	10	N
			Optimal	1	1	1	1	1	1	1	1	1	1			1	3	11	13	10	N
C	3	Execution phase - segments 2,3,4 &5 - Bench marks	ES					1	1	1	1					5	9	9	13	4	N
			Optimal					1	1	1	1					5	9	9	13	4	N
C	4	Segment #2 - main road construction operation	ES		1	1	1	1	1	1	1	1				2	5	10	13	8	N
			Optimal		1	1	1	1	1	1	1	1				2	5	10	13	8	N
C	5	Segment #2 - structures - culverts	ES		1	1	1	1	1	1	1	1				2	5	10	13	8	4ss
			Optimal		1	1	1	1	1	1	1	1				2	5	10	13	8	4ss
C	6	Segment #2 - structures - retaining walls	ES		1	1	1	1	1	1	1	1				2	5	10	13	8	4ss
			Optimal		1	1	1	1	1	1	1	1				2	5	10	13	8	4ss
C	7	Segment #5 - main road construction operation	ES	1	1	1	1									1	9	5	13	4	N
			Optimal	1	1	1	1									1	9	5	13	4	N
C	8	Segment #5 - structures - round about	ES	1	1											1	11	3	13	2	N
			Optimal	1	1											1	11	3	13	2	N
C	9	Segment #5 - structures - culverts	ES	1	1											1	11	3	13	2	7ss
			Optimal	1	1											1	11	3	13	2	7ss
C	10	Segment #5 - structures - retaining walls	ES	1	1	1										1	10	4	13	3	7ss
			Optimal	1	1	1										1	10	4	13	3	7ss
C	11	Segment #5 - structures - geogrid structures	ES	1												1	12	2	13	1	N
			Optimal	1												1	12	2	13	1	N
D	1	Tower crane installation	ES	1	1	1	1									1	3	5	7	4	N
			Optimal	1	1	1	1									1	3	5	7	4	N
D	2	Concrete mix test	ES	1	1	1	1	1	1							1	7	7	13	6	N
			Optimal	1	1	1	1	1	1							1	7	7	13	6	N
D	3	Coffer dam construction - core	ES	1	1	1										1	10	4	13	3	N
			Optimal	1	1	1										1	10	4	13	3	N
D	4	Coffer dam construction - shell	ES	1	1	1										1	10	4	13	3	3ss
			Optimal	1	1	1										1	10	4	13	3	3ss
D	5	Dam body - non reinforced structural concrete	ES	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
			Optimal	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
D	6	Dam body - reinforced structural concrete	ES	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
			Optimal	1	1	1	1	1	1	1	1	1				1	4	10	13	9	N
D	7	Left wing gallery - bottom lining	ES	1												1	12	2	13	1	N
			Optimal	1												1	12	2	13	1	N
D	8	Left wing gallery - crown lining	ES		1	1	1	1	1	1						2	7	8	13	6	7fs
			Optimal		1	1	1	1	1	1						2	7	8	13	6	7fs
D	9	Permanent buildings construction	ES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N
			Optimal	1	1	1	1	1	1	1	1	1	1	1	1	1	1	13	13	12	N

Note: Start of the day is the measuring point

Appendix I. Figure 13- ES and optimal master schedule of the portfolio; case study # 1-4

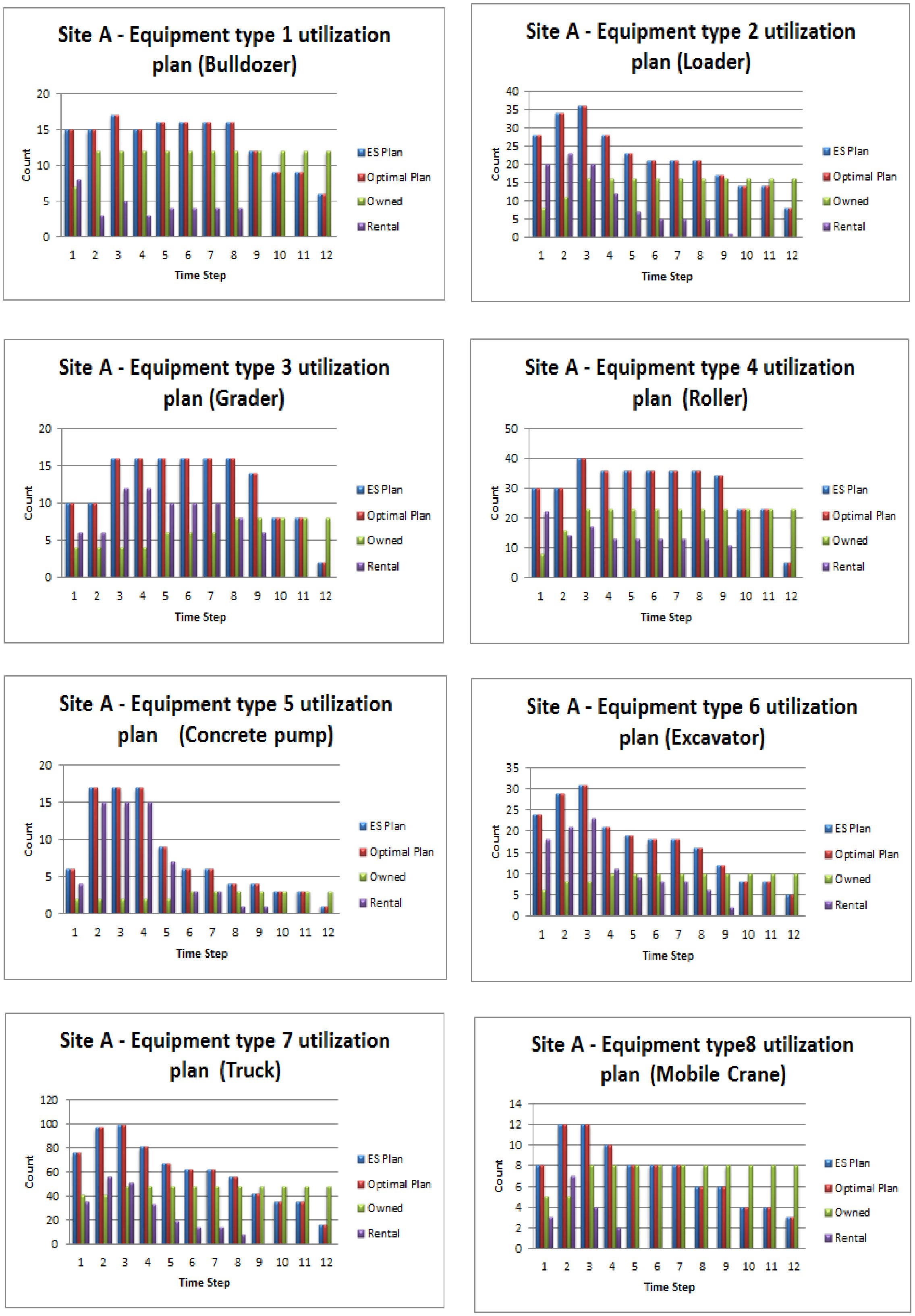
RCPSP						t											
Node (j)	Demand / Provided equipment	Equipment type(S)	Equipment Name	Ownership Status (Owned/Rental)	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12
A	Demand	1	Bulldozer		ES	15	15	17	15	16	16	16	16	12	9	9	6
		2	loader		ES	28	34	36	28	23	21	21	21	17	14	14	8
		3	Grader		ES	10	10	16	16	16	16	16	16	14	8	8	2
		4	Roller		ES	30	30	40	36	36	36	36	36	34	23	23	5
		5	Concrete pump		ES	6	17	17	17	9	6	6	4	4	3	3	1
		6	Excvator		ES	24	29	31	21	19	18	18	16	12	8	8	5
		7	Truck		ES	76	97	99	81	67	62	62	56	42	35	35	16
		8	Mobile Crane		ES	8	12	12	10	8	8	8	6	6	4	4	3
A	Demand	1	Bulldozer		Optimal	15	15	17	15	16	16	16	16	12	9	9	6
		2	loader		Optimal	28	34	36	28	23	21	21	21	17	14	14	8
		3	Grader		Optimal	10	10	16	16	16	16	16	16	14	8	8	2
		4	Roller		Optimal	30	30	40	36	36	36	36	36	34	23	23	5
		5	Concrete pump		Optimal	6	17	17	17	9	6	6	4	4	3	3	1
		6	Excvator		Optimal	24	29	31	21	19	18	18	16	12	8	8	5
		7	Truck		Optimal	76	97	99	81	67	62	62	56	42	35	35	16
		8	Mobile Crane		Optimal	8	12	12	10	8	8	8	6	6	4	4	3
A	Number of owned equipment provided (X)	1	Bulldozer	Owned		7	12	12	12	12	12	12	12	12	12	12	12
		2	loader	Owned		8	11	16	16	16	16	16	16	16	16	16	16
		3	Grader	Owned		4	4	4	4	6	6	6	8	8	8	8	8
		4	Roller	Owned		8	16	23	23	23	23	23	23	23	23	23	23
		5	Concrete pump	Owned		2	2	2	2	2	3	3	3	3	3	3	3
		6	Excvator	Owned		6	8	8	10	10	10	10	10	10	10	10	10
		7	Truck	Owned		41	41	48	48	48	48	48	48	48	48	48	48
		8	Mobile Crane	Owned		5	5	8	8	8	8	8	8	8	8	8	8
A	Number of rental equipment provided (Y)	1	Bulldozer	Rental		8	3	5	3	4	4	4	4	0	0	0	0
		2	loader	Rental		20	23	20	12	7	5	5	5	1	0	0	0
		3	Grader	Rental		6	6	12	12	10	10	10	8	6	0	0	0
		4	Roller	Rental		22	14	17	13	13	13	13	13	11	0	0	0
		5	Concrete pump	Rental		4	15	15	15	7	3	3	1	1	0	0	0
		6	Excvator	Rental		18	21	23	11	9	8	8	6	2	0	0	0
		7	Truck	Rental		35	56	51	33	19	14	14	8	0	0	0	0
		8	Mobile Crane	Rental		3	7	4	2	0	0	0	0	0	0	0	0
B	Demand	1	Bulldozer		ES	10	9	5	2	0	0	0	0	0	0	0	0
		2	loader		ES	14	12	6	2	0	0	0	0	0	0	0	0
		3	Grader		ES	3	3	8	10	9	9	6	3	0	0	0	0
		4	Roller		ES	10	9	19	23	21	21	14	7	0	0	0	0
		5	Concrete pump		ES	4	3	1	0	0	0	0	0	0	0	0	0
		6	Excvator		ES	11	9	6	4	3	3	2	1	0	0	0	0
		7	Truck		ES	21	18	19	18	15	15	10	5	0	0	0	0
		8	Mobile Crane		ES	8	6	2	0	0	0	0	0	0	0	0	0
B	Demand	1	Bulldozer		Optimal	10	9	5	2	0	0	0	0	0	0	0	0
		2	loader		Optimal	14	12	6	2	0	0	0	0	0	0	0	0
		3	Grader		Optimal	3	3	8	10	9	9	6	3	0	0	0	0
		4	Roller		Optimal	10	9	19	23	21	21	14	7	0	0	0	0
		5	Concrete pump		Optimal	4	3	1	0	0	0	0	0	0	0	0	0
		6	Excvator		Optimal	11	9	6	4	3	3	2	1	0	0	0	0
		7	Truck		Optimal	21	18	19	18	15	15	10	5	0	0	0	0
		8	Mobile Crane		Optimal	8	6	2	0	0	0	0	0	0	0	0	0
B	Number of owned equipment provided (X)	1	Bulldozer	Owned		5	0	0	0	0	0	0	0	0	0	0	0
		2	loader	Owned		8	8	3	0	0	0	0	0	0	0	0	0
		3	Grader	Owned		2	2	2	2	2	2	2	0	0	0	0	0
		4	Roller	Owned		8	2	2	2	2	2	2	2	2	2	2	2
		5	Concrete pump	Owned		2	0	0	0	0	0	0	0	0	0	0	0
		6	Excvator	Owned		6	4	4	3	3	0	0	0	0	0	0	0
		7	Truck	Owned		9	9	9	9	9	5	5	5	5	5	5	5
		8	Mobile Crane	Owned		5	5	0	0	0	0	0	0	0	0	0	0
B	Number of rental equipment provided (Y)	1	Bulldozer	Rental		5	9	5	2	0	0	0	0	0	0	0	0
		2	loader	Rental		6	4	3	2	0	0	0	0	0	0	0	0
		3	Grader	Rental		1	1	6	8	7	7	4	3	0	0	0	0
		4	Roller	Rental		2	7	17	21	19	19	12	5	0	0	0	0
		5	Concrete pump	Rental		2	3	1	0	0	0	0	0	0	0	0	0
		6	Excvator	Rental		5	5	2	1	0	3	2	1	0	0	0	0
		7	Truck	Rental		12	9	10	9	6	10	5	0	0	0	0	0
		8	Mobile Crane	Rental		3	1	2	0	0	0	0	0	0	0	0	0

RCPSP						t											
Node (i)	Demand / Provided equipment	Equipment type(S)	Equipment Name	Ownership Status (Owned/Rental)	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12
C	Demand	1	Bulldozer		ES	6	7	7	7	6	6	6	6	5	3	1	1
		2	loader		ES	15	19	15	13	12	12	12	12	11	5	1	1
		3	Grader		ES	3	4	4	4	2	2	2	2	2	0	0	0
		4	Roller		ES	15	21	17	15	10	10	10	10	10	1	1	1
		5	Concrete pump		ES	8	13	9	7	7	7	7	7	6	1	1	1
		6	Excvator		ES	13	17	13	11	11	11	11	11	10	5	2	2
		7	Truck		ES	35	45	37	33	29	29	29	29	28	15	5	5
		8	Mobile Crane		ES	8	10	8	7	7	7	7	7	6	3	2	2
C	Demand	1	Bulldozer		Optimal	6	7	7	7	6	6	6	6	5	3	1	1
		2	loader		Optimal	15	19	15	13	12	12	12	12	11	5	1	1
		3	Grader		Optimal	3	4	4	4	2	2	2	2	2	0	0	0
		4	Roller		Optimal	15	21	17	15	10	10	10	10	10	1	1	1
		5	Concrete pump		Optimal	8	13	9	7	7	7	7	7	6	1	1	1
		6	Excvator		Optimal	13	17	13	11	11	11	11	11	10	5	2	2
		7	Truck		Optimal	35	45	37	33	29	29	29	29	28	15	5	5
		8	Mobile Crane		Optimal	8	10	8	7	7	7	7	7	6	3	2	2
C	Number of owned equipment provided (X)	1	Bulldozer	Owned		5	5	5	5	5	5	5	5	5	5	5	5
		2	loader	Owned		8	8	8	11	11	11	11	11	11	11	11	11
		3	Grader	Owned		2	2	2	2	0	0	0	0	0	0	0	0
		4	Roller	Owned		8	8	1	1	1	1	1	1	1	1	1	1
		5	Concrete pump	Owned		2	2	2	2	2	1	1	1	1	1	1	1
		6	Excvator	Owned		6	6	6	7	7	10	10	10	10	10	10	10
		7	Truck	Owned		25	25	25	25	25	29	29	29	29	29	29	29
		8	Mobile Crane	Owned		5	5	7	7	7	7	7	7	7	7	7	7
C	Number of rental equipment provided (Y)	1	Bulldozer	Rental		1	2	2	2	1	1	1	1	0	0	0	0
		2	loader	Rental		7	11	7	2	1	1	1	1	0	0	0	0
		3	Grader	Rental		1	2	2	2	2	2	2	2	2	0	0	0
		4	Roller	Rental		7	13	16	14	9	9	9	9	9	0	0	0
		5	Concrete pump	Rental		6	11	7	5	5	6	6	6	5	0	0	0
		6	Excvator	Rental		7	11	7	4	4	1	1	1	0	0	0	0
		7	Truck	Rental		10	20	12	8	4	0	0	0	0	0	0	0
		8	Mobile Crane	Rental		3	5	1	0	0	0	0	0	0	0	0	0
D	Demand	1	Bulldozer		ES	5	5	5	3	3	3	3	3	3	1	1	1
		2	loader		ES	11	11	11	8	8	8	7	5	5	1	1	1
		3	Grader		ES	3	3	3	0	0	0	0	0	0	0	0	0
		4	Roller		ES	15	15	15	9	8	8	6	6	6	1	1	1
		5	Concrete pump		ES	11	11	11	11	10	10	9	6	6	1	1	1
		6	Excvator		ES	9	9	9	7	6	6	5	4	4	2	2	2
		7	Truck		ES	30	30	30	20	19	19	18	13	13	5	5	5
		8	Mobile Crane		ES	6	6	6	6	5	5	5	4	4	2	2	2
D	Demand	1	Bulldozer		Optimal	5	5	5	3	3	3	3	3	3	1	1	1
		2	loader		Optimal	11	11	11	8	8	8	7	5	5	1	1	1
		3	Grader		Optimal	3	3	3	0	0	0	0	0	0	0	0	0
		4	Roller		Optimal	15	15	15	9	8	8	6	6	6	1	1	1
		5	Concrete pump		Optimal	11	11	11	11	10	10	9	6	6	1	1	1
		6	Excvator		Optimal	9	9	9	7	6	6	5	4	4	2	2	2
		7	Truck		Optimal	30	30	30	20	19	19	18	13	13	5	5	5
		8	Mobile Crane		Optimal	6	6	6	6	5	5	5	4	4	2	2	2
D	Number of owned equipment provided (X)	1	Bulldozer	Owned		3	3	3	3	3	3	3	3	3	3	3	3
		2	loader	Owned		8	5	5	5	5	5	5	5	5	5	5	5
		3	Grader	Owned		0	0	0	0	0	0	0	0	0	0	0	0
		4	Roller	Owned		8	6	6	6	6	6	6	6	6	6	6	6
		5	Concrete pump	Owned		2	4	4	4	4	4	4	4	4	4	4	4
		6	Excvator	Owned		6	6	6	4	4	4	4	4	4	4	4	4
		7	Truck	Owned		25	25	18	18	18	18	18	18	18	18	18	18
		8	Mobile Crane	Owned		5	5	5	5	5	5	5	5	5	5	5	5
D	Number of rental equipment provided (Y)	1	Bulldozer	Rental		2	2	2	0	0	0	0	0	0	0	0	0
		2	loader	Rental		3	6	6	3	3	3	2	0	0	0	0	0
		3	Grader	Rental		3	3	3	0	0	0	0	0	0	0	0	0
		4	Roller	Rental		7	9	9	3	2	2	0	0	0	0	0	0
		5	Concrete pump	Rental		9	7	7	7	6	6	5	2	2	0	0	0
		6	Excvator	Rental		3	3	3	3	2	2	1	0	0	0	0	0
		7	Truck	Rental		5	5	12	2	1	1	0	0	0	0	0	0
		8	Mobile Crane	Rental		1	1	1	1	0	0	0	0	0	0	0	0

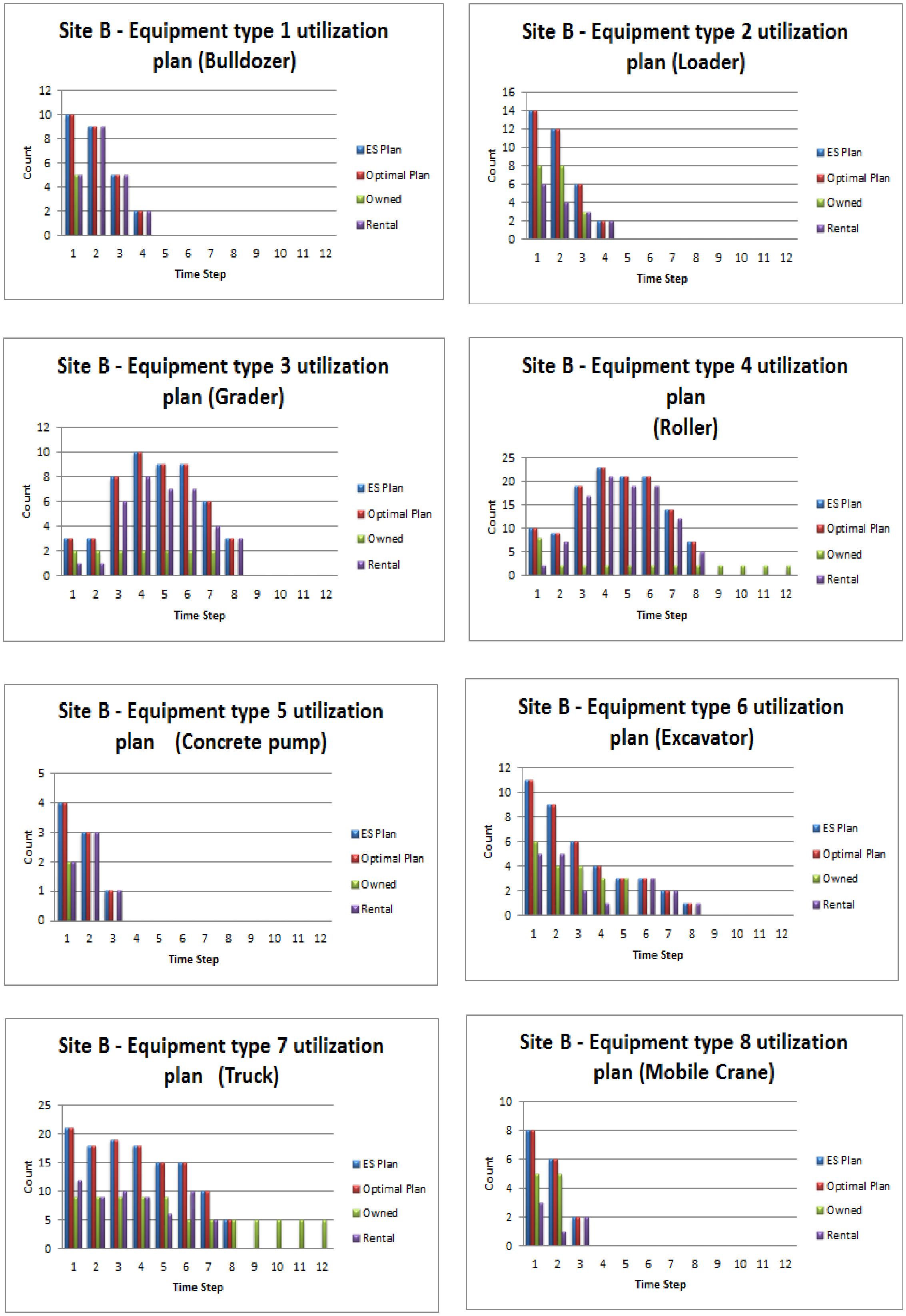
RCPSP						t											
Node (j)	Demand / Provided equipment	Equipment type(S)	Equipment Name	Ownership Status (Owned/Rental)	Schedule type	1	2	3	4	5	6	7	8	9	10	11	12
Total	Demand	1	Bulldozer		ES	36	36	34	27	25	25	25	25	20	13	11	8
		2	loader		ES	68	76	68	51	43	41	40	38	33	20	16	10
		3	Grader		ES	19	20	31	30	27	27	24	21	16	8	8	2
		4	Roller		ES	70	75	91	83	75	75	66	59	50	25	25	7
		5	Concrete pump		ES	29	44	38	35	26	23	22	17	16	5	5	3
		6	Excvator		ES	57	64	59	43	39	38	36	32	26	15	12	9
		7	Truck		ES	162	190	185	152	130	125	119	103	83	55	45	26
		8	Mobile Crane		ES	30	34	28	23	20	20	20	17	16	9	8	7
Total	Demand	1	Bulldozer		Optimal	36	36	34	27	25	25	25	25	20	13	11	8
		2	loader		Optimal	68	76	68	51	43	41	40	38	33	20	16	10
		3	Grader		Optimal	19	20	31	30	27	27	24	21	16	8	8	2
		4	Roller		Optimal	70	75	91	83	75	75	66	59	50	25	25	7
		5	Concrete pump		Optimal	29	44	38	35	26	23	22	17	16	5	5	3
		6	Excvator		Optimal	57	64	59	43	39	38	36	32	26	15	12	9
		7	Truck		Optimal	162	190	185	152	130	125	119	103	83	55	45	26
		8	Mobile Crane		Optimal	30	34	28	23	20	20	20	17	16	9	8	7
Total	Number of owned equipment provided (X)	1	Bulldozer	Owned		20	20	20	20	20	20	20	20	20	20	20	20
		2	loader	Owned		32	32	32	32	32	32	32	32	32	32	32	32
		3	Grader	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		4	Roller	Owned		32	32	32	32	32	32	32	32	32	32	32	32
		5	Concrete pump	Owned		8	8	8	8	8	8	8	8	8	8	8	8
		6	Excvator	Owned		24	24	24	24	24	24	24	24	24	24	24	24
		7	Truck	Owned		100	100	100	100	100	100	100	100	100	100	100	100
		8	Mobile Crane	Owned		20	20	20	20	20	20	20	20	20	20	20	20
Total	Number of rental equipment provided (Y)	1	Bulldozer	Rental		16	16	14	7	5	5	5	5	0	0	0	0
		2	loader	Rental		36	44	36	19	11	9	8	6	1	0	0	0
		3	Grader	Rental		11	12	23	22	19	19	16	13	8	0	0	0
		4	Roller	Rental		38	43	59	51	43	43	34	27	20	0	0	0
		5	Concrete pump	Rental		21	36	30	27	18	15	14	9	8	0	0	0
		6	Excvator	Rental		33	40	35	19	15	14	12	8	2	0	0	0
		7	Truck	Rental		62	90	85	52	30	25	19	8	0	0	0	0
		8	Mobile Crane	Rental		10	14	8	3	0	0	0	0	0	0	0	0

Note: Start of the day is the measuring point

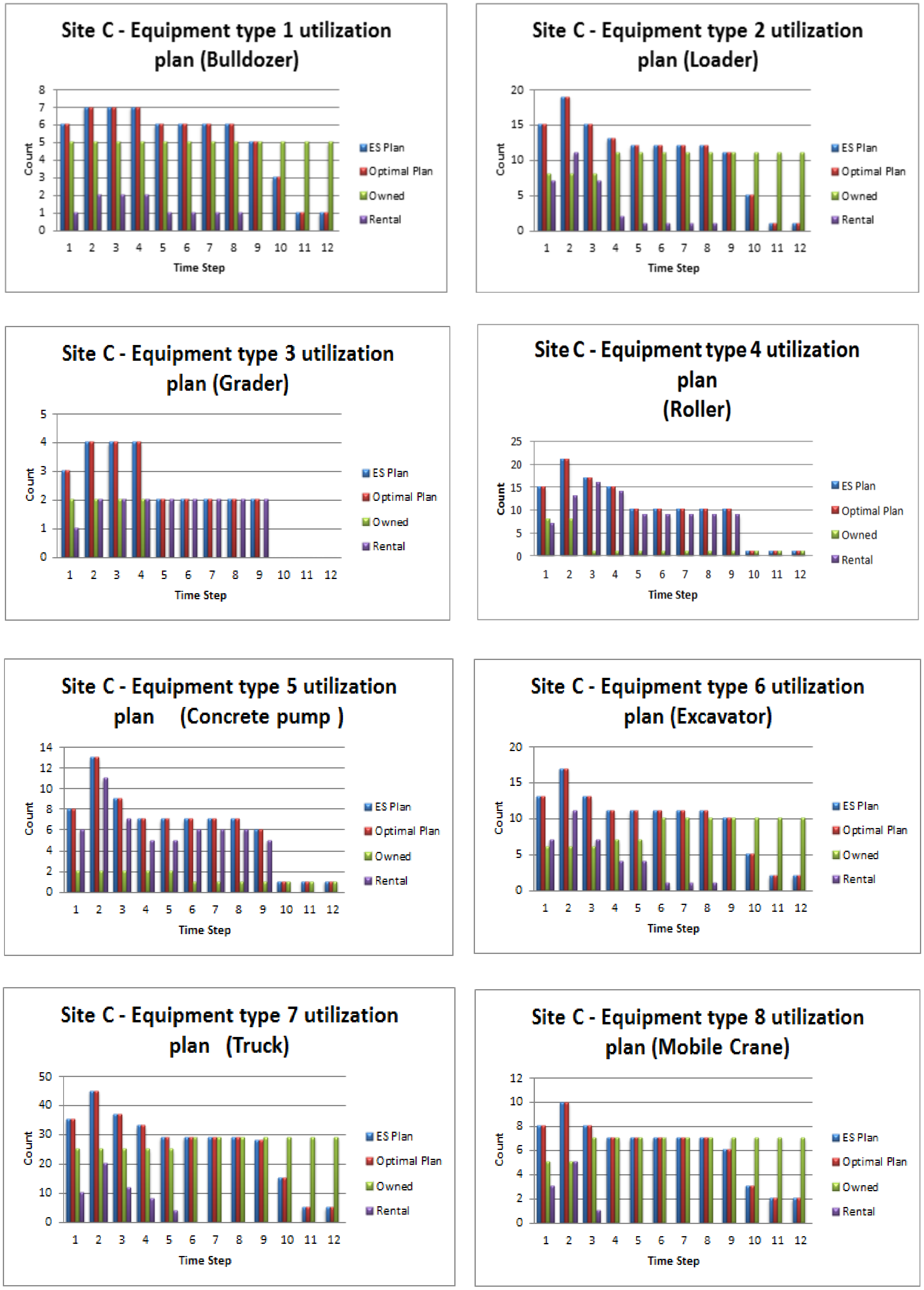
Appendix I. Table 3. - Equipment demand and supply patterns for both ES and optimal schedules for each jobsite individually and for the portfolio as a whole; case study # 1-4



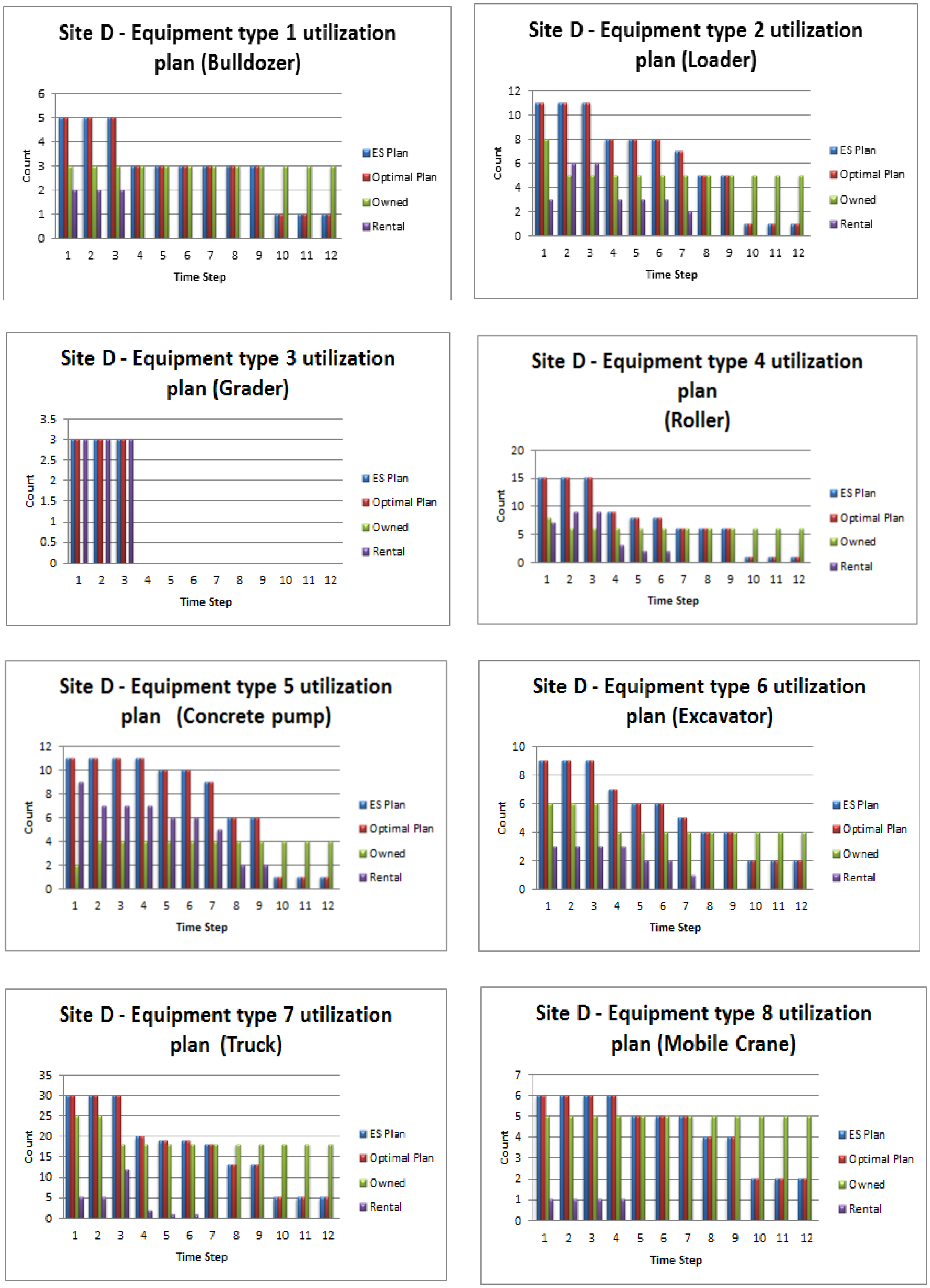
Appendix I. Figure 14- Equipment demand and supply patterns for jobsite A; case study # 1-4



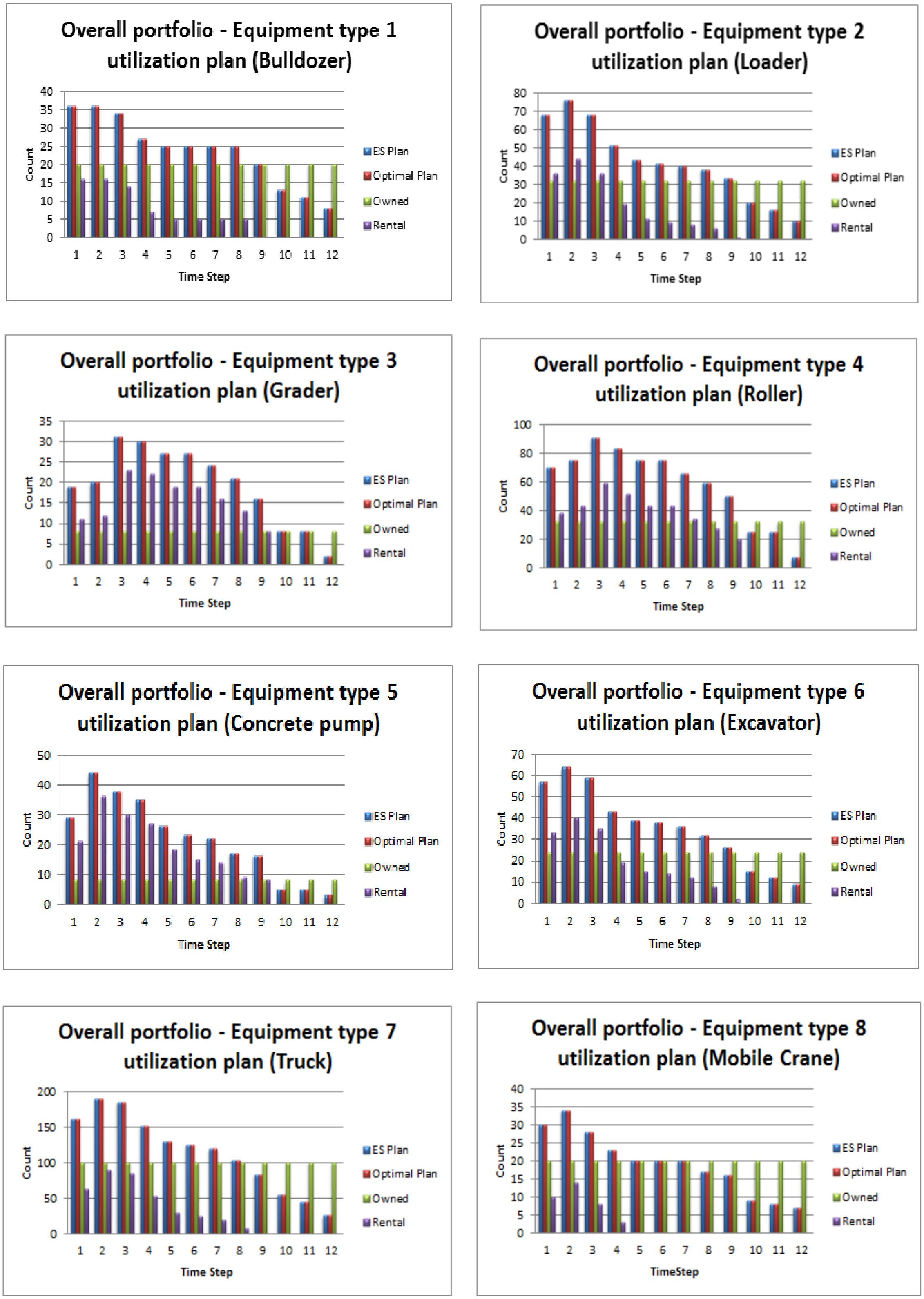
Appendix I. Figure 15- Equipment demand and supply patterns for jobsite B; case study # 1-4



Appendix I. Figure 16- Equipment demand and supply patterns for jobsite C; case study # 1-4



Appendix I. Figure 17- Equipment demand and supply patterns for jobsite D; case study # 1-4



Appendix I. Figure 18- Equipment demand and supply patterns for the whole portfolio; case study # 1-4

References

- Adlakha, V. G., & Kulkarni, V. G. (1989). A classified bibliography of research on stochastic PERT networks:1966-1987. *INFOR* , 272-296.
- Badger, A. (1974). Interrelating project estimates to CPM schedules. *AACE Transactions(18)* , 38-42.
- Baptiste, P., Pape, C. L., & Nuijten, W. (2001). *Constraint Based Scheduling; Applying Constraint Programming to scheduling problems.* Norwell, Massachusetts: Kluwer Academic Publisher.
- Battersby, A. (1970). *Network Analysis for Planning and Scheduling.* New York: J. Wiley.
- Bellmann, R., Esogbue, A. O., & Nabeshima, I. (1982). *Mathematical Aspects of Scheduling and Applications.* Oxford, U.K.: Pergamon Press.
- Bigelow, C. G. (1962). Bibliography on project planning and control by network analysis: 1959-1961. *Operations Research* , 728-731.
- Blazewicz, J., Ecker, K., Schmidt, G., & Welgarz, J. (1993). *Scheduling in Computer and Manufacturing Systems.* Berlin: Verlag.
- Cantor, D. G., & Dimsdale, B. (1969). On direction-preserving maps of graphs. *Journal of Combinatorial Theory* , 165-176.
- Chan, W. T., Chua, D. K., & Kannan, G. (1996). Construction resource scheduling with genetic algorithms. *Journal of construction engineering and management, 122(2)* , 125-132.

- Chelaka, M., Abeyasinghe, L., Greenwood, D. J., & Johansen, D. E. (2001). An efficient method for scheduling construction projects with resource constraints. *International Journal of Project Management (19)* , 29±45.
- Davis, E. W., & Heidorn, G. E. (1971). An algorithm for optimal project scheduling under multiple resource constraints. *Management Science, 27(2)* , 803-816.
- Davis, E. W., & Patterson, J. H. (1975). A comparison of heuristic and optimum solutions in resource-constrained project scheduling. *Management Science, 21(8)* , 944±55.
- Dayanand, N., & Padman, R. (1993). *Payments in projects: A contractor's model.* Pittsburgh: Carnegie Mellon University.
- Deckro, R. F., & Hebert, J. E. (1992). Resource constrained project crashing. *Omega 17* , 106-111.
- Demeulemeester, E., & Herroelen, W. (2002). *Project Scheduling: A Research Handbook.* Kluwer Academic Publishers.
- Demeulemeester, E., & Herroelen, W. S. (1992). A branchand- bound procedure for the multiple resource-constrained project scheduling problem. *Management Science 38* , 1803-1818.
- Dodin, B., & Elimam, A. A. (2008). Integration of equipment planning and project scheduling. *European Journal of Operational Research* , 962–980 .
- Dorndorf, U., Pesch, E., & Phan Huy, T. (2000). A time oriented branch and bound algorithm for resource-constrained project scheduling with generalized precedence constraints. *Management Science, 46(10)* , 1365-1384.

- Elmaghraby, S. (1977). *Activity Networks: Project Planning and Control by Network Models.* New York: Wiley.
- Elmaghraby, S. E. (1995). Activity nets: A guided tour through some recent developments. *European Journal of Operational Research* , 383-408.
- Elmaghraby, S. E., & Kamburowski, J. (1992). The analysis of activity networks under generalized precedence relations (GPRs). *Management Science* , 1245-1263.
- Elmaghraby, S. E., Kamburowski, J., Michael, D. J., & Stallmann, M. (1993). *Minimizing the complexity of a stochastic PERT network.* Raleigh: North Carolina State University.
- ERNST, A. T., JIANG, H., KRISHAMOORTHY, M., OWENS, B., & CSIRO, D. S. (2004). *An Automated Bibliography of Personnel Scheduling and Rostering.* Clayton South: Mathematical and Information Sciences, Private Bag 10.
- Farid, F., & Boyer, L. T. (1985). Fair and reasonable markup (FARM) pricing model. *Journal of Construction Engineering and Management* , 374-390.
- Gargeya, V. B., & Deane, R. H. (1996). Scheduling research in multiple resource constrained job shops: A review and critique. *International Journal of Production Research* , 2077-2097.
- Gavish, B., & Srikanth, K. (1986). An optimal solution method for large-scale multiple traveling salesmen problems. *Operations Research 34 (5)* , 698–717.
- Goldratt, E. M. (1997). *Critical chain.* The North River Press.
- Harris, R. B. (1990). Packing method for resource leveling. *Journal of construction management, ASCE, 61(2)* , 331-351.

- Harris, R. (1978). *Resource and arrow networking techniques for construction.* New York: Wiley.
- Hegazy, T. (1999). Optimization of resource allocation and leveling using genetic algorithms. *Journal of construction engineering and management* .
- Herroelen, W. (1991). *Operationele Produktieplanning.* Leuven: Acco.
- Herroelen, W., De Reyck, B., & Demeulemeester, E. (1998). RESOURCE-CONSTRAINED PROJECT SCHEDULING: A SURVEY OF RECENT DEVELOPMENTS. *Computers Ops Res. Vol. 25, No. 4* , 279-302.
- Kaplan, L. (1988). Resource constrained project scheduling with preemption of jobs. *Ph.D. Thesis* . Ann Arbor, Michigan, USA: University of Michigan.
- Karshenas, S., & Haber, D. (1990). Economic optimization of construction project scheduling. *J. Constr. Mgmt. and Economics, E&FN Spon* , 135-146.
- Kerzner, H. (1979). *Project Management: A Systems Approach to Planning, Scheduling and Control.* New York: Van Nostrand Reinhold.
- Khattab, M. M., & Choobineh, F. (1991). A new heuristic for project scheduling with a single resource constraint. *Computers and industrial engineering , 20* , pp. 381-387.
- Krishnamoorthy, M. S., & Deo, N. (1979). Complexity of the minimum-dummy-activities problem in a PERT network. *Networks* , 189-194.
- Kumar, V. K., & Rajendran, C. R. (1993). Manpower resource leveling in the maintenance of drillship: a computer simulation approach . *International journal of modeling and simulation, 13(4)* , pp. 152-155.

- Laporte, G. (1992). The traveling salesman problem: An overview of exact and approximate algorithms. *European Journal of Operational Research - 59* , 231–247.
- Lee, Y., & Gatton, T. M. (1994). Construction scheduling based on resource constraints. *AACE Trans. ,3,* , 1-6.
- Lerda-Olberg, S. (1966). Bibliography on network-based project planning and control techniques: 1962-1965. *Operations Research* , 925-931.
- Leu, S., & Yang, C. (1999). GA based multi-criteria optimal model for construction scheduling. *Journal of construction engineering and management, 125(6)* , 420-427.
- Leu, S., Chen, A., & Yang, C. (1999). Fuzzy optimal model for resource-constrained construction scheduling. *journal of computing in civil engineering, 13(3)* , 207-216.
- Lu, M., & Li, H. (July/August 2003). Activity Critical –Path Method for Construction Planning. *Journal of construction engineering and management ,ASCE* .
- Moder, J. P. (1983). *Project Management with CPM and PERT.* New York: Van Nostrand Reinhold.
- Moslehi, A. a. (1993). Least impact algorithm for resource allocation. *Can. J. Civ. Energ., CSCE* , 180-188.
- O'Brien, J. J. (1969). *Scheduling Handbook.* New York: McGraw-Hill.
- Pantouvakis, J. P., & Manoliadis, O. G. (2006). A practical approach to resource-constrained project scheduling. *Operational research* , 299-309.

- Patterson, J. H., & Roth, G. (1976). Scheduling a project under multiple resource constraints: A zero-one programming approach. *liE Transactions 8* , 449-455.
- Patterson, J. H., Slowsinki, P., Talbot, F. B., & Weglarz, J. (1989). An algorithm for a general class of precedence and resource constrained scheduling problems. In R. Slowinski, & J. Weglarz, *Advances in Project Scheduling.* Amsterdam: Elsevier.
- Senouci, A. B., & Adeli, H. (2001). Resource scheduling using neural dynamics model of Adeli and Park. *Journal of construction engineering and management, 127(1)* , 28-34.
- Sepil, C., & Kazaz, B. (1994). *Project scheduling with discounted cash flows and progress payments.*
- Shah, k., Farid, F., & Baugh, J. (1993). optimal resource leveling using integer-linear programming. *5th international conference in computing in civil and building engineering* (pp. 501-508). Reston, VA: ASCE.
- Slowinski, R., & Weglarz, J. (1989). *Advances in Project Scheduling.* Amsterdam: Elsevier Science Publishers.
- Sterboul, F., & Wertheimer, D. (1980). Comment construire un graphe PERT minimal. *RAIRO Recherche Operationhelle* , 85-98.
- Stinson, J. P., Davis, E. W., & Khumawala, B. M. (1978). Multiple resource-constrained scheduling using branch and bound. *AIIE Transactions 10* , 252-259.
- Syslo, M. (1984). On the computational complexity of the minimum dummy activity problem in a PERT network. *Networks* , 37-45.

- Talbot, B. F., & Patterson, J. H. (1978). An efficient integer programming algorithm with network cuts for solving resource-constrained scheduling problems. *Management Science 24* , 1163-1174.
- Trautmann, N., Baumann, P., & Fleischmann, B. (2008). Project Scheduling with Precedence Constraints and Scarce Resources: An Experimental Analysis of Commercial Project Management Software. *Operations Research Proceedings.*
- Whitehouse, G. (1973). *Systems Analysis and Design Using Network Techniques.* Englewood Cliffs, NJ: Prentice-Hall.
- Williams, H. (1990). *Model building in mathematical programming.* Chichester: John Wiley & Sons Ltd.
- Younis, M. A., & Saad, B. (1996). OPTIMAL RESOURCE LEVELING OF MULTI-RESOURCE PROJECTS. *Computers ind. Engng VoL 31,No. 1/2* , 1-4.