FACTORY LEVEL PREVENTIVE MAINTENANCE IN TURKISH AIR FORCE

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By
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August 2006

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

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ABSTRACT

FACTORY LEVEL PREVENTIVE MAINTENANCE IN TURKISH AIR FORCE

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In this thesis, we study the Factory Level Preventive Maintenance Problem (FLPM) experienced by Turkish Air Force (TUAF). This problem is a specific case of Nonpreemptive Resource Constrained Multiple Project Scheduling with Mode Selection (NRCMPSMS); allocation of limited resources to competing activities of multiple project of different types in which the duration of an activity is determined by the mode selection and the activity flow is dependent on the type of the project. The objective is to determine the start (finish) time and the mode of each project's each activity so that the minimal total weighted tardiness and total incurred cost are obtained. We proposed a heuristic for this problem definition which is composed of two phases and apply it to a real life problem experienced by TUAF. In the first phase, the aim is to construct an initial schedule with minimum total weighted tardiness and in the second phase, this schedule is improved in terms of total incurred cost by the mode selection exchanges. Since the activity due date information is not available but required in prioritization of the activities, we develop five FLPM specific activity due date estimation methods. We run the proposed heuristic for three different weight figures which are determined by the Analytic Hierarchy Process and the one being used by TUAF. In addition, we study the influence of the release and the due dates of the aircrafts on the objective functions. We propose a determination method for each of the release and the due dates that aims finding the tightness levels of these two parameters. The release date determination method that we propose relates the arrival rate of the aircrafts with the utilization of the bottleneck resource whereas the due date determination method that we propose relates the due dates of the aircrafts with the fraction of the number of tardy jobs in percentages. We investigate the performance of the activity due date estimation methods in terms of the objective functions and the computational effort required by the tightness levels of the release and the due date that are found by the determination methods that we propose.

Keywords: Resource constrained project scheduling, multiple projects, mode selection, project types, weighted tardiness.

ÖZET

TÜRK HAVA KUVVETLERİNDE FABRİKA SEVİYESİ KORUYUCU BAKIM

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Bu tezde Türk Hava Kuvvetleri'nin (THK) tecrübe ettiği Fabrika Seviyesi Koruyucu Bakım (FSKB) problemini çalıştık. Mod Seçimli, Kaynak Kısıtlı ve Kesintisiz Çoklu Proje Çizelgelemesi Probleminin özel bir hali olan bu problemde, kısıtlı kaynakların değişik türden projelerin birbiriyle rekabet eden aktivitelerine tahsis edilmesi konu alınmıştır. Buna ek olarak bu problemde, aktivitelerin süreleri mod seçimi ile belirlenmektedir ve aktivite akışı proje türüne bağlıdır. Bu problemde hedeflenen sonuç, en az ağırlıklı toplam gecikmeyi sağlayarak, her projenin her aktivitesinin başlangıç ve bitiş zamanını ve seçilen modu belirlemektir. Bu problemin çözümü için iki fazdan oluşan bir sezgisel yöntem önerdik ve bu sezgisel yöntemi THK'nın tecrübe ettiği bir probleme uyguladık. Birinci fazda amaç, minimum toplam ağırlıklı gecikme zamanına sahip bir çizelge elde etmektir ve ikinci fazda amaç bu çizelgeyi mod seçim değişimleriyle toplam oluşan maliyet açısından iyileştirmektir. Aktivitelerin önceliklendirilmesinin gerekmesi, ayrıca bu aktivitelerin istenilen bitiş zamanı bilgisinin elimizde olmaması nedeniyle, FSKB'ye özel ve aktivitelerin istenilen bitiş zamanını tahmin eden beş adet metod geliştirdik. Önerilen sezgisel yöntemi, ikisi Analitik Hiyerarşi

Metodu ile belirlenmiş ve birisi THK tarafından kullanılmakta olan üç değişik ağırlık figürü için çalıştırdık. Bununla birlikte, uçakların bırakılma ve istenen bitme zamanı parametrelerinin hedefler üzerindeki etkilerini çalıştık. Ayrıca, uçakların bırakılma ve istenen bitme zamanı parametrelerinin sıklık seviyelerini bulmayı amaçlayan belirleme metodları da önerdik. Önerdiğimiz uçakların bırakılma zamanını belirleme metodu, uçakların varış sıklık değeri ile dar boğaz olan kaynağın kullanım oranını ilişkilendirirken, uçakların istenen bitme zamanını belirleme metodu uçakların istenen bitme zamanlarını geciken uçakların yüzdesi ile ilişkilendirmektedir. Aktivitelerin istenilen bitme zamanı tahmin metodlarının hedefler ve hesaplama zamanı açısından performanslarını, uçakların bırakılma ve istenen bitme zamanları sıklık seviyelerine göre araştırdık.

Anahtar Sözcükler: Kaynak kısıtlı proje çizelgeleme, çoklu proje, mod seçimi, proje türleri, ağırlıklı geç kalış.

To my family,

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Chapter 1

Introduction

Resource Constrained Project Scheduling (RCPS) problem has been an interesting topic in the past decades since it is encountered in many areas with unlimited number of problem types varying from management to operational level situations. It is concerned with the allocation of limited resources over time to perform a collection of activities as stated by Dorndorf [18]. Meanwhile, the projects consists of activities between which a precedence relationship exists. While allocating the resources, specific objectives are taken into account such as the minimization of total completion time or total cost. Assignment of limited resources to competing activities is in fact determining the exact activity start and finish times.

The mathematical model representations for the RCPS are initially formed in the mid sixties by Bowman [10] and Huber and Patterson [43]. However, the computational effort for finding an optimal solution usually grows exponentially with the problem size, thus the underlying problems are difficult to solve. Therefore, different solution procedures in the literature have been launched recently in the late nineties. Even the question for the existence of a feasible schedule can be answered with exponentially growing effort as stated by Dorndorf [18]. In practice, this problem is even more difficult to solve since the actual conditions under which a schedule will be executed change over time. According to the survey by Fox and Ringer [20], less than 5% of the time spent in practice on scheduling is for developing new schedules, while 95% of the time spent is revising and maintaining schedules based on daily progress and changing environment. The difficulty arises because of the combinatorial nature of the problem and the difficulty in putting the schedules into practice because of the changing conditions lead the project managers to develop special case solutions. However, there are unfortunately no problem specific studies in the literature. Nevertheless, industry specific heuristics can serve as more qualified decision tools. One of the areas this situation observed is the maintenance shops of aircrafts.

In this study we will consider Factory Level Preventive Maintenance (FLPM) of the aircrafts belonging to Turkish Air Force (TUAF) and propose a new solution procedure to this real life problem. TUAF has five war aircraft configurations which are F16, F5, F4, T37, and T38. All the aircrafts of these configurations are sent to Military Supply Point in Eskisehir in predetermined periods for FLPM. It is important to notice that the aircraft is unavailable during FLPM as expected. Since one of the main objective of TUAF is having as many available aircrafts as possible in case of a arising war, TUAF aims minimizing the time elapsed to complete the FLPM. A task plan exists for FLPM where the order of the operations, the time, and the resources required to perform each operation are gathered in. The resources required are the docks in the shelters and the workers who are certified by skill levels 7, 5, and 3. In addition, different FLPM task plans are used for each aircraft configuration.

At the beginning of each year, the fleets prepare a list of the aircrafts which has FLPM due in that year. These lists also include release and due dates of FLPM for each aircraft. The Military Supply Point (MSP) in Eskisehir is asked for the cost, which consists of only the labor cost, to complete all the FLPMs of the aircrafts in the lists. After estimating the required cost, MSP could be asked for a rescheduled FLPM list with a decreased cost but an increased total weighted tardiness and again the MSP calculates the required cost. This cycle is carried out till MSP ends up with a reasonable cost estimate.

The FLPM is a special case of Nonpreemptive Resource Constrained Multiple Project Scheduling with Mode Selection (NRCMPSMS) [38]. A set of activities

($\upsilon = \{1, 2, \ldots, J\}$) of a set of weighted projects ($\beta = \{1, 2, \ldots, I\}$), for which due dates are set, compete for the shared resources, and are to be processed in one of multiple possible execution modes. These modes differ with respect to their processing time. The objectives that are considered are minimizing the total weighted tardiness and the total required cost. Here, the projects are the FLPM of each arriving aircraft, the resources are the workers and the docks in the shelters, and the modes are the worker skill levels.

For this real life problem, we propose a new solution procedure which consists of two phases. In the first phase, an initial feasible schedule that has minimal total weighted tardiness is generated. In the second phase, this initial feasible schedule is improved in terms of total cost required. The proposed heuristic requires the activity due date information which is not available in the existing FLPM problem. Therefore, five activity due date estimation methods are developed considering the properties of the FLPM problem and the method developed by Vepsailanen and Morton [58] is also studied. For this problem definition, we also develop a release and a due date determination methods. The methods that we propose aim finding the tightness levels of these two parameters. The release date determination method that we propose relates the arrival rate of the aircrafts with the utilization of the bottleneck shelters whereas the due date determination method that we propose relates the due dates of the aircrafts with the fraction of the number of tardy jobs in percentages. Then, we solve the FLPM problems using different tightness levels of the release and the due dates generated by the release and the due date determination methods that we propose. Then, we investigate the performance of the activity due date estimation methods in terms of the total weighted tardiness, the total incurred cost, and the computational effort required.

The remainder of this thesis is organized as follows: In the next chapter an extensive review of the literature is provided. In Chapter 3, firstly, the FLPM problem is defined and then the assumptions, the variables, and the parameters used in developing the mathematical model of the problem, that is a specific case of NRCMPSMS, are stated and lastly the proposed heuristic is explained step by step and accompanied by a numerical example. In Chapter 4 we propose the release and the due date determination methods and examine the influence of the tightness levels of these parameters on the objectives and the computational effort required by the heuristic that we proposed. Using the results obtained, we compare the activity based due date estimation methods that are used in our heuristic. The last chapter is devoted to concluding remarks and future research directions.

Chapter 2

Literature Review

Resource Constrained Project Scheduling (RCPS) is a commonly encountered problem in industrial engineering and management science. It has been studied by a large number of researchers for different environments in the past decades resulting with different versions of the problem. The nuances between these problems studied in the literature are the availability of alternative resources for the execution of an activity with different cost and duration figures, the number of the projects to be scheduled simultaneously, and the performance measures to be improved. In addition, the solution procedures proposed are the other distinguishing factors in the RCPS literature.

Before reviewing these problems and the solution procedures, let us first introduce notation, some definitions, and terminology that will be used throughout this study. We will use the following parameters:

$i =$ Project index, $i = 1, 2, \dots, I$.

$j =$ Activity index, $j = 1, 2, \dots, J$.

$k =$ Resource index, $k = 1, 2, \dots, K$.

The following definitions are borrowed from [35] and [18].

Definition 2.1 Renewable resources are constrained on a period basis only. That is, regardless of the project length, each renewable resource is available for every single period. Examples are machines, equipment, and manpower.

Definition 2.2 Nonrenewable resources are limited over the entire planning horizon with no restrictions within each period. The classical example for this case is the capital budget of a project.

Definition 2.3 Doubly constrained resources are limited on a period basis as well as on a planning horizon basis. Budget constraints that limit the capital availability for the entire project as well as limiting its consumption over each time period is an example of this type of resource.

Definition 2.4 Partially renewable resources limit the utilization of the resources within a subset of the planning horizon. An example for this case is a planning horizon of a month with workers whose weekly working time, not the daily time, is limited by the working contract.

Definition 2.5 The type classification further distinguishes each category according to the function of the various resources.

Definition 2.6 Each resource type has a value associated with it, representing the available amount.

Definition 2.7 Activities can not be processed independently from each other due to scarcity of resources and additional technological requirements. Technological requirements will be modelled by temporal constraints or, as synonyms, generalized precedence constraints or time windows.

After presenting the definitions and the terminology, we can now review the problems and the solution procedures considered in the literature. In this chapter, each nuance mentioned above gives the name of the sections and the assortment that stems from the model properties and the solution procedures in these studies will be considered within these sections.

2.1 Single Project Scheduling with Limited Resources

In this section, the current research on the timing of the activities of a single project with a restricted number of resources, namely RCPS, is considered.

We will begin with the mathematical formulations of RCPS problem derived in the literature. There are two linear models, the objective of which is to minimize completion time of the project subject to temporal and resource constraints. Bowman [10] constructed the first linear model where RCPS problem is represented as a zero-one programming problem. His formulation uses 0-1 variables to indicate for each period over a scheduling horizon whether or not an activity is being processed. To reduce the number of decision variables, this formulation is modified by Huber and Patterson [43] in which the 0-1 variables denote for select periods (depends on precedence relations) whether or not an activity is completed in those periods.

The second model was formed by Balas [4] and is an integer programming where the project duration is minimal among all possible completion times. The reason in developing this model is to avoid the large number of binary variables in the first model since zero-one programming requires too much computational time as compared to integer programming. The binary variables in the first model, which are used to capture whether activity j is completed in period t or not, is incorporated into the solution procedures by structuring the problem in compact integer arrays so that they can be avoided. However as it is guessed, it is more difficult to understand this mathematical model than the zero-one programming. Because, the set of all activities active in period t and the amount of available resource type k in period t are determined simultaneously with the determination of the finish times of each activity j. By this modification, the number of binary variables are reduced as well as the per period resource usage constraints. It is important to note that two arrays are kept during the solution procedures: the first one is for required resources independent of time and the second one for remaining resource that has a time index, to take the resource limitations into account. Therefore, it is not so easy to track it computationally. Moreover, it can not accommodate real-world situations; for instance it is not possible to embed the due date restrictions of the activities in the project into the integer program. This is because of the choice of the variables in the integer program as explained above.

Having noted the formulations used in the literature and the comparison between them, the next step is to explain the exact solution procedures and the heuristics proposed. In recent years, great advances have been made in the solution procedures, which take into account these two approaches. The exact approaches include methods such as:

i. Zero-one programming,

ii. Dynamic programming,

iii. Implicit enumeration with branch-and-bound.

The last method has been the exact procedure most widely used in recent years. Nevertheless, the NP-hard nature of the problem makes it difficult to solve realistic sized projects [5], thus the use of heuristics is necessary. Heuristics for the RCPS can be classified into four methodologies:

i. Priority-rule based scheduling,

ii. Truncated branch-and-bound,

iii. Disjunctive arcs concepts,

iv. Metaheuristics (such as simulated annealing, tabu search, genetic algorithms, or ant systems).

Having categorized the heuristic methodologies in the current literature, now comes the brief description of these items. Priority-rule based heuristics combine priority rules and schedule generation schemes in order to construct a specific algorithm. Single-pass priority-rule based heuristics employ one scheduling generation scheme and one priority rule in order to obtain a feasible schedule. The low computational effort needed in the priority-rule based single-pass approach has brought out the idea of performing several passes. There are many possibilities to combine the schedule generation scheme and priority rules into a multi-pass method. The most common ones are multi-priority rule methods, forward backward scheduling methods, and sampling methods [26]. Multi-priority rule methods employ a schedule generation scheme several times. Each time, a different priority rule is used and the best schedule is selected. Forward-backward scheduling methods employ a schedule generation scheme in order iteratively to schedule the project by alternating between forward and backward scheduling. In random sampling methods, a probability of being selected is assigned to each activity from the set of unscheduled activities. Each pass of the method may obtain a different schedule and the best one will be the final schedule.

Truncated branch-and-bound which is well-known in job shop scheduling, is a branch-and-bound procedure truncated at different stopping points depending upon some criteria. In other words, it is a partial enumeration. Therefore, it is an approximate method. The commonly used idea is to terminate the execution of branch-and-bound whenever the limits of computational resources are met.

Disjunctive arcs concept method is a branch-and-bound solution technique that employs disjunctive arcs to resolve conflicts that may occur because of the temporal and the resource constraints. Precisely, let us assume that two activities j and l are disjunctive, and we will denote it $j \leftrightarrow l$ due to

- the temporal constraints either require $j \leftrightarrow l$ or require that $l \leftrightarrow j$
- the start time domains allow to rule out the possibility that j and l are performed in parallel
- the resource availability is too low to perform j and l in parallel.

so that j and l can not be processed simultaneously. This method is proposed by Christofides et al. [12].

After explaining the heuristic techniques used in the RCPS literature, we will discuss the well-known survey papers. The reason behind this choice is that many papers have been published about the RCPS problem. The surveys published on the solution procedures for the RCPS problem are by Hartmann and Kolisch in 1999 [25], in 2000 [26], and in 2005 [27], Kolisch and Padman in 2001 [35], Demeulemeester and Herroelen in 2002 [26], Demeulemeester, Herroelen and De Reyck in 1998 [29], Icmeli, Erenguc and Zappe in 1993 [31] and Ozdamar and Ulusoy in 1995 [41].

Hartmann and Kolisch, in their latest survey paper [27], summarized and categorized a large number of heuristics that have recently been proposed in the literature. They formed a standard experimental design, applied the heuristics, and compared them with each other in terms of the average deviation percent from the optimal makespan. With this information, they pointed out the characteristics of the good heuristics. They noted Alcaraz et al. [3], Debels et al. [14], Hartmann [23], Kochetov and Stolyar [32], and Valls et al. [56], [57] as outperforming the genetic algorithm of Hartmann [22], and the simulated annealing procedure of Bouleimen and Lecocq [9] which were accepted as the best performing heuristics by them in their previous study [26]. Another important result of their paper was that the forward-backward improvement technique (also called justification) which is used to improve schedules constructed by X-pass methods or metaheuristics (developed by Tormos and Lova [54]) works quite well in combination with any other approach. The solution technique proposed by Tormos and Lova combines random sampling procedures with this simple procedure where the activities are shifted to the right within the schedule and then to the left [54]. Another conclusion was that genetic algorithms and tabu search have been the most popular strategies among the metaheuristics paradigms applied to the RCPS problems and priority rule-based X-pass methods have attracted less attention.

In the survey paper by Demeulemeester and Herroelen [29], the authors focussed on the progress made till 1998 with branch-and-bound procedures for the basic RCPS problem and its important extensions. These extensions involved activity preemption, the use of release and due dates, variable resource requirements and availabilities, generalized precedence relations, time/cost, time/resource, and resource/resource trade offs, and non-regular objective functions. They listed the attributes of an efficient optimal solution procedure for the RCPS problem. In addition, they showed that the Patterson [44] problem set, which is a set of 110 test problems with 7 up to 50 activities and 1 up to 3 renewable resource types, can not uniquely serve as the benchmark test set for the RCPS problem. They claimed that the optimal and suboptimal procedures recently developed should be validated on a wider set of instances which they call as the ProGen. The Progen satisfies pre-set problem parameters; 30 activities, 4 renewable resource types, the problem generator developed by Kolisch [36] as the benchmark test set. The most important result of they presented is that properly designed depth-first branch-and-bound procedures offer the best potential for solving the RCPS problem. Meanwhile, they focussed on the time required for computation and come up with the fact that the truncated exact procedures are promising tools for solving real problems within an acceptable computational burden and with acceptable solution quality.

Icmeli, Erenguc, and Zappe [31] different from the other survey papers, provided a survey on the current research which combines two or more of time/cost, time/resource, and resource/resource trade off problems under a common framework. They concluded that when two or more of these fundamental problems are integrated, the resulting problems do not, in general, preserve the structures present in the original problems. Consequently, the exact algorithms available for the three fundamental problems can not be directly extended to their generalizations.

Kolisch and Padman [35] pointed out that the survey papers bypass the research advances in the decision support area that facilitate use and deployment considerations. Therefore, they presented the literature of the RCPS problem in integration with the methodologies, models, and data that builds up the complete decision support model. They emphasized the recent research results as well as the data generation and decision support issues. They concluded that much of the research has not yet found its way into practice.

Ulusoy and Ozdamar [41] reviewed the RCPS problem based on the objective and the constraints classification. They emphasized the difference between single and multiple-objective approaches and noted that the latter are scarce in the literature because of problem difficulty. They concluded that robust algorithms, which dynamically evaluate the resource and temporal conflicts among activities and hence eliminate the problem dependent nature of performance, are the needs of practitioners. Therefore, they encouraged the researchers to develop flexible heuristic decision-making procedures to meet these needs. They stated that most of the resource planning modules of most commercial software packages are misleading and far from scientific and confusing which was also the remark of De Wit and Herroelen [17].

2.2 Resource Constrained Project Scheduling with Multiple Modes

The way in which resources are consumed by activities also represents a distinguishing factor in project scheduling models. The function representing the relationship between activity duration and resource consumption can be continuously divisible or discrete. A practical example for a continuous time-resource function is the allocation of electric current among machines with electric motors when the rotational speed depends directly on the resource amount. A discrete time-resource function implies the representation of an activity by different execution modes. Each activity mode contains information on its operating duration and the amounts of resources it requires during its realization. As an example, the activity j can be performed by unskilled labor in 1 working day and an unskilled worker can do the activity in 1.5 working days where unskilled labor and skilled labor are represented as the execution modes of activity j in the models of these problems which are discrete.

The multi-mode RCPS problem includes time/cost, time/resource, and resource/resource trade-offs, multiple renewable, nonrenewable, and double constrained resources, and a variety of objective functions. A solution to RCPS with multiple modes has to determine the timing of activities as in traditional scheduling and the assignment of modes. This adds further complexity to the already complex case of resource constraints and results with an NP-hard optimization problem. Even worse, if more than two nonrenewable resources are taken into account, the problem of finding a feasible solution becomes NP-hard [34].

The objective functions considered in multi-mode RCPS models are classified into two classes the first one of which is finding the schedule of jobs that minimizes project completion time accompanied by a budget limitation and the second one is determining the schedule of jobs that minimizes overall project costs coupled with a due date constraint. The studies within the latter class, which were called as Resource Constrained Time/Cost Trade off problem, aimed to be a bridge to connect the gap between discrete time/cost trade off scheduling techniques and methods for scheduling under resource constraints. Time/cost trade off problems have been based on the assumption that resources are available in unlimited quantities. On the other hand, resource constrained models have not dealt with the cost features of project scheduling. To eliminate the restrictions imposed by both models, monetary objective functions are derived. No matter which type of objective function is used, the aim is to specify how each activity should be performed, that is, which mode should be selected and when each activity should begin and end.

Talbot [52] is the first researcher who proposed an exact enumeration scheme to Resource Constrained Time-Cost Trade off problem. Talbot in his paper [52] considered models both with a monetary objective function which is the minimization of total project cost and the nonmonetary objective function which is the minimization of project completion time where in both models the modes are assumed to be discrete and the all resource categories are included in. Again, the multi-mode RCPS Problem was formulated as either integer program or zero-one program. An additional index was included in the binary decision variables for the modes of the activities and because of this additional index the sums in the constraints were increased by one in these programs. In addition, to guarantee that each activity is assigned only one mode, a constraint was included in the models. Then Talbot [52] provided a solution procedure to both models which is the continuation of his previous work [53]. The solution procedure consists of two stages, in the first one of which the sequencing of the activities of the project for the scheduling process is accomplished. After ordering the activities to consider for the scheduling process, which is held in the second stage, renewable resources are sorted such that the resource having the maximum frequency of highest per period requirement relative to average resource availability has the smallest numerical value. This is done to notice the infeasibility due to resource scarcity as early as possible. Then, depending on the objective the modes are sorted, for instance if the objective is to minimize project cost, then modes are sorted according to increasing total cost or if the objective is to minimize project duration, modes are sorted by increasing duration. Next, possible latest and earliest times for the activities are computed which is the last step of stage one. In the stage two, similar to employing network cuts in the previous paper of the author, the partial schedules are found and then they are classified as good and inferior. The formulations for the multi-mode case were derived in the paper. The good ones are then put into a list where good partial schedules are kept for each activity. Again there is a limit on the size of the list. Continuing to the last activity by this way, the optimal schedules are obtained. The solution procedure is, as noticed, basic enumeration with some logical directions of the feasible solutions to the optimal one in a shorter computational time. The proposed solution procedure should give feasible results (if the feasible region is not empty) when it is stopped at any time.

Sprecher [48] improved this method in three aspects that are by correcting some flaws, introducing the notion of an i-partial schedule which uniquely describes a node i of the enumeration tree and the associated partial schedule, and adding four dominance and one feasibility bounding rule. Further refinements of this procedure, including new and powerful bounds, were given in Sprecher and

Drexl [49].

Speranza and Vercellis [47] proposed a depth-first branch-and-bound procedure which enumerates the set of active schedules. However, Hartmann and Sprecher [28] showed that the method might fail to find optimal or feasible solutions. Then Sprecher et al. [50] extended the enumeration scheme of Demeulemeester and Herroelen [16] for the single mode to the multi-mode case. Hartmann and Drexl [24] generalized the exact procedure of Stinson et al. [51] to the multi-mode context. Furthermore, they made an in-depth comparison of the three branch-and-bound strategies of Sprecher [48], Demeulemeester and Herroelen [16] and Stinson et al. [51] to solve the RCPS with multiple modes problem. Finally, Sprecher and Drexl [49] proposed new dominance criteria making their branch-and-bound algorithm to be able to solve problems up to 20 activities. According to results presented by Hartmann and Drexl [24], this algorithm is recently the most effective one for exact solution the RCPS with multiple modes problem.

Other exact procedures for solving the multi-mode RCPSP with makespan objective have been presented in [23], [50], [44], and [47]. All of these are extensions of branch-and-bound procedures originally proposed for the single-mode RCPSP.

Ahn, Erenguc, and Conway studied the RCPS with multiple modes where crashing -expending additional resources to make the completion time of the project better off- is possible within each mode. They proposed an exact procedure that uses branch-and-bound procedure during which the resource constraints are relaxed [1]. In their model, the required resources to perform an activity within a shorter duration does not change relative to the resource requirement when the activity is performed within its normal duration. The only change is in the cost figures. To bring clarity to this new view, let us consider the following example presented in their paper. Activity j can be done by "worker A using machine X (mode 1)" or by "worker B using machine Y (mode 2)". Worker A, using machine X, can finish activity j in 10 working days at a price of 400 dollars, assuming 8 hours of work per day. Worker B, using machine

Y, can complete the activity in eight working days at a price of 500 dollars assuming 8 hours of work per day. Furthermore, workers A and B can shorten the activity duration by working additional hours each day. For example, worker A can finish the job in 8 days by working 10 hours per day. Of course additional cost is incurred for overtime. As seen in this example, the duration and cost of performing activity j depend not only on the mode selection, but also on the duration selection within a mode. This model is named as RCPS with Multiple Crashable Modes. The authors used integer programming in their formulation. To capture crashing feature, different from the formulations considered till now, the duration of performing activity j is a decision variable instead of a parameter. In addition, a T value representing predetermined due date and a corresponding predetermined penalty cost for each period the project is delayed denoted by P, are specified. As it is guessed, the crashability can also be represented by the help of modes since the relation between time and cost is discrete. However, this will increase the number of variables and the constraints and thus makes the problem computationally time demanding.

Till now, the proposed solutions were aimed to find the optimal schedule. The necessity to solve real life problems of practical size and the belief of researchers that struggling for the optimal is impractical have motivated researchers to develop effective heuristics [18], [38]. Moreover, Sprecher and Drexl [49] showed that even the most powerful optimization procedures are currently unable to solve highly resource-constrained problems with more than 20 activities and more than two modes per activity optimally in reasonable computational times.

Heuristics start with a feasible schedule without considering the objective function value. Then some logical processes modify the initial feasible schedule modified so that the objective is improved. Therefore, these logical processes strongly depend on the model. Heuristic solution methodologies for (special cases of) the multi-mode RCPSP use:

i. single- and multi-pass priority-rule-based scheduling ([46], [34], [6], [8], [42], and [19])

ii. simulated annealing ([46] and [7])

iii. genetic algorithms ([21], [40])

iv. tabu search ([9])

v. Bender's decomposition ([39])

Boctor [6] employed a modified parallel scheduling scheme where an activity is in the decision set if it is at least resource feasible in one mode. Seven activity ranking criteria were studied in conjunction with three mode selection criteria. They concluded that the activity and mode selection criteria combination during which activities are chosen with the minimum smallest total slack rule, and modes are chosen on account of the minimum duration, seems to be the most appropriate to minimize project duration. A multi-pass variant uses five ordered pairs of activity- and mode-priority rules. In Boctor [8], instead of choosing schedulable activities seperately and schedule only one activity at a time, the set of nondominated schedulable activities is chosen by calculating a lower bound of the prolongation of the resource-unconstrained makespan.

Drexl and Grünewald [19] presented a stochastic scheduling method which uses a weighted random selection technique. The stochastic nature of this method emerges from using some criteria measuring the impacts of job selection and mode assignment in a probabilistic way. Unfortunately, this heuristic failed to solve any of the test problems. The main reason for this failure is that it schedules jobs at their earliest start times regarding precedence relations only. However it is often necessary to schedule some jobs to start after their earliest start time in order to get a feasible solution. This is obvious for example in the case where there are two or more jobs with the same earliest start time that, because of the resource restrictions and whatever the selected resource-duration mode, can not start at the same time.

Slowinski et al. [46] solved the multi-mode RCPSP with multiple objectives. They presented single-pass and multi-pass approaches as well as simulated annealing algorithm. First, a (precedence-feasible) priority list of the activities is derived with one of 12 priority rules. In the order of the priority list (precedence-feasible) activities are scheduled in the mode with shortest resource-feasible duration at the earliest period possible. The procedure was extended to multi-pass approach by randomly selecting from the ranked activities instead of scheduling the first activity on the list. Meanwhile, Sowiski et al. [46] is the first group who tried simulated annealing to solve the multi-mode RCPSP. Based on the activity list, they proposed a pairwise interchange neighborhood where a new list is generated by exchanging the positions of two randomly chosen activities which are not precedence-related. Meanwhile, an activity list is a permutation of the activities that are precedence feasible. They also developed a decision support system which helps the user to identify strategies for choosing the activities to be put in progress in case of resource conflicts and multiple criteria.

Özdamar and Ulusoy [42] broadened their local constraint-based analysis-approach to solve the multi-mode RCPSP. They reported results which are consistently better than the single-pass priority rule-based approaches and a multi-pass approach respectively.

Kolisch and Drexl [34] applied a local search strategy which especially takes into account scarce nonrenewable resource. They proposed a new local search method that first tries to find a feasible solution and then performs a single-neighborhood search on the set of feasible mode assignments. This is because heuristic solution approaches fail to generate feasible solutions when problems become highly resource-constrained. Every feasible mode-assignment was evaluated by running the adaptive search algorithm of Kolisch and Drexl [33]. Furthermore, they proved that the feasibility problem is already NP-complete.

Boctor [7] also suggested a simulated annealing approach to RCPS with multiple modes without nonrenewable resources. In this work, a solution is represented by the activity list in contrast to Slowinski et al. [46] and neighbors are generated using the shift operator followed by the construction of a schedule from this activity list. The author favored a shift-neighborhood approach where one randomly chosen activity is shifted to a new precedence feasible position on the list.

Bouleimen and Lecocq [9] described a new simulated annealing algorithm for multi-mode RCPSP problem, they introduced an original approach using two embedded search loops alternating activity and mode neighborhood exploration.

Hartmann [21] reported excellent results with a genetic algorithm with encoding based on a precedence feasible list of activities and a mode assignment. The method of Mori and Tseng [40] employed similar ideas for instances with renewable resources only. In their paper, they compared their method with the one proposed by Drexl and Gruenewald [19].

Maniezzo and Mingozzi [39] proposed a new mathematical formulation for the RCPS with multiple modes and used it to derive two new lower bounds and a new heuristic algorithm based on Bender's decomposition.

Ahn and Erenguc [2] also proposed a heuristic procedure to RCPS with Multiple Crashable Modes. In their heuristic, first by the use of a dispatching rule an initial feasible solution is obtained, and then six improvement rules are applied to this initial feasible schedule. These rules are in fact controls whether the schedule at hand can be improved. They are obtained from simple and practical conclusions such as controlling whether a given activity can be rescheduled at a smaller by searching for the possible modes and crashing. Computational results showed that it gives near optimal solutions in a smaller computational time. Moreover, it offers feasible schedules to the problems that can not be optimally solved.

2.3 Multiple Project Scheduling with Limited Resources

In project scheduling models, there is yet another distinguishing aspect which is the number of projects to be scheduled. In real-world situations, the project schedulers have to consider multiple projects simultaneously in general. Specifically, if the performance of a company, which directs multiple projects, is to be analyzed, then all of its projects' key performance measures should be considered. Since all the projects that the company directs use the common resources, evaluating the projects individually is meaningless. Because, it is not possible to sense the resource scarcity due to nonexistence of the common resource usage constraints in the Single Project Scheduling formulations. To satisfy this requirement of scheduling multiple projects simultaneously, studies have been performed under the title Multiple Project Scheduling with Limited Resources (MPSLR). MPSLR involves sequencing of the projects in addition to scheduling them, which makes it more complex relative to RCPS. Similar to RCPS, the formulations are either integer programs or zero-one programs. Since this problem has a global scale with respect to the RCPS, various objective functions and the solution methods have been investigated in these formulations. Among these objectives; the minimization of the total throughput time for all of the projects, the minimization of the whole system's makespan (not the individual makespan values of the projects), and the minimization of the total lateness or lateness penalty for all of the projects are the widely preferred ones.

In the model considered by Pritsker, Watters, and Wolfe, a zero-one program is used [45] where their formulation is on the activity level. That is to say, the resultant schedule consists of the start and end dates of all the activities of all the projects. The only change from the zero-one project scheduling formulation, is that all the parameters and the decision variables include an additional index for specifying the projects. Three objectives were derived, which are the minimization of the total throughput time for all projects, the minimization of the whole system's makespan (not the individual makespan values of the projects), and the minimization of the total lateness or lateness penalty for all of the projects. But among these objectives, a solution procedure is provided only for the first one. The authors compared the schedules found by applying two popular dispatching rules with the optimal schedules which are First Come First Served and Minimum Project Slack First. It is important to note that they did not compare with the dispatching rules with the basic enumeration one by one. Instead they stated that the dispatching rules give good results in case of many variables (more than 33) and constraints (more than 37).

Different from Pritsker, Watters, and Wolfe [45], some studies dealt with MPSLR at the project level. Their solution procedures' output is all of the projects' start and end dates. The reason behind taking the problem on a high level is just to reduce the complexity of the problem in cases where other conditions such as introducing modes to the MPSLR problem. One of those cases is the study of Lei and Lee called Multiple Project Scheduling with Controllable Project Duration and Hard Resource Constraint: Some Solvable Cases [38]. As the name implies, they introduced the concept mode. The relation between the time and cost is continuous in their model. Two types of functions representing this relation were considered. In type one, the duration of each project includes a constant and a term that is inversely proportional to the amount of resource allocated. In type two, the duration of each individual project is a continuous decreasing function of the amount of resource allocated. So, they handled the case where more resources are employed and thus the same job is performed within a less duration. Their analysis was on nonmonetary objectives such as minimization of the total project completion times. Their conclusions are thus valid for the cases where all the cost parameters are identical for all projects.

Kurtulus [37] also investigated the MPSLR problems. In particular, he introduced four new scheduling rules which are maximum duration and penalty, maximum penalty, maximum total duration penalty, and maximum total work content. He assessed the performance of these rules as well as six other scheduling rules with respect to project summary measures such as resource constrainedness, location of peak requirements, and problem size. Upon performing tests with 3000 multi-project scheduling problems with unequal and equal penalties, he concluded that the maximum total work content rule performed well for small problems with equal penalties. Moreover, he found that the maximum penalty rule worked well in solving problems with unequal penalties and more constraining values of the average utilization factor. Finally, it was shown that in all the other cases, the minimum slack rule was the most effective.

Speranza and Vercellis [47] proposed a model-based approach to nonpreemptive multi-project management problems which is based on a hierarchical two-stage decomposition of the planning and scheduling process. Hartmann and Sprecher [28] focused on this approach for finding makespan minimal solutions.

2.4 Motivations for this study

The RCPS problem has been extensively studied in the literature. Different versions of RCPS Problem were considered in the project scheduling literature. Other than the number of projects, the availability of the modes -resource duration combinations for each activity-, and crashing within each mode cause the problem to be analyzed with a different model and solved by different exact or heuristic solution procedures. In addition, over the five years, considerable progress has been obtained in designing different solution procedures for the RCPS problem.

To the best of our knowledge, however, in RCPS literature, there has not been conducted a study on Nonpreemptive Resource Constrained Multiple Project Scheduling with Mode Selection where the resultant schedule is on the activity level. In this thesis, we considered a real life application of this problem which is the Factory Level Preventive Maintenance (FLPM) of aircrafts belonging to Turkish Air Force and proposed a new solution procedure for this problem. The primary aim of the heuristic is to obtain a feasible schedule with minimal total weighted tardiness and the secondary aim is to improve the total cost required to apply this feasible schedule. The FLPM problem is basically to allocate the resources -docks in the shelters and the workers of different skill levels- to the operations of the FLPM projects of the aircrafts of different aircraft configurations. The precedence diagram and the weight depend on the aircraft configuration. This makes the problem different from the problems studied in the literature. In the next section, we will define the FLPM problem in detail, provide a mathematical model, and explain the single-pass priority rule based heuristic.

Chapter 3

The Factory Level Preventive Maintenance Problem in Turkish Air Force

In this chapter, we will present the problem; Factory Level Preventive Maintenance (FLPM) of aircrafts belonging to Turkish Air Force (TUAF) and propose a solution procedure. Recall that, in the previous chapter we note that this problem is a specific case of Nonpreemptive Resource Constrained Multiple Project Scheduling with Mode Selection (NRCMPSMS) and there are no suggested solution procedure in the current literature. In this chapter, firstly in Section 3.1, the FLPM problem is defined and the equivalents of the problem specific terms used in this definition, which are obtained from the literature, are given. In Section 3.2, the assumptions, the variables, and the parameters used in developing the mathematical model of the problem are stated and in the Section 3.3 the model is constructed. A stepwise representation of the proposed solution procedure is explained in the Section 3.4. A numerical example is provided to show the efficacy of the solution procedure in the following section and the chapter is concluded in the Section 3.6.

3.1 The Factory Level Preventive Maintenance (FLPM) Problem

In this section, FLPMs of aircrafts belonging to TUAF, which is a well fit real life application of NRCPSMS, is considered. In addition, the properties of the problem, which direct us in developing the solution procedure, are emphasized. The representations in the literature corresponding to the terms used in the FLPM problem definition are also listed.

TUAF has five war aircraft configurations which are F16, F5, F4, T37, and T38. All the aircrafts of these configurations are sent to Military Supply Point in Eskişehir in predetermined periods for FLPM. It is important to notice that the aircraft is unavailable during FLPM as expected. Since one of the main objective of TUAF is having as many available aircrafts as possible in case of an arising war, TUAF aims to minimize the time elapsed to complete the FLPM. On the other hand, the FLPM guarantees and increases the airworthiness of an aircraft. Therefore, it cannot be abandoned and when such a maintenance is due for an aircraft, that aircraft cannot be used in the fleet flights and this is a rule in TUAF which has never been neglected.

A task plan exists for FLPM where the order of the operations, the time, and the resources required to perform each operation are gathered in. This plan includes operations such as removal of all parts of the aircraft configuration, maintenance and repair of these items, and affixing the functioning parts to the aircraft so that the aircraft can fly without any problems. These operations in the task plans are well-known and fixed. In addition, different FLPM task plans are used for each aircraft configuration. Table 3.1 gives the task plan of the FLPM of F4. A row in Figure 3.1 can be read as: The activity 1 of a F4 during FLPM is in the shelter Landing Airfield and a F4 covers 3 docks space in this shelter. This activity is performed in 8 half days if a worker of skill level 7 does, 10 half days if a worker of skill level 5 does, 12 half days if a worker of skill level 3 does.

Fortunately, the operation flow logic used in FLPM of all aircraft configurations is the same (e.g. the aircraft has to be washed before painting process)

Oper. No	Oper. Name	Shelter	t-7	t-5	t-3	# of Docks
1	FLPM entry control	Landing Airfield	8	10	12	3
2	Vacating the fuel	Fuel	1	2	3	2
3	Dismantling the external loads	F4H	3	6	8	1
4	Pulling up the paint	BLS	16	22	28	1
5	Entry washing	Washing	4	6	9	3
6	X-RAY control	NDI	2	6	7	2
7	Functional exploration	F4D	20	38	42	1
8	Cable rigging test	KDT	9	10	18	1
9	Main workshop dismantling	F4D	50	80	109	1
10	Main workshop assembly and adjustment	F4D	11	12	22	1
11	Jet engine exploration	JET	10	20	21	1
12	Fuel system control	Fuel	3	4	6	2
13	Fuel tap assembly	F4D	2	4	7	1
14	Engine assembly	F4D	4	8	10	1
15	Preparations to engine strength control	F4H	1	2	3	1
16	Engine strength control	TAK	2	4	5	1
17	Radar and avionic system control	F4H	7	10	18	1
18	Exit washing	Washing	1	2	3	3
19	Exit painting	Painting	5	12	18	3
20	Weight balance control	F4H	3	4	5	1
21	FLPM lasting operations	Landing Airfield	3	8	9	3

Table 3.1: The task plan of the FLPM of a F4

since the nature of the maintenance is similar. Therefore, the operations are called with the same names and the order of them are same; but the place they are performed and the workers used are different in these plans.

The place, where the operation is performed, is called a shelter. Some of the shelters are peculiar to the aircraft configurations which we call as PAC and some of them are used by all aircraft configurations which we call as common. Because the operation flow logic used in FLPM of all aircraft configurations is the same as mentioned before, the order of the operations performed in the common shelters are same in all precedence diagrams. There are eight PAC shelters that are F4H, F4D, F5H, F5D, T37H, T37D, T38H, and T38D. Their names imply to which aircraft configuration they are peculiar. As it is noticed, there is no shelter specialized to aircraft configuration F16. Instead, the shelters F4D and F4H are used for the operations during the FLPM of F16. Some of the shelters are common and are used during some time of FLPM of each aircraft configuration which are Fuel, BLS, Washing, NDI, KDT, JET, TAK, and Painting. As an instance, the precedence diagram of the FLPM of a F4 aircraft with the shelter, in which the operation is performed, is given in Figure 3.1.

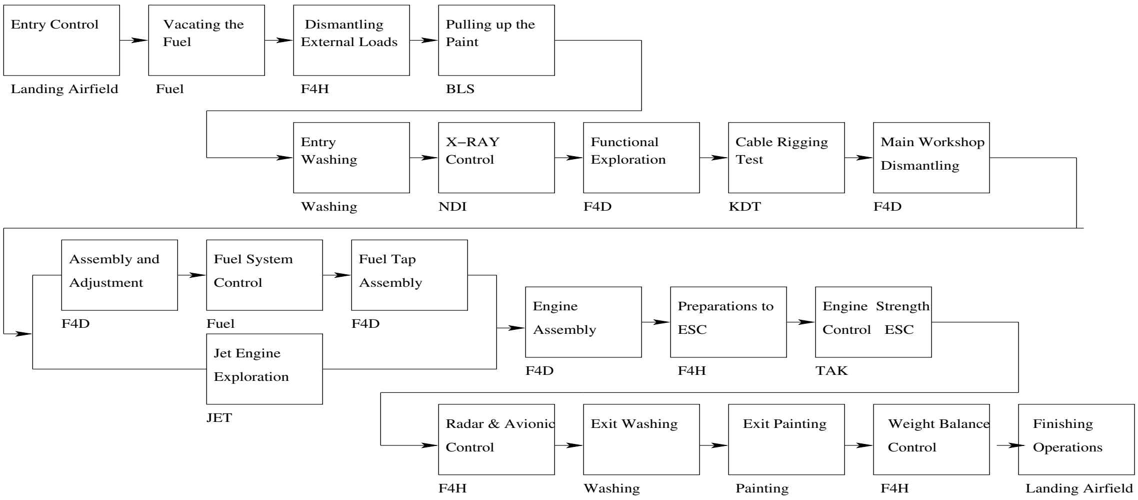


Figure 3.1: Precedence diagram of a F4 aircraft

The number of docks determines the capacity of a shelter. Meanwhile, the docks are the sledges to which the aircrafts are fastened during the operations. Because the size of different aircraft configurations varies, the number of docks that they occupy is another point of consideration. For instance, F16 is a huge aircraft therefore it covers 2 docks in the shelter Fuel whereas the other aircraft configurations cover 1 dock in the same shelter. In addition, in each shelter the number of docks is known and constant. It is important to note that, the landing airfield is also represented as a shelter in our model since two operations are performed in this shelter for all aircraft configurations. Although there are no docks in the landing airfield, the space it covers is limited, which can hold 4 F4s or 6 F5s or 6 T37s or 6 T38s or 4 F16s simultaneously. In our model, we assume that the shelter landing airfield has 12 docks and the aircraft configurations F4, F5, T37, T38, F16 occupy 3, 2, 2, 2, and 3 docks respectively.

Another limited resource required to perform the operations is the workers. The operations are done by the workers who are certified by skill levels 3, 5, and 7, such that the worker of skill level 7 does operation faster than the one of skill level 5 and so on. Meanwhile, the time units that are required to perform the operations by all these 3 worker skill levels are known and given. The labor cost of the workers is constant and increases as the skill level increases as expected. In the model, we call each skill level as a mode which are discrete. The number of workers of all three skill levels are known and constant and since they are certified to the specific operations done in each shelter, worker exchange is not possible between the shelters. Since the F4H and F4D shelters are used by both F4s and F16s, the workers in these shelters are certified to perform both the F4 and F16 specific operations which is also true for all the common shelters.

To model the FLPM exactly, the work load due to the aircrafts, which are currently in FLPM, is also taken into account. Because of this consideration, the solution procedure we propose can be applied to the problems in steady state.

Having noted a general view of the FLPM, now comes the work flow in TUAF. At the beginning of each year, the TUAF Commandership asks for the aircrafts which has FLPM due in that year from the fleets. The fleets prepare a list of those aircrafts which also includes release and due dates of FLPM for each aircraft. The arrival date of an aircraft to the Military Supply Point (MSP) for FLPM is named as release date and is known with certainty. The due date is calculated by the sum of the release date with the total processing time of FLPM assuming there are no resource constraints and a worker of level 5 is assigned to all operations. As it is noticed, the due dates set by TUAF are very tight. The TUAF Commandership sends these lists to the MSP in Eskişehir and asks for the cost, which consists of only the labor cost, to complete all the FLPMs of the aircrafts in the lists. In fact, the MSP determines the number of working hours required to perform the FLPMs of the aircrafts in the lists. After having the information of cost required, the TUAF Commandership could ask for a rescheduled FLPM list for a subset of the aircrafts in the initial schedule list. The MSP again calculates the incurred cost. This cycle between the commandership and the MSP is carried out till MSP ends up with a cost that can be accepted by the commandership. The reason behind this cycle is that it is not easy to find an optimal schedule, in fact even finding a feasible one under the resource and the cost constraints is not easy. In addition, the fleets and the MSP in Eskişehir have conflicting objectives. The fleets aim at maximizing the percentage of available aircrafts,

FLPM	Literature
FLPM of an aircraft	Project
Operation performed during FLPM of an aircraft	Activity
Worker skill level	Mode
Aircraft configuration	Project type
Worker	Resource
Dock in the shelter	Resource

Table 3.2: The specific terms used in the FLPM problem and their equivalents in the literature

whereas MSP in Eskişehir aims at maximizing the capacity utilization. Therefore, the primary objective of the Military Supply Point is to schedule the FLPMs of the aircrafts such that the number of available aircrafts at some time instant is maximized. In order to transform this objective into scheduling terminology, the total tardiness is used as a surrogate measure. Because, the deviations from the due dates result with an increase in the number of tardy FLPMs of the aircrafts as well as a decrease in the number of available aircrafts. So by minimizing these deviations, that is minimizing the total tardiness, we can estimate the number of available aircrafts more accurately. In fact, because a ranking is made between the aircraft configurations from the availability point of view, the total weighted tardiness is to be minimized. The secondary objective of TUAF is to minimize the cost incurred for achieving this feasible schedule. However, the total weighted tardiness has much higher priority than the total incurred cost.

The described problem is an example of NRCMPSMS. The Table 3.2 shows the appropriate representations in the literature of the terms used in the FLPM problem.

After having the problem described, to develop the mathematical model of the problem, the assumptions are stated and the variables and the parameters are defined in the next section.

3.2 Preliminaries and Problem Definition

In this section, we give a formal definition of our problem described in the previous section which is the FLPM of aircrafts belonging to TUAF. The variables and the parameters used here are the ones used in the study conducted by Ahn, Erenguc and Conway in which there is only one project to be scheduled and crashability is available with the objective of minimal cost ([1], [2]). As explained in the previous section, the existence of multiple aircraft configurations differing in the precedence diagram followed and the importance weights are the additional properties of FLPM problem that are not considered in the RCMPSMS in the literature.

Throughout this work explained in this chapter, we study a deterministic project scheduling problem where all the parameters that define a problem instance are known with certainty in advance. In other words, the projects to be scheduled are known with all of their properties a priori with certainty which are the project type, the release date, the due date, and the weight. Here, the activities and the activity flows depend on the project type of the project to be scheduled, and thus project type is an important input.

We first state the assumptions and then define the variables and the parameters necessary to formulate the FLPM problem. We are to schedule I projects of arrivals A_i of different weights w_i. Each of the coming projects consists of activities to be performed are denoted by j and a project consists of J activities. Two dummy activities, 1 and $J+1$ are introduced to denote the start and the completion of the projects. These activities do not require any time for processing. There are precedence relations between some activities due to technological requirements. No preemption is allowed; once an activity is started, it cannot be interrupted. The notation follows the activity-on-node format. A succeeding node gets a higher number than all of its preceding nodes. The arrivals of the projects occur at the beginning of the periods. It is important to notice that the project with a higher arrival time gets a higher number than all of its preceding projects. S_{ji}, $1 \leq j$, denotes set of immediate successors of the activity j of project i. Each activity j of project i can be executed in one mode available from the mode set $\{1, 2, \ldots, M_{ji}\}$. Each mode of activity j of the project i corresponds to one duration value which is d_{ji}. Meanwhile, the duration values obtained by mode selection are discrete.

For the completion of the projects, we assume that K types of renewable resources, which make mode selection available, and D types of renewable resources, which has no alternatives, are required. The D types of resources has no relation with the modes. R_k, $k = 1, 2, \ldots, K$, units available in each period for the former resource class and P_d, $d = 1, 2, \ldots, D$, units available in each period for the latter resource class. Again, $r_{jm_{ji}k}$ denotes the per period usage of resource k, $k = 1, 2, \ldots, K$ required to perform activity j of the project i in mode m_{ji} for the former class and p_{jid} denotes of resource d, $d = 1, 2, \ldots, D$ required to perform activity j of the project i for the latter. Considering the indices, there is an index showing the dependency of the resource to the mode, m_{ji}, where there is no such an index in the latter notation. In addition, a resource can be used by an activity of all projects in some point of the corresponding flow and a resource can be required more than once by different activities of a project type. Meanwhile, each project is assumed to have a predetermined due date, $\overline{T_i} > 0$.

A schedule for this problem definition consists of the finish time and mode couples for each of the J activities of all projects. A schedule is said to be feasible if:

- each activity j of each project i is assigned a mode $m_{ji} \in \{1, \ldots, M_{ji}\}$
- all the precedence relations are satisfied
- resource requirements in each period do not exceed their respective capacities.

The objective of this problem is to find a feasible schedule that minimizes the total weighted tardiness. For the formulation of the problem, we introduce two additional variables which are f_{ji} and z_i. f_{ji} denotes the completion time of the activity j of the project i, j = 1,2, $\ldots$, J; i = 1,2,$\ldots$, I. Finish time for the activity j of a specific project i equals to the release time for the succeeding activities of the same project, S_{ji}, namely $f_{ji} = a_{vi}$, $v \in \mathrm{S}_{ji}$. Accordingly, f_{Ji} denotes the completion time of the project i. z_i denotes the tardiness of the project i, and is computed as $max\{0, f_{Ji} - \overline{T_i}\}$ where $\overline{T_i}$ is the due date of project i.

In the next section, the mathematical model is given according to the definition described in this section.

3.3 Modelling the Problem

Now, consider the problem defined in the previous section, NRCPSMS where the activity flow is dependent on the type of the project and the projects have different weights. The variables and the parameters used here are the ones used in the study conducted by Ahn, Erenguc and Conway in which there is only one project to be scheduled and crashability is available with the objective of minimal cost ([1], [2]). For the objective, minimum total weighted tardiness, the model can be constructed as follows:

$$\text{min} \qquad \sum_{i=1}^{I} w_i \cdot z_i \qquad (1)$$

$$\text{st} \qquad \sum_{m_{ji}=1}^{Mji} x_{jim_{ji}} = 1 \qquad \forall j, i \qquad (2)$$

$$f_{li} \leq f_{ji} - d_{ji} \qquad l = 1, 2 \ldots, J-1, j \in S_{li}, \forall i \qquad (3)$$

$$f_{1i} = 0, \qquad \forall i \qquad (4)$$

$$\sum_{i=1}^{I} \sum_{j \in SA_{ti}} \sum_{m_{ji}=1}^{M_{ji}} r_{jm_{ji}k} \cdot x_{jim_{ji}} \leq R_k, \qquad \forall k, t = min(a_{ji}), \ldots, max(f_{Ji}) \qquad (5)$$

$$\sum_{i=1}^{I} \sum_{j \in SA_{ti}} p_{jid} \leq P_d, \qquad \forall d, t = min(a_{ji}), \ldots, max(f_{Ji}) \qquad (6)$$

$$z_i \geq f_{Ji} - T_i, \qquad \forall i \qquad (7)$$

$$z_i \geq 0, \qquad \forall i \qquad (8)$$

$$d_{1i}, d_{Ji} = 0, \qquad \forall i \qquad (9)$$

$$x_{jim_{ji}} \in \{0, 1\} \qquad \forall j, i, m_{ji} \qquad (10)$$

where

Decision Variables:

$$x_{jim_{ji}} = \begin{cases} 1, & \text{if activity } j \text{ of project } i \text{ is executed using mode } m_{ji} \\ 0, & \text{otherwise} \end{cases}$$

m_{ji} = mode of the activity j of project i, $\in$M(j, i)

d_{ji} = duration variable of the activity j of project i

f_{ji} = finish time of the activity j of project i

SA_{ti}= the set of activities of project i that are in progress in period t; $SA_{ti} = \{j : f_{ji} - d_{ji} < t \leq f_{ji}\}$

$\overline{z_i}$ = tardiness of project i; Z = max{0, f_{Ji}-$\overline{T_i}$}

Parameters:

M_{ji} = the number of modes available to the activity j of project i

$M(j, i)$ = {1, 2,…,M_{ji}) the available mode set of the activity j of project i

A_i = arrival time of the project i

w_i = weight of the project i

a_{ji} = arrival time of the activity j of project i

S_{ji} = set of immediate successors of the activity j of project i

$r_{jm_{ji}k}$ = per period usage of renewable resource k required to perform the activity j of project i in mode m_{ji}

p_{jid} = per period usage of renewable resource d required to perform the activity j of project i

R_k= units of resource type k, that makes mode selection, available per period

P_d= units of resource type k available per period

$\overline{T_i}$ = the due date of project i

In the above formulation, $x_{jim_{ji}}$ is a binary variable, if the activity j of the project i is executed in mode m_{ji}, then it is set to 1, otherwise it is set to 0. The time interval $(t - 1,\ t]$ is expressed by the integer period index t. Expression (1) shows the objective function, the minimization of the total weighted tardiness which is the sum of the tardiness of each project multiplied by its weight. The constraints (2) and (10) ensure that each activity is performed in only one mode. The expression (3) guarantees the temporal constraints, namely, the precedence relationships. Note that constraints (5) and (6) are conceptual statements of the resource constraints and the resource usage in each period must not exceed the resource capacity. They are conceptual, because SA_{ti} the set of activities of project i that are in progress in period t, is formed just after the modes are selected and the finish times are determined. In addition, the former constraint is for the resources that make mode selection available. The remaining constraints are self-explanatory. As noticed from the above formulation, the problem is a linear integer program in which the resource constraints are expressed conceptually.

Considering the difficulty of Resource Constrained Project Scheduling problem, it is no surprise that a specific case of NRCPSMS, formulated above, is a difficult problem to solve optimally. In addition, there is no solution procedure in the literature that can be applied to the problem studied here because of the reasons mentioned in Section 2.4. Thus, we need another way and in the next section we will describe our solution procedure for this problem.

3.4 A Heuristic Procedure for the FLPM Problem

In this section, we will propose a heuristic procedure for the FLPM problem which is a specific case of NRCPSMS formulated in the previous section. In this problem, which is an instance of Preemptive Priority Scheme, the total weighted tardiness, ($P1$), has much higher priority than the total incurred cost, ($P2$), that is $P1 >> P2$. The proposed heuristic procedure for this problem consists of two phases. In the first phase, a feasible schedule is generated to achieve the primary objective of TUAF which is the minimization of the total weighted tardiness as explained in 3.4.1. In the second phase, we try to improve this feasible schedule to achieve the secondary objective of TUAF which is the minimization of the total cost incurred as explained in 3.4.2. In fact, the aim in the second phase is to come up with a dominant schedule, specifically, a lower cost value is to be found out with the equivalent total weighted tardiness value obtained in the first phase. The second phase is repeated until the application of the proposed algorithm does not yield further improvements.

3.4.1 Generation of the initial feasible schedule

In this phase, the activities of the FLPM projects are ordered, and then are assigned to the dock(s) in the suitable shelter with the workers to achieve the primary objective of TUAF which is to obtain a feasible schedule yielding minimum total weighted tardiness. As it is recalled from the Section 3.1, it is not possible to find an optimal schedule under the resource and cost constraints; it is not even easy to find a feasible one. The tightness of the due dates strengthens this difficultness. Therefore, in this phase we relax the problem by ignoring the cost constraint and solve the relaxed problem to obtain a feasible schedule.

This phase starts up with prioritizing the activities competing for the allocation of the docks and the workers. It is important to mention that the prioritizing takes place among the activities waiting for assignment to the same shelter at the present time. In other words, not all of the activities in the whole problem are prioritized. The prioritizing rules used in ordering the activities waiting for assignment to the common and the PAC type shelters are different. The reason behind using different prioritizing rules is that the processing time required for the achievement of the activities in the common shelters varies depending on the aircraft configuration, while this is not the case for the achievement of activities in the PAC shelters. Meanwhile, these rules are the critical steps in the solution procedure proposed.

Let us explain the rule used for the common shelters first. To order the activities of the FLPM projects to be performed in a common shelter, a modified version of Apparent Tardiness Cost (ATC) rule is used since Vepsalainen and Morton [58] have shown that the ATC rule is superior to other sequencing heuristics and close to the optimal for the $1||\Sigma w_i T_i$ scheduling problem. In addition, they emphasized that the ATC rule, which is a composite rule, performs better than all of the other dispatching rules in terms of weighted tardiness performance in large scale job shops for all load conditions. Therefore the ATC rule is preferred during the assignment of resources in the common shelters. The rank and priority index calculation used by the ATC rule is:

$$max[\frac{w_i}{d_{ji}} exp(-\frac{max(0, \bar{t}_{ji} - t_{now} - d_{ji})}{k\bar{d}})]$$

where

w_i = the weight of project i

d_{ji} = duration variable of the activity j of project i

$\bar{t}_{ji}$ = the due date of the activity j of project i

t_{now} = the time at which the ATC value is calculated

k = look ahead parameter

$\bar{d}$ = average processing time required for the activities to be scheduled in the list

The activity that has the largest ATC value is scheduled first. The weight of the projects, the due dates for the activities of the projects, and the duration variable required to perform the activity in that common shelter at that decision time are used (if skill level 7 worker is available at that time, then processing time of skill level 7 worker mode is used, if skill level 5 is available and skill level 7 is not available, then processing time of skill level 5 worker mode is used and so on). As it is noticed, time dependent processing time values are used in the modified ATC rule. This modification on the ATC rule is in fact for enabling the mode selection. It is important to notice that the t_{now} value used in calculating the ATC values is the time when there is worker and a dock to assign, not the finish time of the preceding activity. This is another important modification on the ATC calculation we propose. Our rule also considers the existence of multiple projects since a resource can be used by an activity of all projects, and as noticed there is a project index i in the parameters. In addition, because a resource can be required by different activities of a project, there is an index j presenting the activity. These are also the main changes on the known ATC rule. Furthermore, the ATC values of the activities of two projects of same aircraft configuration type are also calculated and compared if they are waiting for an assignment to the same shelter at the same time, since an aircraft can reenter to a waiting list of a common shelter for the performance of a different activity. In other words, because our problem is not a flow shop and different activities of a project is to be performed in the same common shelter, the comparison based on the release dates of the projects between the activities of different projects of same aircraft configurations competing for allocation to the same shelter, is not valid and sufficient, thus the ATC values have to be calculated and compared.

As explained the problem definition, the due date information for the activities of the specific projects to be performed in each shelter, $\bar{t}_{ji}$, is not available in our model. Only the due date for the last activity in the precedence diagram is known which is the due date of that specific project, denoted as $\overline{T_i}$ in Section 3.2. Therefore, the due dates of the activities of the specific projects for each shelter, $\bar{t}_{ji}$, have to be determined. We develop five different methods used for the estimation of the due dates of each activity j of each project i. It is important to mention that while developing these methods, the aim is to find out the most appropriate lead time estimate for our problem, namely estimate the most suitable value of the due date of the activity j of project i. For this purpose, the method developed by Vepsailanen and Morton [58] is also studied. These six methods are explained below where the term slack refers to the difference between the due date of the project and the sum of the total processing time of the project without resource constraints and mode selection (simply sum of the processing times of the activities of the project when worker of level 5 is selected since they are the most representative) and the project arrival time, $\overline{T_i} - (A_i + \Sigma d_{ji})$. To make these six methods more clear and understandable, a numerical example will be given later.

i. equally distributing the slack among all activities (we call it ES)

ii. the possible latest due date values are set to $\bar{t}_{ji}$ by the help of backward scheduling (we call it BS)

iii. equally distributing the slack among the activities that are performed in common shelters (we call it CES)

iv. distributing the slack among the activities that are performed in common shelters in proportion to the processing time required for the corresponding activities if a worker of skill level 5 is assigned to the activity (we call it PCS)

v. subtracting some reasonable estimates of the expected leadtimes on the subsequent activities (Vepsailanen and Morton's operation due date estimation rule [58], we call it VM). The formulation they propose is:

$$\bar{t}_{ji} = \overline{T_i} - \sum_{q=j+1}^{J} (E(w_{qi}) + p_{qi})$$

where w_{ji} is the waiting time of the activity j of the project i and $E((w_{ji})$ is the expected waiting time of the activity j of the project i. The parameter

p_{ji} is the processing time if the activity j of project i is performed by a worker of skill level 5.

In simulation studies conducted by Carroll [11] and Conway [13], it was found convenient to estimate the waiting time of project i at activity j, w_{ji}, as a multiple of the corresponding processing time p_{ji}:

$$w_{ji} = b \cdot p_{ji}$$

vi. distributing the slack among the activities that are performed in common shelters in reverse proportion to the processing time required for the corresponding activities if a worker of skill level 5 is assigned to the activity (we call it RPCS)

In the first method, the tightness due to work load in all shelters is relaxed by introducing equal slacks in addition to the duration variable of the activity. In the second method, the possible latest due date values are set to $\bar{t}_{ji}$ parameters by subtracting the processing time of the succeeding activity from its finish time. Due to this property, we expect this method to give minimum total weighted tardiness for the FLPM problem under congested shop load. Because, under congested shop load, the waiting times in the queues are very long and so the jobs can be performed very close to its due date and most of the time the completion time exceeds the due date. So the best estimate for the due date of the job is the possible latest due date. The logic used in the third method, distributing the slack among the common shelters, is because of the fact that the common shelters are the most utilized shelters. By introducing larger slacks to the activities to be performed in those common shelters, this tightness is to be eliminated insofar as it is possible. However, the processing time required for the corresponding activities in the common shelters are not close values. For instance, the second activity of the FLPM of a F4 is in the common shelter Fuel and requires 2 half day if a worker of skill level 5 is assigned where the fourth activity of the it is in the common shelter BLS and requires 22 half day if a worker of skill level

5 is assigned. Therefore, the work congestion due to the processing times in these common shelters vary. The fourth method, which is distributing the slack among the activities that are performed in common shelters in proportion to the processing time required for the corresponding activities if a worker of skill level 5 is assigned, is proposed to normalize this variety. The sixth method employs the opposite of the logic used in the PCS. Meanwhile, these six methods are to be compared in chapter 4 in terms of total weighted tardiness, CPU requirements, and the total incurred cost separately.

The activities to be performed in the shelters that are peculiar to the aircraft configurations (PAC) are scheduled by the help of another chain of rules. They are ordered firstly in ascending release time for that specific shelter, a_{ji}. Then, the ones that have equivalent a_{ji} value are grouped and they are ordered in ascending system release time, A_i. Again the ones that have equivalent A_i and a_{ji} are ordered in ascending the due date, $\overline{T_i}$. At the end, we get a order for shelters that are PAC.

After prioritizing the activities to be performed, the dock and the worker assignment process begins. The resource assignment takes place firstly for the activity that is the first one in the order of the first shelter. Meanwhile, the shelters are numbered as Landing Airfield, Fuel, F4H, BLS, Washing, NDI, F4D, KDT, Jet, TAK, Painting, F5H, F5D, T37H, T37D, T38H, and T38D. Firstly, the availability of the dock(s) is checked since the aircraft should be fixed to the dock(s) to be worked on. If there is enough dock(s), the assignment takes place and then the worker assignment is carried out. While assigning worker to the activity among the available workers, the worker with the highest qualification is assigned first. It is logical to utilize the available worker of highest level as much as possible to come up with a schedule that has the minimal tardiness values. Meanwhile, the number of available docks and the worker values in the current shelter are updated and the activity is removed from the activities to be scheduled list if the resource assignment is achieved. Then, if there is activity in the activities to be scheduled list for the current shelter at that decision time, the resource assignment process restarts, otherwise the algorithm passes to the next shelter. If there are neither available workers nor available docks, the release time of the activity or activities (if more than one activity exist in the activities to be scheduled list for the current shelter at that decision time) is increased by 1 and the algorithm passes to the next shelter. The same logic explained above is applied for the next shelter and so on.

Algorithm of the first phase explained above is as follows:

1. Order the projects in ascending release time; A_i; order. Set $t_{now} = 0$.
2. Set $A_i = a_{ji}$ and $h = 1$.
3. For shelter h, form a set consisting of activities which have a_{ji} values equivalent to t_{now}, call them W_{th}.
4. For h, if $W_{th} \neq \emptyset$, depending on the type of the shelter; whether common or PAC; goto 4.1 if common, goto 4.2 else. If $W_{th} = \emptyset$, increase h by 1, goto 4. If there is no shelter left increase t_{now} by 1 and goto 3.
    - 4.1. Has Available Docks and Worker: For the activities of the projects waiting for the common shelter h; W_{th}; check whether there is available dock(s) and worker in the shelter h or not, if there is goto 4.1.1, else goto 4.1.2.
        - 4.1.1. Calculate the ATC values and order them in descending ATC value order. If the number of activities in W_{th} is greater than 1, that is $N(W_{th}) > 1$, take the activity j of project i which has largest ATC value and goto 5. If the ATC values are equivalent, take the one that has smaller due date and goto 5. If the ATC and the due date values are equivalent, take the one that has smaller project number j and goto 5. If $N(W_{th}) = 1$, goto 5.
        - 4.1.2. Hasn't Available Dock(s) and Worker: Increase release times of the activities, a_{ji}, $j \in W_{th}$ by 1 put them to the set $W_{(t+1)h}$. Increase h by 1. Goto 4.

- 4.2. If $N(W_{th}) > 1$, make subgroups from W_{th} which has equivalent system release time, A_i; g_{thl}. Order the subgroups, g_{thl} in ascending system release time order, A_i. Set $l = 1$. If $N(W_{th}) = 1$, goto 5.
- 4.3. Order the aircrafts in the subgroups formed, g_{thl} in ascending project due date order, $\overline{T_i}$. The projects that have equivalent due date, are ordered in ascending project number, i, order. If there is no subgroup left, increase h by 1 and goto 4.
- 4.4. Take the first activity of the order, the activity j of the project i. If $g_{thl} = \emptyset$, increase l by 1 and goto 4.3, else goto 5.

5. Has Enough Dock(s) and Worker: Check whether there is enough dock(s) and worker in the shelter h to perform the activity j of project i or not. If yes goto 5.1, else goto 5.2.

- 5.1. Assign worker to the activity, highest available qualified worker first and assign activity to the dock. Calculate finish time of the activity performed at shelter h, and set it equal to the release times of the succeeding activities of the same project, S_{ji}, namely $f_{ji} = a_{vi}$, $v \in \mathrm{S}_{ji}$. Update the number of available dock and worker values in the current shelter. Remove the activity from the set W_{th} and g_{thl}. If the shelter is PAC and $W_{th} = \emptyset$ increase h by 1 and goto 4, If the shelter is PAC and $W_{th} \neq \emptyset$ goto 4.4. If the shelter is common goto 4.
- 5.2. Increase release times of the activities, a_{ji}, $j \in W_{th}$ by 1 put them to the set $W_{(t+1)h}$. Increase h by 1. Goto 4.

3.4.2 Improvement of the initial feasible schedule

In this phase, the waiting times of the activities of the projects in the queues before the common shelters are utilized. The aim is to find out a schedule incurring smaller cost value than the value required by the feasible schedule obtained in the first phase which is the secondary objective of TUAF.

The method used in this phase is an exchange of mode selection which is switching from the worker of higher skill level to the worker of lower skill level. Utilizing the workers of lower skill level causes a decrease in the labor cost and the incurred cost since the cost of a worker decreases as the skill level decreases. To remind, the cost consists of only the labor cost. Here, a schedule that incurs smaller cost is obtained. This phase is applied to eliminate the negative effects of the rule used in the first phase on cost which is the assignment of the worker with high qualification first. It is important to renote that the FLPM of an aircraft is a must, hence whatever the incurred cost, the projects have to be achieved and the goal is to have as few aircrafts as possible in maintenance. On the other hand, having a schedule incurring less cost with equivalent total weighted tardiness is also a natural inclination.

The algorithm starts with the calculation of the waiting time of the activities that are performed in the PAC shelters and succeeded by activities that are performed in the common shelters in the queue, denoted by w_{ji}. w_{ji} is calculated by subtracting finish time of the activity of a project at the shelter preceding to the common shelter, f_{ji}, from the release time of the activity of that project at the common shelter h, a_{ji}. Then the aircrafts are ordered in descending w_{ji}.

After finding out the activity that has the largest w_{ji}, the existence of an available worker of lower skill level and a dock in the time interval if he is assigned to this activity, is checked. Additionally, a check on whether the waiting time of the activity, w_{ji}, is higher than the difference between the processing times of the modes found out is done. If there exist a worker and a dock satisfying these conditions then the mode selection exchange can be achieved. The mode selection is switched from the worker of higher skill level to the worker of lower skill level. The reason behind the exchange of mode selection is that the common shelters are highly utilized and thus the waiting times are very long. So, the activities ensuring these conditions are performed by a worker of lower skill level instead of waiting for an assignment to the succeeding common shelter. Meanwhile, by the conditions on the selection of the activities mentioned just before, the mode exchange does not cause a change in the release times of the activities for the common shelter, so at the decision time the ATC values are calculated, the same activities exist. Therefore, this mode exchange does not cause a change in the ATC values, so the order of the activities to be performed in the common shelter does not change.

The second phase starts processing after the termination of the first phase and continues till there is no activity satisfying the conditions required to apply the second phase. The algorithm of the second phase is the following:

1. Calculate the waiting time of the activities that are performed in the PAC shelters and succeeded by activities that are performed in the common shelters in the queue, which is denoted by w_{ji}.

2. Select the activity with the largest w_{ji}.

3. Find out the mode of the worker assigned to the activity found in 2.

4. Check whether there is available worker at the lower skill level in the time interval if he is assigned to this activity. If there are any, goto 4.1, else goto 4.2.

    4.1. Available Worker: Choose the worker that has the lowest skill level.

        4.1.1. Check whether the waiting time, w_{ji}, is higher than the difference between the processing times if the activity is performed by the already assigned worker and the worker to be assigned. If it is higher, goto 4.1.1.1, else goto 4.1.1.2.

            4.1.1.1. Check whether there is available dock in the time interval if the worker of lower skill level is assigned to the activity. If there is, goto 4.1.1.1.1, else goto 4.1.1.1.2.

                4.1.1.1.1. Check whether the mode selection exchange cause a decrease in the total incurred cost. If the cost decreases goto 4.1.1.1.1.1, else remove this activity from the activities list formed in 1 and goto 2.

            - 4.1.1.1.1.1. Change the mode selection: Update the finish time of this activity. Recalculate the release time of the activity in the common shelter, a_{ji}, and the waiting time in the queue, w_{ji}. Remove this activity from the activities list formed in 1. Goto 2.
          - 4.1.1.1.2. Check the existence of an available worker that has skill level lower than the skill level of the already assigned worker and higher than the skill level of the worker chosen in 4.1. If there is, goto 4.1.1, else remove this activity from the activities list formed in 1. Goto 2.
        - 4.1.1.2. Check the existence of an available worker that has skill level lower than the skill level of the already assigned worker and higher than the skill level of the worker chosen in 4.1. If there is, goto 4.1.1, else remove this activity from the activities list formed in 1. Goto 2.
- 4.2. Remove this activity from the activities list formed in 1. Goto 2.

In the following section, we will illustrate the two phases of the heuristic with a numerical example.

3.5 A Numerical Example

To make the algorithm more clear and understandable, a numerical example is introduced in this section. The critical steps of ATC calculation and mode selection exchange are illustrated. In addition, the estimation of due date of each activity j of each project i are carried out by the proposed five methods and the VM method during ATC calculation. Let us give the data firstly, then apply the algorithm.

The existing work load in each shelter is presented in Figure 3.2. In Table 3.3, the planes to be scheduled are listed. The resource capacity in each shelter is stated in Table 3.4.

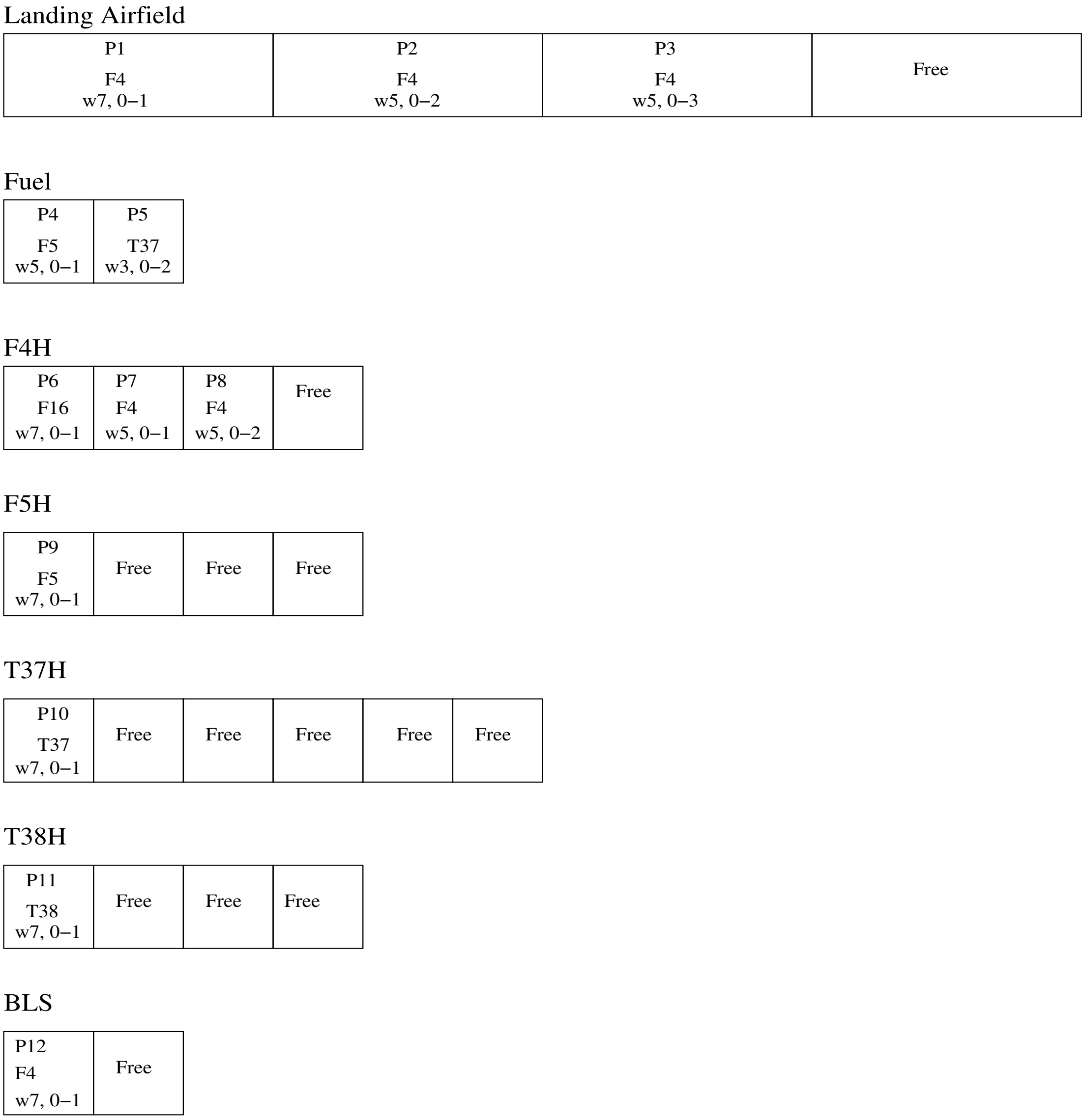


Figure 3.2: Existing work load

In Table 3.5, the resource usage information for each aircraft configuration are presented. A row in Figure 3.5 can be read as follows: The activity 1 of a F4 during FLPM is in the shelter Landing Airfield and a F4 covers 3 docks space in this shelter. This activity is performed in 3 time units if a worker of skill level 7 does, 4 time units if a worker of skill level 5 does, 9 time units if a worker of

Aircraft No	Configuration	A_i	T_i	Weight
p1	F4	-1	17	0.364
p2	F4	0	12	0.098
p3	F4	-1	6	0.364
p4	F5	-4	7	0.098
p5	T37	-4	7	0.074
p6	F16	-4	11	0.407
p7	F4	-7	11	0.364
p8	F4	-7	5	0.364
p9	F5	-6	9	0.098
p10	T37	-6	7	0.074
p11	T38	-6	5	0.058
p12	F4	0	8	0.364

Table 3.3: The aircrafts to be scheduled

Shelter	Common/Not	Dock Cap.	Level 7 Cap.	Level 5 Cap.	Level 3 Cap.
Landing Airfield	C	12	1	2	3
Fuel	C	2	0	1	2
F4H	N	4	1	2	3
F5H	N	4	1	2	3
T37H	N	6	1	2	3
T38H	N	4	1	2	3
BLS	C	2	1	2	0

Table 3.4: The resource capacity in each shelter

Conf.	Activity No	Shelter	Dock Cap.	t-7	t-5	t-3
F4	1	Landing Airfield	3	3	4	9
	2	Fuel	2	1	2	3
	3	F4H	1	2	3	6
	4	BLS	1	1	2	3
F5	1	Landing Airfield	2	2	3	7
	2	Fuel	1	1	2	3
	3	F5H	1	1	2	6
	4	BLS	1	1	2	3
T38	1	Landing Airfield	2	2	3	7
	2	Fuel	1	1	2	3
	3	T38H	1	1	3	6
	4	BLS	1	2	3	5
T37	1	Landing Airfield	2	2	3	7
	2	Fuel	1	1	2	3
	3	T37H	1	1	3	6
	4	BLS	1	2	3	5
F16	1	Landing Airfield	3	1	2	5
	2	Fuel	2	1	2	3
	3	F4H	1	2	3	4
	4	BLS	1	1	2	3

Table 3.5: The resource usage information

skill level 3 does. Meanwhile, to keep the example small, a part of the precedence diagram given in Figure 3.1 is used and the activities 1-4 are considered while the rest are ignored.

Having noted the data of the numerical example, let us proceed with the critical steps of the heuristic we propose. We will first illustrate the ATC calculation. Consider the situation presented in Figure 3.3.

At $t_{now} = 1$ the activities 4 of projects $P6$, $P7$, $P9$, $P10$ and $P11$ are waiting for assignment to the shelter BLS. Because BLS is a common shelter, the ATC values of the waiting activities have to be calculated to determine their positions in the order. First, the due dates of the activities, $\overline{t}_{ji}$, have to be determined, because this information is not defined in the problem. Note again that, there are six methods used in calculating $\overline{t}_{ji}$. All these methods except the BS and the VM, require the information about the slack values which are calculated as $s_{ji} = \overline{T_i} - (A_i + \Sigma d_{ji})$. Let us calculate the slack values first and then apply these methods to obtain the ATC values.

$s_{46} = 11 - (-4 + 9) = 6$

$s_{47} = 11 - (-7 + 12) = 6$

$s_{49} = 9 - (-6 + 9) = 6$
$s_{4(10)} = 7 - (-6 + 11) = 2$
$s_{4(11)} = 5 - (-6 + 11) = 0$

The average processing time required for the activities to be scheduled in the list, $\overline{d}$, used in the ATC formula is:

$$\overline{d} = (1 + 1 + 1 + 2 + 2)/5 = 1.4$$

Since all the slack values are calculated, now we can calculate the $\bar{t}_{ji}$ values.

i. equally distributing the slack among all activities

$\bar{t}_{46} = -4 + 9 + 4 \cdot 1.5 = 11,$
$\bar{t}_{47} = -7 + 12 + 4 \cdot 1.5 = 11,$
$\bar{t}_{49} = -6 + 9 + 4 \cdot 1.5 = 9,$
$\bar{t}_{4(10)} = -6 + 11 + 4 \cdot 2/4 = 7,$
$\bar{t}_{4(11)} = -6 + 11 + 4 \cdot 0 = 5.$

ii. backward scheduling

$\bar{t}_{46} = \overline{T}_6 = 11,$
$\bar{t}_{47} = \overline{T}_7 = 11,$
$\bar{t}_{49} = \overline{T}_9 = 9,$
$\bar{t}_{4(10)} = \overline{T}_{10} = 7,$
$\bar{t}_{4(11)} = \overline{T}_{11} = 5.$

iii. equally distributing the slack among the activities that are performed in common shelters

$\bar{t}_{46} = -4 + 9 + 3 \cdot 2 = 11,$
$\bar{t}_{47} = -7 + 12 + 3 \cdot 2 = 11,$
$\bar{t}_{49} = -6 + 9 + 3 \cdot 2 = 9,$
$\bar{t}_{4(10)} = -6 + 11 + 3 \cdot 2/3 = 7,$
$\bar{t}_{4(11)} = -6 + 11 + 3 \cdot 0 = 5.$

iv. distributing the slack among the activities that are performed in common shelters in proportion to the processing time required for the corresponding activities if a worker of skill level 5 is assigned to the activity

$\bar{t}_{46} = -4 + 9 + (2 + 2 + 2) \cdot 6/(2 + 2 + 2) = 11,$
$\bar{t}_{47} = -7 + 12 + (4 + 2 + 2) \cdot 6/(4 + 2 + 2) = 11,$
$\bar{t}_{49} = -6 + 9 + (3 + 2 + 2) \cdot 6/(3 + 2 + 2) = 9,$
$\bar{t}_{4(10)} = -6 + 11 + (3 + 3 + 3) \cdot 2/(3 + 3 + 3) = 7,$
$\bar{t}_{4(11)} = -6 + 11 + (3 + 3 + 3) \cdot 0/(3 + 3 + 3) = 5.$

v. subtracting some reasonable estimates of the expected leadtimes on the subsequent activities ($\sum_{q=j+1}^{J}(b \cdot p_{qi} + p_{qi})$)

$\bar{t}_{46} = 11 - (1 + 2) \cdot 0 = 11,$
$\bar{t}_{47} = 11 - (1 + 2) \cdot 0 = 11,$
$\bar{t}_{49} = 9 - (1 + 2) \cdot 0 = 9,$
$\bar{t}_{4(10)} = 7 - (1 + 2) \cdot 0 = 7,$
$\bar{t}_{4(11)} = 5 - (1 + 2) \cdot 0 = 5.$

vi. distributing the slack among the activities that are performed in common shelters in reverse proportion to the processing time required for the corresponding activities if a worker of skill level 5 is assigned to the activity

$\bar{t}_{46} = 0 + 2 + 0.5 \cdot 8/0.5 = 10$, since 10 is smaller than the p6's project due date, 11, we set project due date to the $\bar{t}_{46}$.

$\bar{t}_{47} = 0 + 2 + 0.5 \cdot 8/0.5 = 10$, since 10 is smaller than the p7's project due date, 11, we set project due date to the $\bar{t}_{47}$.

$\bar{t}_{49} = 0 + 2 + 0.5 \cdot 6/0.5 = 8$, since 8 is smaller than the p9's project due date, 9, we set project due date to the $\bar{t}_{49}$.

$\bar{t}_{4(10)} = 0 + 3 + 0.3333334 \cdot 3/0.33333334 = 6$, since 6 is smaller than the p10's project due date, 7, we set project due date to the $\bar{t}_{4(10)}$.

$\bar{t}_{4(11)} = 0 + 3 + 0.3333334 \cdot 1/0.3333334 = 4$, since 4 is smaller than the p11's project due date, 5, we set project due date to the $\bar{t}_{4(11)}$.

$$ATC(P6) = max[\frac{0.407}{1}exp(-\frac{max(0, \bar{t}_{46} - 1 - 1)}{3 \cdot 1.4})]$$

$$ATC(P7) = max[\frac{0.364}{1}exp(-\frac{max(0, \bar{t}_{47} - 1 - 1)}{3 \cdot 1.4})]$$

$$ATC(P9) = max[\frac{0.098}{1}exp(-\frac{max(0, \bar{t}_{49} - 1 - 1)}{3 \cdot 1.4})]$$

$$ATC(P10) = max[\frac{0.074}{2}exp(-\frac{max(0, \bar{t}_{4(10)} - 1 - 2)}{3 \cdot 1.4})]$$

$$ATC(P11) = max[\frac{0.058}{2}exp(-\frac{max(0, \bar{t}_{4(11)} - 1 - 2)}{3 \cdot 1.4})]$$

Since all the $\bar{t}_{ji}$ values obtained from all of six methods are equivalent, the ATC values calculated for each method are equivalent. In fact, there is no need for calculation of the $\bar{t}_{ji}$ values for this case since all the activities are the final activities, so $\bar{t}_{ji}$ value is equal to the project due date, $\overline{T_i}$. When we put these values in place of the parameter $\bar{t}_{ji}$ in the above ATC calculation, we found out:

$ATC(P6) = 0.047748897$, $ATC(P7) = 0.04270417$, $ATC(P9) = 0.018509807$, $ATC(P10) = 0.014275388$, $ATC(P11) = 0.01801321$.

Since the activity 4 of aircraft $P6$ has the largest ATC value by all six methods found, first the activity 4 of $P6$ is assigned to the dock in the shelter BLS. The worker of skill level 7 performs the operation. After this resource assignment, there exists an available dock in BLS and a worker of skill level 5. The ATC values of the remaining activities will be recalculated to find out which of them will be assigned to this free dock. The reason behind this recalculation is that the value of d_{ji} changes since the available worker is now of skill level 5. The ATC values obtained in these conditions are:

$$\bar{d} = (2 + 2 + 3 + 3)/4 = 2.5$$

$$ATC(P7) = max[\frac{0.364}{1}exp(-\frac{max(0, 11 - 1 - 2)}{3 \cdot 2.5})]$$

$$ATC(P9) = max[\frac{0.098}{1} exp(-\frac{max(0, 9-1-2)}{3 \cdot 2.5})]$$

$$ATC(P10) = max[\frac{0.074}{2} exp(-\frac{max(0, 7-1-3)}{3 \cdot 2.5})]$$

$$ATC(P11) = max[\frac{0.058}{2} exp(-\frac{max(0, 5-1-3)}{3 \cdot 2.5})]$$

$ATC(P7) = 0.06263599$, $ATC(P9) = 0.022017118$, $ATC(P10) = 0.016534561$, $ATC(P11) = 0.016920017$.

Since the activity 4 of aircraft $P7$ has the largest ATC value by all six methods found, first the activity 4 of $P7$ is assigned to the dock in the shelter BLS. The worker of skill level 5 performs the operation. After this assignment, there is no available dock left in the shelter BLS. Therefore, we increase the t_{now} by 1 and goto the start of the algorithm. In Figure 3.4, the activities being performed after these assignments are presented.

To illustrate another ATC calculation since it is a critical step in our heuristic, consider the situation presented in Figure 3.5.

At $t_{now} = 2$, the planes $P1$ and $P2$ are waiting for assignment to the shelter Fuel. Since Fuel is a common shelter, the ATC values of these activities have to be calculated:

$$ATC(P1) = max[\frac{0.364}{2} exp(-\frac{max(0, \bar{t}_{21} - 2 - 2)}{3 \cdot 2})]$$

$$ATC(P2) = max[\frac{0.364}{2} exp(-\frac{max(0, \bar{t}_{22} - 2 - 2)}{3 \cdot 2})]$$

The due dates of the activities of the specific, $\bar{t}_{ji}$, also have to be determined. Let us first calculate the slack, $s_{ij} = \overline{T_i} - (A_i + \Sigma d_{ji})$.

$s_{2(1)} = 17 - (1 + 7) = 9$

$s_{2(2)} = 12 - (2 + 7) = 3$

There are six methods which are used to calculate the $\bar{t}_{ji}$ values;

i. equally distributing the slack among all activities

   $\bar{t}_{21} = 1 + 2 + 1 \cdot 3 = 6,$

   $\bar{t}_{22} = 2 + 2 + 1 \cdot 1 = 5,$

   If these are put in the place of corresponding ATC calculations above, we get:

   $ATC(P1) = 0.1304087$, $ATC(P2) = 0.15405968$

ii. backward scheduling

   $\bar{t}_{21} = 17 - 5 = 12,$

   $\bar{t}_{22} = 12 - 4 = 8,$

   If these are put in the place of corresponding ATC calculations above, we get:

   $ATC(P1) = 0.047974676$, $ATC(P2) = 0.11038858$

iii. equally distributing the slack among the activities that are performed in common shelters

   $\bar{t}_{21} = 2 + 3 = 5,$

   $\bar{t}_{22} = 2 + 1 = 3,$

   If these are put in the place of corresponding ATC calculations above, we get:

   $ATC(P1) = 0.15405968$, $ATC(P2) = 0.182$

iv. distributing the slack among the activities that are performed in common shelters in proportion to the processing time required for the corresponding activities if a worker of skill level 5 is assigned to the activity

   $\bar{t}_{21} = 0 + 2 \cdot 2.25 = 6.5$, because we floor the values we take 6.

   $\bar{t}_{22} = 0 + 2 + 0.75 \cdot 2 = 3.5$, because we floor the values we take 3.

   If these are put in the place of corresponding ATC calculations above, we get:

$ATC(P1) = 0.1304087$, $ATC(P2) = 0.182$

v. subtracting some reasonable estimates of the expected leadtimes on the subsequent activities ($\sum_{q=j+1}^{J}(b \cdot p_{qi} + p_{qi})$)

$\bar{t}_{21} = 17 - (1+2) \cdot (2+3) = 2$,

$\bar{t}_{22} = 12 - (1+2) \cdot (2+3) = -3$,

If these are put in the place of corresponding ATC calculations above, we get:

$ATC(P1) = 0.182$, $ATC(P2) = 0.182$

vi. distributing the slack among the activities that are performed in common shelters in reverse proportion to the processing time required for the corresponding activities if a worker of skill level 5 is assigned to the activity

$\bar{t}_{21} = 0 + 2 + 0.5 \cdot 9/1.25 = 5.6$, because we floor the values we take 5.

$\bar{t}_{22} = 0 + 0.5 \cdot 3/1.25 = 3.2$, because we floor the values we take 3.

If these are put in the place of corresponding ATC calculations above, we get:

$ATC(P1) = 0.15405968$, $ATC(P2) = 0.182$

The activity 2 of aircraft $P2$ has the largest ATC value for all methods except the VM. As a coincidence equivalent ATC values are obtained when the VM is employed. We choose the activity 2 of $P2$ and assign it. Since the aircraft $P2$ is F4, it will cover 2 docks. So there are no available docks in the shelter Fuel. Meanwhile, the worker of skill level 7 is assigned to this activity.

Having presented the ATC calculations, let us give the Gantt Chart we get from the first phase of the heuristic proposed in which the method BS is used, given in Figure 3.6. Remember that, we call this schedule an initial feasible schedule.

The total weighted tardiness of the proposed schedule is $(0.074 \cdot (8-7)) + (0.058 \cdot (9-5)) + (0.364 \cdot (10-6)) = 1.762$, the FLPM of the planes, $P3$, $P10$

and $P11$ are tardy with the values 1, 4, and 4 time units respectively. The total working time of skill levels 7, 5, and 3 are 22, 27, and 2 time units respectively.

Let us apply the second phase of the heuristic to the feasible schedule given in Figure 3.6. As can be seen from the Figure, w_{21}, w_{23}, w_{44}, w_{45}, w_{49}, $w_{4(10)}$, and $w_{4(11)}$ are nonzero. In other words, there are seven possibilities that we can exchange the mode with the lower one. All the activities are waiting for an assignment to a common shelter. This observation supports our claim that the common shelters are utilized more than the PAC ones. Note again that, the mode selection exchange is applied in the PAC shelters in order not to change the order of the activities in the common shelters. The reason behind this restriction is stated in 3.4.2. Therefore, we will eliminate the w_{21} and w_{23}, because the first activities of $P2$ and $P3$ are performed in a common shelter which is landing airfield. If we order the remaining activities in descending w_{ji} order, we obtain the order as follows: $P11$, $P10$, $P9$, $P5$ and $P4$. The next step is to reduce $w_{4(11)}$. The activity 3 of $P11$ is performed in the shelter T38H and a worker of skill level 7 is assigned. The assignment takes place at $t = 0$. From the available workers at $t = 0$, the worker of lowest skill level is of level 3. In addition, this worker and the dock in the shelter T37H is not assigned to any of the activities in the interval that the activity 3 of $P11$ is being performed with this new assignment. If we exchange the skill level from 7 to 3, then $f_{3(11)}$ is changed to 6. Because $a_{4(11)}$ is higher than $f_{3(11)}$, we can make this mode selection exchange and we obtain the Gantt Chart given in Figure 3.7.

If we apply the algorithm of phase 2 to all remaining candidates, $P10$, $P9$, $P5$ and $P4$, we obtain the Gantt Chart figured in 3.8. As can be seen from the figure, the total weighted tardiness of the proposed schedule is again 1.762 and the total working time of skill level 7, 5, and 3; 18, 34, and 14 time units respectively. To remind, we claim that a schedule with a lower cost can be obtained by the application of phase 2. To prove this claim, take the values 7, 2, and 1 for the cost of the one working time unit of skill level 7, 5, and 3 respectively. Then, the cost incurred for the initial feasible schedule is 210. The total cost incurred after each application of phase 2, mode exchange, to the candidates $P11$, $P10$,

$P9$, and $P4$, is plotted in Figure 3.9. The $P5$ is not among the candidates since the mode exchange for $P5$ does not cause a decrease in the total cost incurred. As it is noticed, the total cost incurred decreases for each change as we claim in 3.4.2.

3.6 Conclusion

In this chapter, we consider the problem of FLPM of aircrafts belonging to TUAF which is a real life example of NRCMPSMS. In Section 3.1, we described the problem and modelled it mathematically in Section 3.3 with the assumptions, the variables, and the parameters used in developing the mathematical model of the problem stated in Section 3.2. A stepwise representation of the proposed solution procedure is explained in the Section 3.4. The heuristic is composed of two phases. In the first phase an initial feasible schedule is obtained with the objective of minimum total weighted tardiness and in the second phase this schedule is modified by mode selection exchanges to obtain a smaller total incurred cost value.

A critical step of our heuristic was ordering the activities waiting for the common shelters. We adapted the known ATC rule and incorporate the existence of multiple projects and availability of the mode selection. In addition, six methods were proposed to estimate the due date of each activity j of each project i, $\bar{t}_{ji}$, since this parameter is endogenous in our model and it is used in ATC calculation. Among those, backward scheduling method was claimed to give better results in terms of total weighted tardiness. Another important step was the exchange of mode selection. To end up with smaller cost values, we change the modes of the activities performed only in the PAC shelters with the lower ones. A numerical example was provided to illustrate these critical steps and the results of the heuristic were noted.

To build up the complete decision support model for the FLPM of aircrafts belonging to TUAF, the FLPM problem should be treated as a NRCMPSMS in integration with the generation of the data required. To realize this, in the next chapter, the data of the the release and the due date of the aircrafts, is changed to present the tightness levels of these factors. With the data obtained after these changes, the problems are solved by the solution procedure explained in Section 3.4. According to the computational results, the efficiency of the six methods used for estimating the $\bar{t}_{ji}$ under these levels, from the total weighted tardiness, total incurred cost, and the CPU time required for the execution of the proposed heuristic, will be investigated. Furthermore, the efficacy of the second phase which is for improving the feasible schedule obtained from will also be studied under tight or loose release and due dates. It is important to note that an example experienced by TUAF will be used.

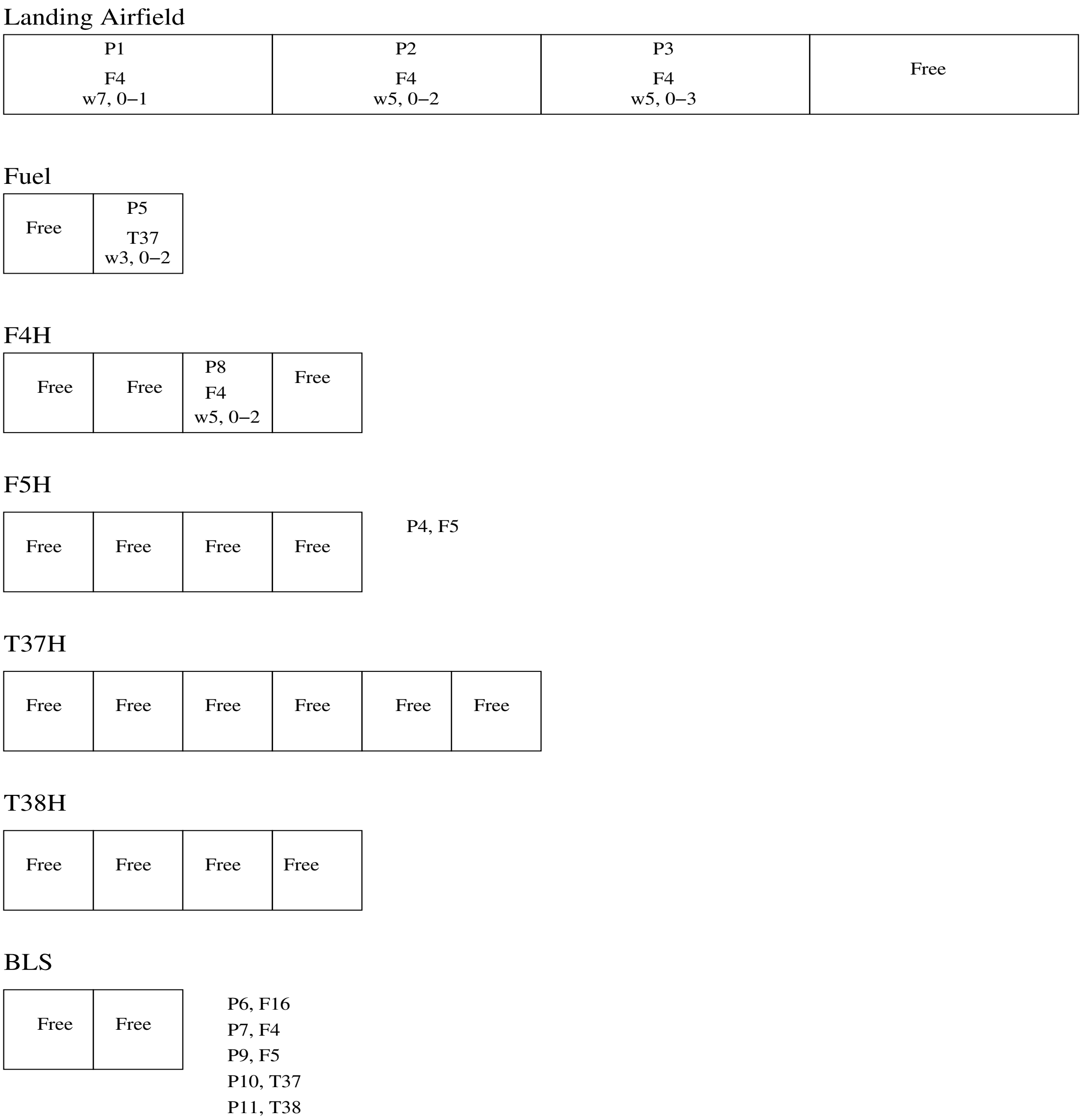


Figure 3.3: The work load at t=1

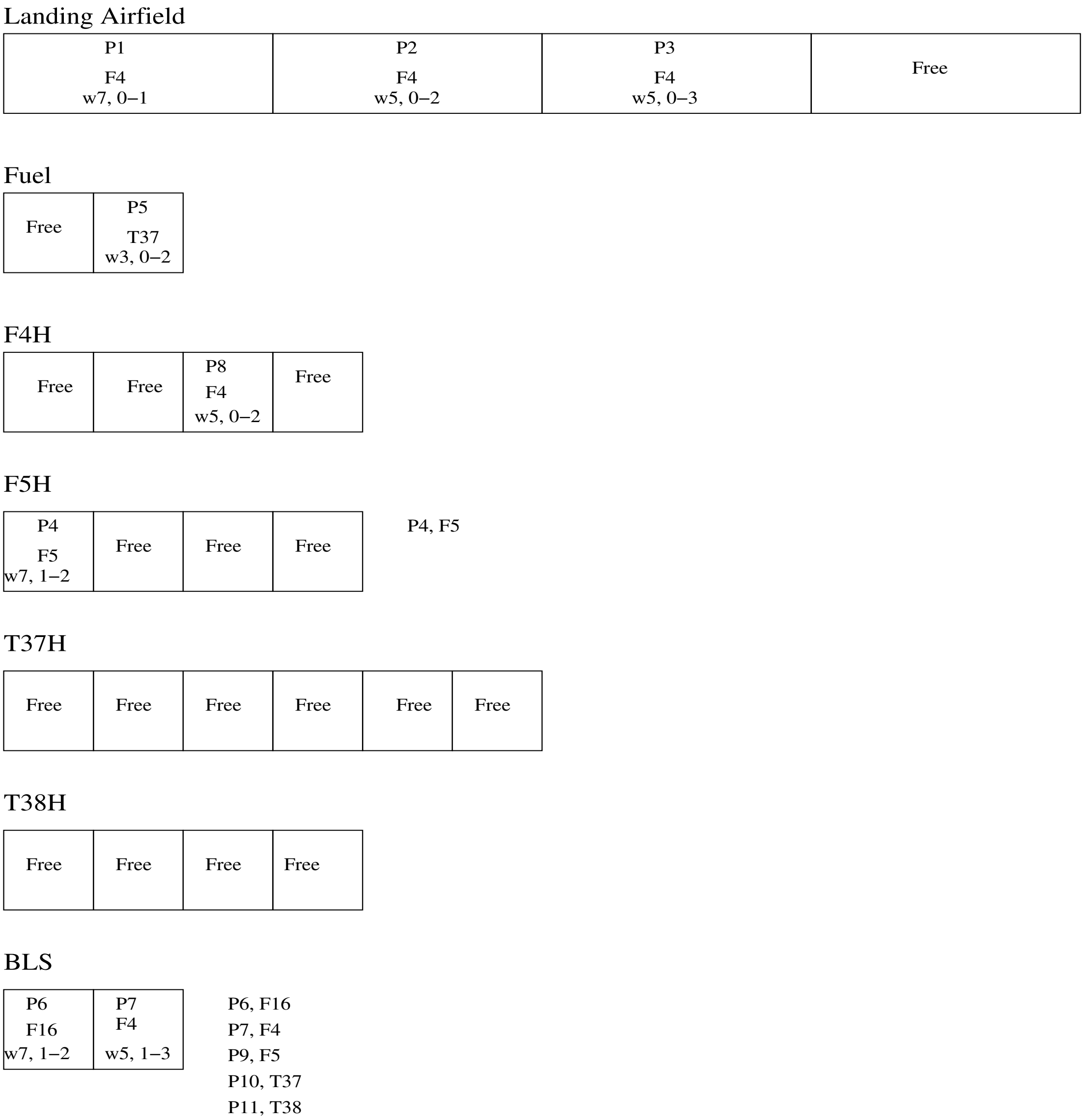


Figure 3.4: Work load after resource assignment

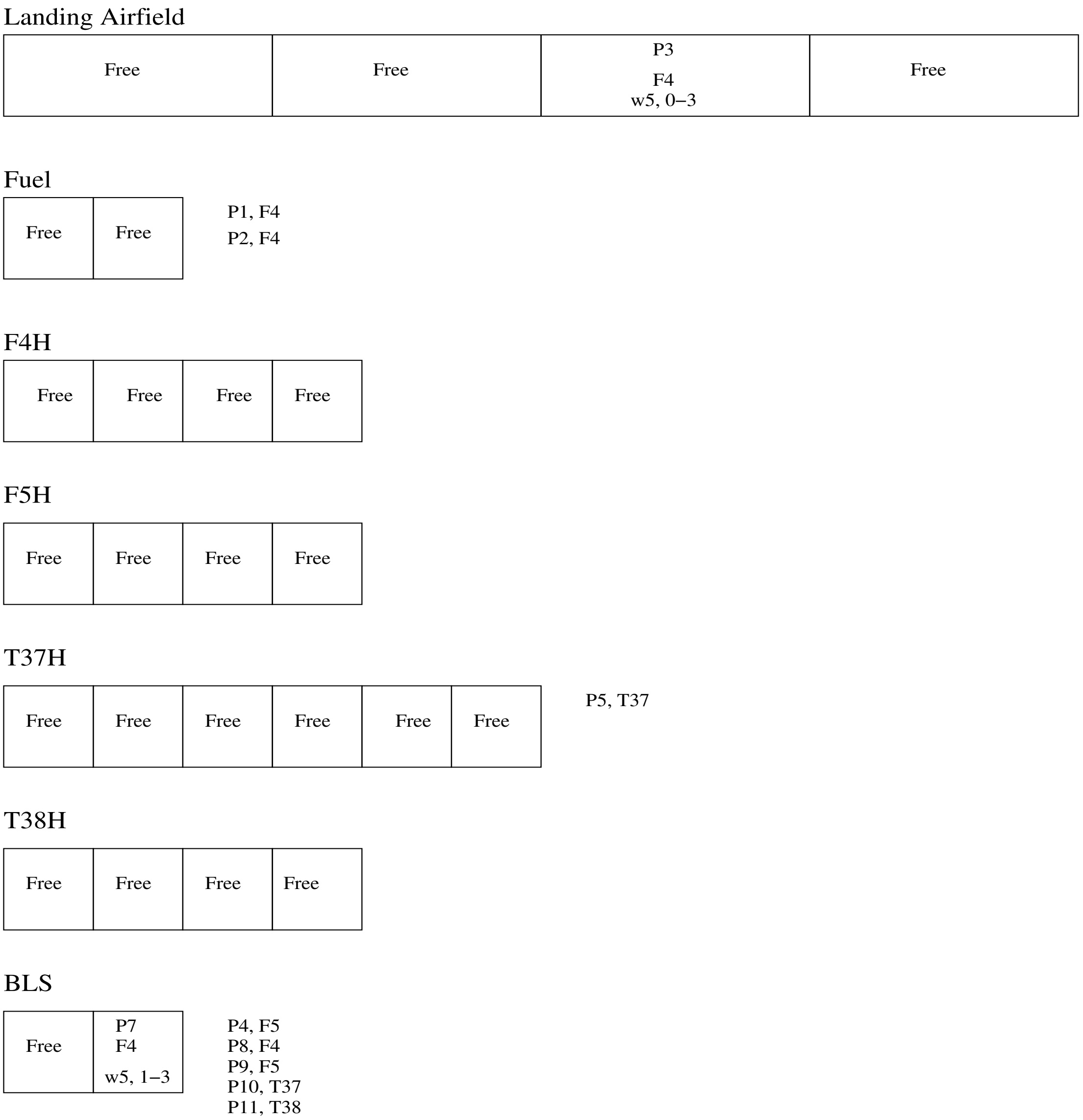


Figure 3.5: Work load at t=2

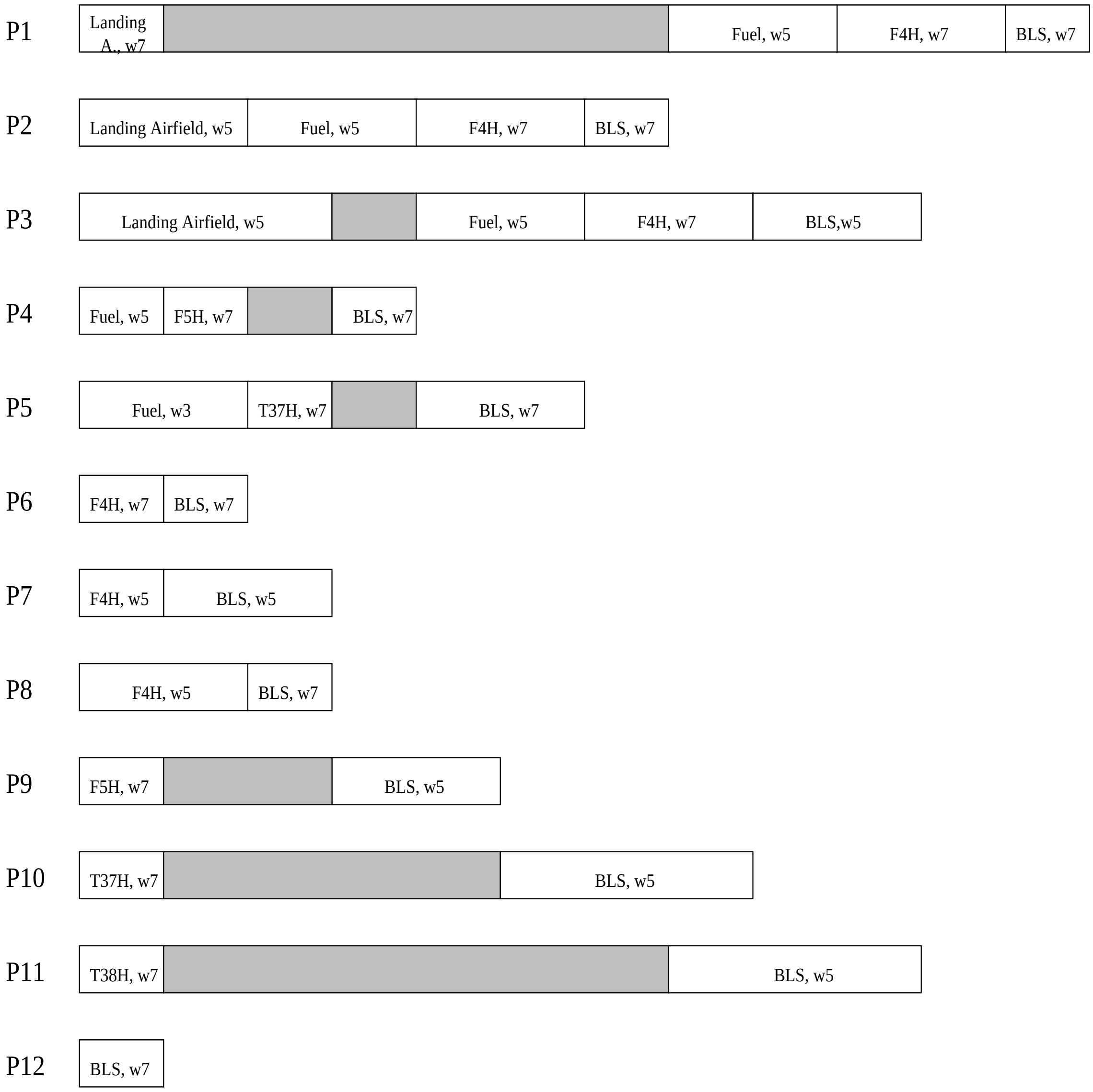


Figure 3.6: Initial Feasible Schedule

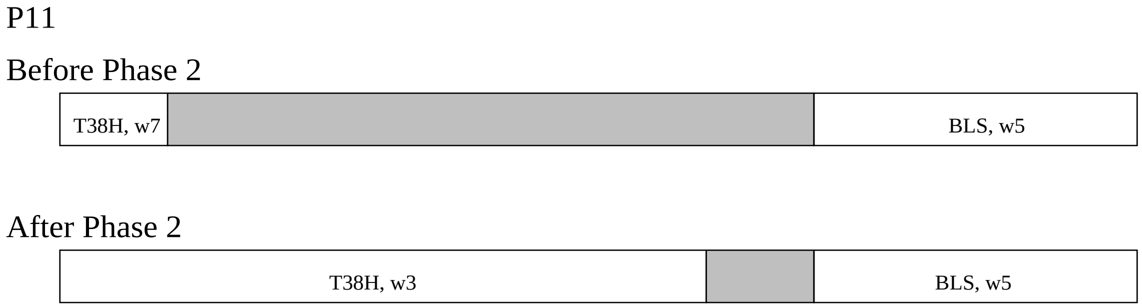


Figure 3.7: The Gantt Chart before and after phase 2 for P11

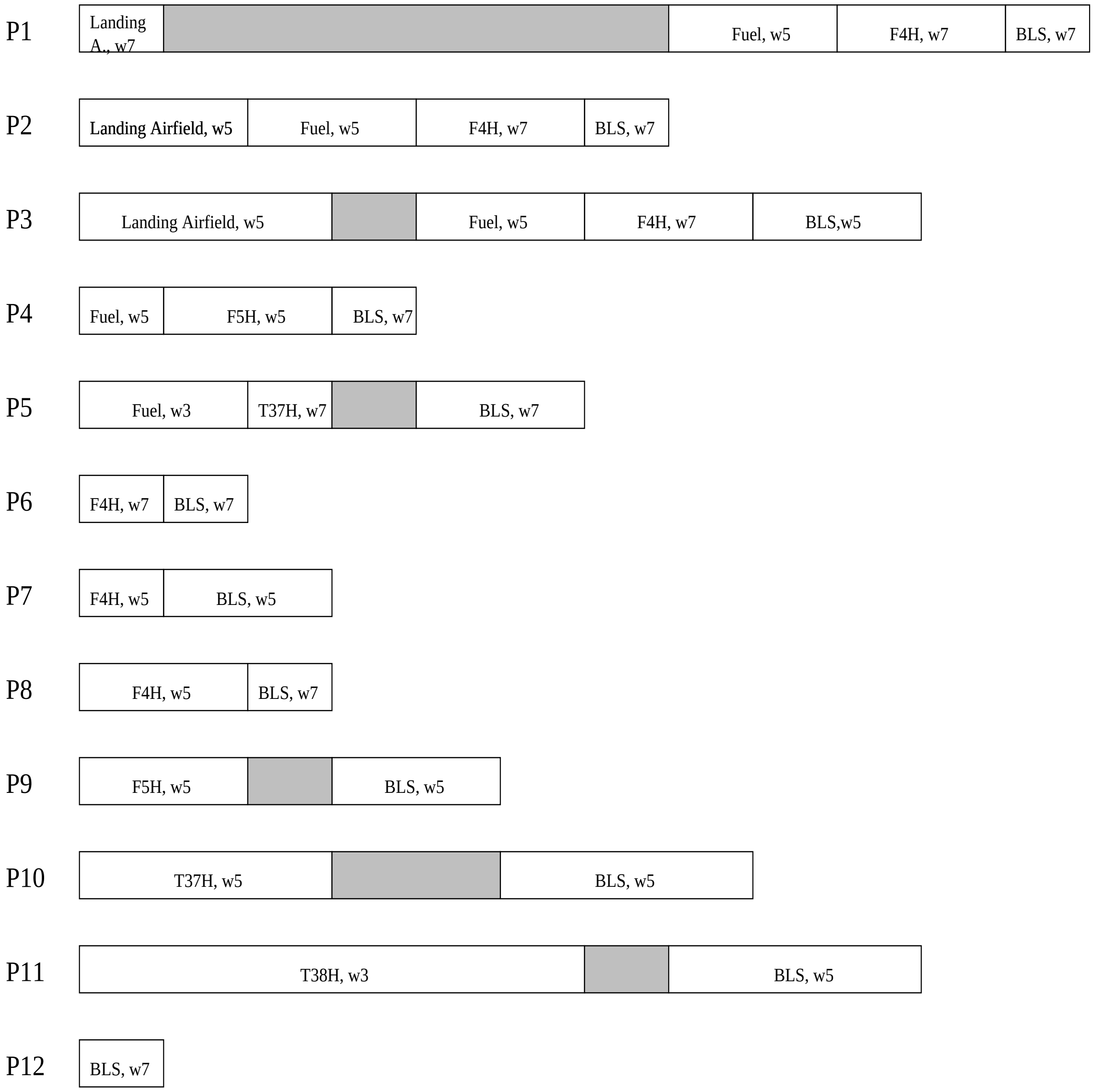


Figure 3.8: The Gantt Chart after phase 2

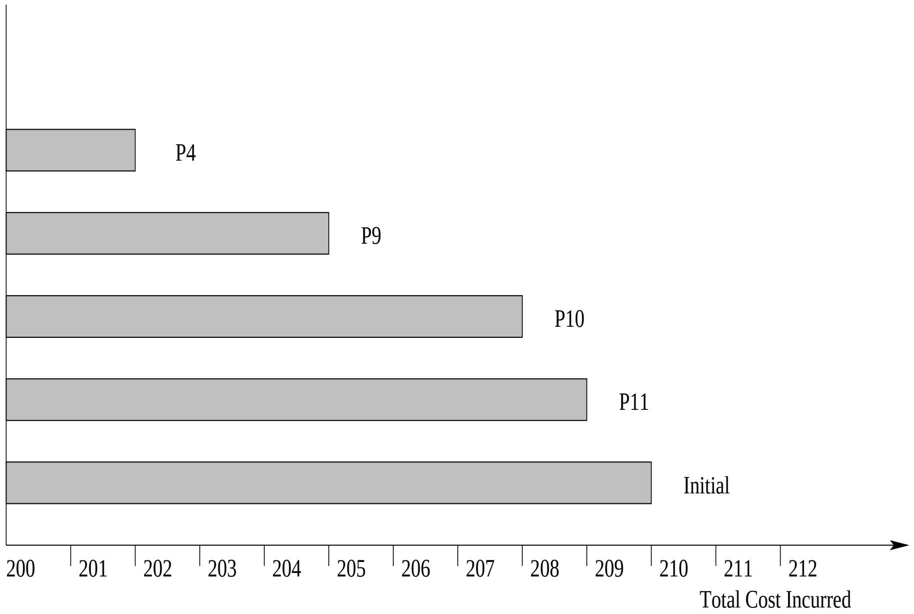


Figure 3.9: Total incurred cost obtained after each mode selection exchange

Chapter 4

Computational Study

In this chapter, we will study the influence of problem parameters in the previous chapter, which are the release and the due date of the aircrafts, on the objective functions of total weighted tardiness and total incurred cost obtained from, and the computational time required for the execution of the proposed heuristic to the Factory Level Preventive Maintenance (FLPM) problem of aircrafts belonging to Turkish Air Force (TUAF) that is explained in 3.4.

We will first present the parameters of the problem which are known with certainty and determined by TUAF. Next, we will specify the levels of the release and the due date of the aircrafts. For each different release and due date tightness level combination, we will try to determine the best performing $\bar{t}_{ji}$ estimation method in terms of the objectives total weighted tardiness, total incurred cost and the CPU time required at initial schedule. To recall, $\bar{t}_{ji}$ is the due date of the activity j of the specific project i, that is the desired completion time of the activity j of the specific project i from the corresponding shelter and the values of this parameter is not available in the problem definition. Consequently, we will decide on adding the improvement phase, which is the phase 2 and explained in 4.4, into our single-pass algorithm. The $\bar{t}_{ji}$ estimation methods will also be compared after improvement. Meanwhile, the analysis on finding best performing $\bar{t}_{ji}$ estimation method and deciding on adding the improvement phase will be presented and analyzed from the Military Supply Point (MSP) and the fleets points of view separately. The reason behind this representation is that the MSP and the fleets determine the weight matrices of the aircraft configurations differently.

The solution procedure that we have proposed and the data generation was coded in JAVA language and complied with JCreator LE 2.0. The code was run on a standard PC with AMD Duron 1.20 GHz processor with 256 MB memory under Windows XP.

In Section 4.1 we present the fictive but representative data specific to FLPM experienced by TUAF. In Section 4.2, we define the experimental settings of the problem. The problem experienced by TUAF is solved with the heuristic that we have proposed in Section 4.3. The computational results of the initial scheduling phase, which is phase 1, and the improvement phase, which is phase 2, are provided in Sections 4.4 and 4.5, respectively. Then, we evaluate the results of the proposed heuristic with different release and due date tightness level combinations and determine the best performing $\bar{t}_{ji}$ estimation method for the MSP and the fleets separately in Section 4.6. The final evaluation of the results and the decision on adding the final improvement phase or not is presented in Section 4.7.

4.1 FLPM Specific Data

In this section, the values of the parameters of the FLPM problem which are specific to TUAF are presented. These values are obtained from a past year FLPM evaluation report prepared by the MSP. However, due to the information security, the fictive representatives of the values in this report are used in this thesis. The parameters of the FLPM problem specific to TUAF are the aircraft configuration types, the number of aircrafts to be scheduled, the release and the due dates of the aircrafts, the shelters, the precedence diagrams for each aircraft configuration, the number of docks within the shelters, the number of workers of each skill level in each shelter, the processing time required for each activity and the cost of a working time unit for each skill level, and the initial load of the system.

As stated in Section 3.1 the aircraft configurations that are sent to MSP for the FLPM are F16, F5, F4, T37, and T38. The aircrafts to be scheduled with the information release and the due dates of them are listed in Table 4.1.

The task plan for the FLPM of a F4 was given in Section 3.1 with the order of the operations, the time, and the resources required to perform each operation. The operations involved in the FLPM of the F5, T37, and T38 and the precedence relationship between them are similar but the shelter the operations are performed in, so the worker capable of performing the operation and the required processing times for each skill level, are different. In fact, only the operations that are to be performed in PAC type shelters are different, namely an operation in the task plan of a F4 that is performed in F4D is performed in F5D for a F5. Another difference is that the task plan for the FLPM of a F16 involves a subset of the operations involved in the task plan of a F4. After having noted the properties of the task plans used in our real-life example, the values of the processing times for each skill level and the number of docks the aircrafts occupy with the corresponding shelter information are gathered in the Table 4.2 for each aircraft configuration. The precedence relationship diagram for a F16 is given in Figure 4.1.

The resource capacity in each shelter is stated in Table 4.3. To model the FLPM exactly, the work load in each shelter due to the aircrafts, which are currently in FLPM, are presented in Figures 4.2 and 4.3 for the common and the PAC type shelters, respectively. The aircrafts that are in the shelters currently are listed in Table 4.4 with their configuration type, the activity number being performed, the release date, and the due date information. As noticed, there are more than one activity being performed for some of the aircrafts at the same time interval. This is because either the aircraft is disassembled beforehand and these subassemblies are sent to different shelters for different activities or different activities are performed on different places of the aircraft simultaneously. Another important thing is the release and the due dates can take nonpositive values. In addition, these aircrafts that are currently in FLPM has names starting with

Aircraft	Conf. Type	A_i	$\overline{T_i}$	Aircraft	Conf. Type	A_i	$\overline{T_i}$
n1	f4	0	128	n47	f5	167	276
n2	f4	6	133	n48	f5	176	283
n3	f4	15	143	n49	f5	193	301
n4	f4	29	135	n50	f5	203	310
n5	f4	37	165	n51	f5	213	320
n6	f4	47	175	n52	f5	223	331
n7	f4	52	180	n53	f5	234	342
n8	f4	57	185	n54	t37	28	129
n9	f4	61	189	n55	t37	37	136
n10	f4	69	198	n56	t37	50	151
n11	f4	74	203	n57	t37	66	167
n12	f4	81	210	n58	t37	86	186
n13	f4	88	216	n59	t37	96	197
n14	f4	95	223	n60	t37	110	211
n15	f4	106	234	n61	t37	128	227
n16	f4	117	243	n62	t37	140	239
n17	f4	126	252	n63	t37	153	252
n18	f4	133	260	n64	t37	170	271
n19	f4	140	266	n65	t37	196	297
n20	f4	145	271	n66	t37	215	316
n21	f4	152	278	n67	t37	223	324
n22	f4	160	286	n68	t37	234	333
n23	f4	170	296	n69	t37	245	343
n24	f4	181	306	n70	t38	28	129
n25	f4	188	313	n71	t38	40	141
n26	f4	192	317	n72	t38	48	149
n27	f4	199	323	n73	t38	65	166
n28	f4	203	329	n74	t38	71	172
n29	f4	209	334	n75	t38	87	187
n30	f4	213	338	n76	t38	112	213
n31	f4	217	342	n77	t38	129	228
n32	f4	222	347	n78	t38	135	234
n33	f4	230	355	n79	t38	154	253
n34	f4	236	361	n80	t38	166	265
n35	f5	29	140	n81	t38	185	324
n36	f5	46	157	n82	t38	198	296
n37	f5	61	172	n83	t38	220	315
n38	f5	70	181	n84	t38	230	328
n39	f5	79	189	n85	t38	241	339
n40	f5	91	202	n86	f16	133	160
n41	f5	95	206	n87	f16	133	160
n42	f5	105	216	n88	f16	182	209
n43	f5	113	224	n89	f16	211	238
n44	f5	126	235	n90	f16	226	253
n45	f5	142	251	n91	f16	226	253
n46	f5	152	261	n92	f16	263	290

Table 4.1: The aircrafts to be scheduled

	F5				T37				T38				F16			
Act.	t-7	t-5	t-3	Docks	t-7	t-5	t-3	Docks	t-7	t-5	t-3	Docks	t-7	t-5	t-3	Docks
1	3	8	14	2	4	8	15	2	3	8	10	2	2	4	7	3
2	1	2	3	1	1	2	3	1	1	2	3	1	1	2	3	2
3	5	6	11	1	3	6	11	1	4	6	10	1	1	2	3	1
4	10	20	22	1	10	18	32	1	17	18	28	1	4	8	14	1
5	4	6	10	2	2	6	8	2	5	6	8	2	3	6	9	3
6	3	6	7	1	5	6	8	1	4	6	7	1	2	4	7	1
7	15	32	59	1	24	28	29	1	24	28	55	1	4	8	14	1
8	4	8	15	1	7	8	11	1	3	8	13	1	1	2	3	2
9	40	66	113	1	40	60	102	1	50	60	84	1	1	2	3	1
10	7	10	15	1	5	10	11	1	5	10	13	1	2	4	6	1
11	8	16	28	1	8	16	24	1	14	16	20	1	1	2	3	1
12	2	4	6	1	3	4	6	1	2	4	6	1	1	2	3	1
13	1	2	3	1	1	2	3	1	1	2	3	1	2	4	5	1
14	4	8	11	1	3	6	10	1	4	6	11	1	1	2	3	3
15	1	2	3	1	1	2	3	1	1	2	3	1	3	4	7	3
16	3	4	5	1	2	4	5	1	3	4	5	1	1	2	3	1
17	3	8	12	1	4	8	10	1	6	8	13	1	2	4	6	3
18	1	2	3	2	1	2	3	2	1	2	3	2	-	-	-	-
19	7	10	18	2	6	10	17	2	9	10	18	2	-	-	-	-
20	3	4	6	1	2	4	5	1	3	4	5	1	-	-	-	-
21	6	8	13	2	3	8	9	2	4	8	13	2	-	-	-	-

Table 4.2: The task Plan of the FLPM of F5, T37, T38 and F16

"p". There are also aircrafts waiting for an assignment to the shelters at the beginning. These aircrafts are listed in Table 4.5 with their configuration type, the number of the activity that the aircraft is waiting for, the release date, and the due date information.

In addition to the logistic specific information presented till now, to calculate the incurred cost value for the schedules obtained, the cost values per working time unit for each skill level are required. In our experimental design, again due to the information security the fictive but representative proportions 7/2/1 are used for the skill levels 7, 5, and 3 respectively.

Meanwhile, for the look-ahead parameter k used in the ATC formulation, 3 is used since Vepsalainen and Morton [58] noted that this value is a reasonable "average" for dynamic job shops to compensate for longer average queue lengths. In addition, they mentioned that, the exponential look-ahead works by ensuring timely completion of short jobs (steep increase of priority close to due date), and by extending the look ahead far enough to prevent long tardy jobs from overshadowing clusters of shorter jobs. Additionally, for the leadtime estimation parameter b, Vepsailanen and Morton [58] took the value as 2 for all shops and load conditions. After having noted the FLPM specific data experienced by TUAF, in the next section the experimental setting used and the expectations

Shelt.	Common/Not	Dock Cap.	Level 7 Cap.	Level 5 Cap.	Level 3 Cap.
Landing Airfield	C	12	1	4	8
Fuel	C	2	1	2	3
BLS	C	1	0	4	5
Washing	C	6	1	2	4
NDI	C	2	1	1	2
KDT	C	1	0	2	4
JET	C	16	1	4	8
TAK	C	2	1	1	2
Painting	C	6	1	3	6
F4D	N	16	1	12	20
F4H	N	4	1	2	4
F5D	N	12	1	5	8
F5H	N	4	1	1	2
T37D	N	12	1	4	6
T37H	N	6	1	1	2
T38D	N	12	1	4	5
T38H	N	4	1	1	2

Table 4.3: The resource capacity in each shelter

Aircraft	Conf. Type	A_i	$\overline{T_i}$	Act. No	Aircraft	Conf. Type	A_i	$\overline{T_i}$	Act. No
p1	f4	-163	-38	17	p21	f4	-2	123	1
p2	f4	-153	-28	14	p22	f16	-17	10	6, 7
p3	f4	-144	-19	19	p23	f16	-4	23	3
p4	f4	-144	-19	19	p24	f5	-103	5	16
p5	f4	-131	-6	12, 13	p25	f5	-87	21	10, 11
p6	f4	-83	42	9	p26	f5	-76	32	9
p7	f4	-83	42	9	p27	f5	-56	52	9
p8	f4	-83	42	9	p28	f5	-38	70	7
p9	f4	-83	42	9	p29	f5	-31	77	7
p10	f4	-80	45	9	p30	t38	-77	24	9
p11	f4	-57	68	9	p31	t38	-77	24	9
p12	f4	-45	80	7	p32	t38	-45	56	8
p13	f4	-45	80	7	p33	t38	-37	64	7
p14	f4	-39	86	7	p34	t38	-37	64	7
p15	f4	-33	92	7	p35	t38	-21	80	5
p16	f4	-33	92	7	p36	t38	-23	78	4
p17	f4	-27	98	6	p37	t37	-34	67	7
p18	f4	-25	100	5	p38	t37	-34	67	7
p19	f4	-2	123	1	p39	t37	-8	93	3
p20	f4	-2	123	1	p40	f5	-121	-13	21

Table 4.4: The aircrafts in the shelters currently

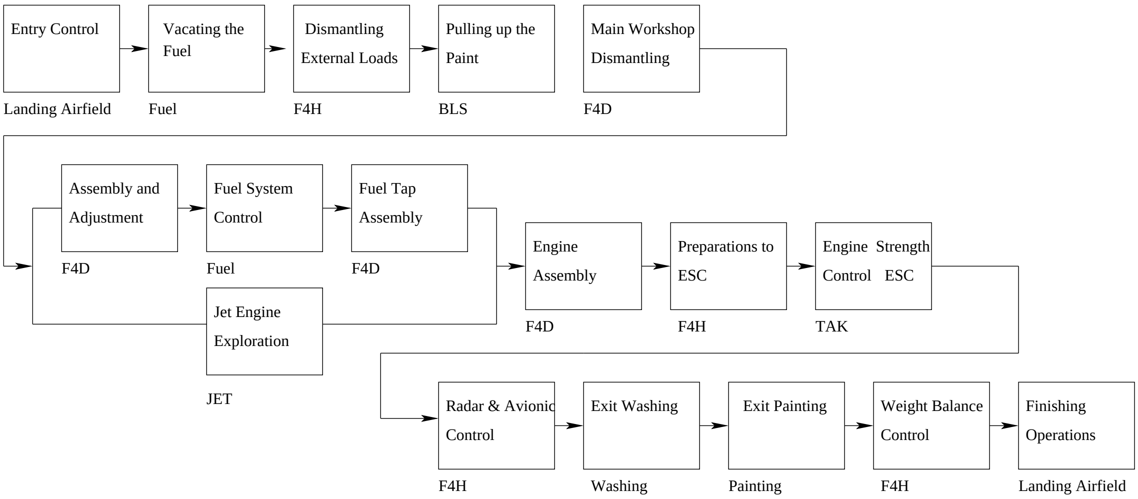


Figure 4.1: Precedence diagram of a F16 aircraft

Aircraft	Conf. Type	A_i	$\overline{T_i}$	Act. No
p41	f4	-12	113	2
p42	f5	-26	82	6
p43	f5	-3	105	1
p44	t38	-21	80	5
p45	t37	-105	-4	19
p46	t37	-15	86	4
p47	t37	-15	86	4
p48	t37	-15	86	4
p49	t37	-1	100	1

Table 4.5: The aircrafts waiting for an assignment to the shelters and currently in FLPM

on the performance of the $\bar{t}_{ji}$ estimation methods and the improvement phase will be presented.

4.2 Experimental Setting

In the preceding section, the logistic and financial information experienced during the FLPM of the aircrafts belonging to TUAF in one of the past years, are provided. Among this information, only the release and the due dates of the FLPM of the aircrafts can be changed since they are operational data. On the other hand, the rest of the information is strategic data and was determined before the construction of the MSP, so it cannot be changed unless a capital is to be invested which is out of the scope of this thesis. In addition to being an operational data, these two parameters are critical in scheduling and affect the performance measures of the schedules. In other words, the release and the due date information are the determinants in the success of the scheduling. Therefore, in this section we focus on the determination of these two operational parameters.

The release and due date determination method used by TUAF is very simple, but not comprehensive in spite of the criticality of these values. TUAF determines the release dates by adding 5 years for F4 and F16, 4 years for F5, T37 and T38 to the finish time of the last FLPM of the aircrafts. After TUAF calculates the release date data, as can be noticed from the data tabulated in the preceding section, TUAF adds 125 days for F4, 108 days for F5, 101 days for T37 and T38, and 27 days for F16 to these values to determine the due dates of the aircrafts. These 125, 108, 101, and 27 values are the length of the critical path of the preceding relationship diagrams of the corresponding aircraft configurations assuming all of the activities are performed by a worker of skill level 5 and both the workers and the docks are unlimited. The insufficiency of the release and due date determination method for the FLPM experienced by TUAF leads us to develop a method for each parameter which is presented in this section. The methods we propose aims at finding the tightness levels of these two parameters. In this section, after having determined these levels, for each release and due date tightness level combination, we also criticize the performance of the $\bar{t}_{ji}$ estimation methods and the success of the improvement phase in terms of the total weighted tardiness and the total incurred cost. In addition, as noticed TUAF treats all the aircraft configurations same during the FLPM scheduling although they are weighted differently by the scheduler in the MSP and the officer in the fleet. In this section, we also find out the weight matrices for both of these two points of view since our heuristic is capable of handling the weight factor. Furthermore, the analysis on the effect of these two different weight matrices on the objectives the total weighted tardiness and the total incurred cost.

The release date determination method we propose relates the arrival rate of the aircrafts with the utilization of the bottleneck shelter. This preference is because of a known fact that the arrival rate is a strong determinant on the shop load and the utilization of the bottleneck resource is an important indicator for the shop load. Meanwhile, in general being bottleneck is related with the largeness of the processing time required in the corresponding machine. However, in the FLPM problem of TUAF there is more than one processing time value for each activity since workers of different skill levels do the activity in different time units. In addition, in one shelter, more than one activity can be processed and the processing times required can be different. Due to these two properties of the FLPM problem, it is not possible to find out the bottleneck shelter by just evaluating the processing times required. Therefore, we determine the bottleneck shelter by evaluating the utilization levels of the shelters. We take the shelter that has the largest utilization level as the bottleneck shelter. We calculate the utilization level by dividing the total time units spent in that specific shelter by all of the aircrafts to the sum of the number of docks of all skill levels in that shelter multiplied by the scheduling horizon. Meanwhile, the scheduling horizon is the finish time of the lastly scheduled aircraft. Additionally, to carry out our method, we use a parameter called release date coefficient. This parameter is multiplied by 260, which is the number of working days in one year. The value obtained is the horizon that the aircrafts can arrive to the MSP. After having noted the utilization level calculation formula and defined the release date coefficient we propose, now comes the steps of the release date determination method:

1- Take a value for the release date coefficient.

2- Multiply the release date coefficient by 260.

3- Find out the number of the aircrafts for each aircraft configuration and divide the value obtained in the second step to the values of the number of aircrafts for each aircraft configuration.

4- Generate the interarrivals of the aircrafts for each aircraft configuration uniformly, where the quotient obtained in the third step is used as the q

parameter of the uniform distribution, $U(0, q)$.

5- Calculate the release date of the aircrafts by summing up the interarrivals generated in the fourth step.

6- Run the heuristic explained in Section 3.4 with the release dates obtained in the fifth step.

7- Check whether the utilization level of the bottleneck shelter is the predetermined value of the utilization level of the bottleneck shelter. If the utilization level of the bottleneck shelter is not the predetermined value take a different value for the release date coefficient and goto 1, else terminate.

As noticed our method is based on trial and error. The bottleneck cannot be determined without a schedule at hand since the utilization level is not an available information at the beginning. Therefore, with the help of the release date coefficient, we can adjust the arrival rates and after running the heuristic, we can evaluate the utilization levels of all of the shelters and so determine among which of the shelters is the bottleneck. In other words, we try for different arrival rates to obtain the predetermined values for the utilization level of the bottleneck shelter. These predetermined values in fact represent the shop load, and the corresponding release date coefficients and so the arrival rates represent the tightness levels. Vepsailanen and Morton [58] take the following values for the utilization level of the bottleneck shelter:

i. 80%

ii. 85%

ii. 90%

iv. 95%

v. 97%

They find out the arrival rates resulting with the above values. Different from our problem, the bottleneck machine is known with certainty at the beginning in their model. They take these arrival rates that they have obtained as the tightness levels of the arrival rates, similar to our logic in determining the release date tightness levels.

After employing the release date determination method explained above, we get the release date coefficient versus utilization level of the bottleneck shelter diagram figured in Figure 4.4 for our problem. Meanwhile, for all cases the bottleneck shelter is found as the BLS. Then the values of the release date coefficients corresponding to the predetermined utilization level of the bottleneck shelter are the following. It is important to mention here that, these release date coefficients are valid for our problem setting, for other problem settings different values will be obtained.

i. 8.5

ii. 7.35

ii. 7.3

iv. 7.1

v. 6.3

As expected, the release date coefficient value in the first item stands for the loose release date level where the value in the last item stands for the tight release date level.

The next critical experimental factor is the due date of the aircrafts. Similar to the release date coefficient, we use a parameter called due date coefficient in our due date determination method. In fact, our method is similar to the total work content rule. Instead of adding the total processing time of the FLPM, assuming there are no resource constraints and a worker of level 5 is assigned to all operations to the release date, in our method a multiple of this processing time is summed up with the release date of the aircraft. The due date determination method we propose relates the due dates of the aircrafts with the fraction of the number of tardy jobs in percentages. Similar to obtaining the predetermined values for the utilization level of the bottleneck shelter in the release date determination method, in due date determination method we try to obtain the predetermined values for the fraction of number of tardy jobs in percentage for different values of the due date coefficient. After having defined the due date coefficient and explained briefly the due date determination method, now comes the steps of the due date determination method:

1- Take a value for the due date coefficient.

2- Determine the due dates of the aircrafts by summing up the release date of the aircraft and the the due date coefficient multiple of the processing time assuming there are no resource constraints and a worker of level 5 is assigned to all operations that is specific to the aircraft configuration.

3- Run the heuristic explained in Section 3.4.

4- Check whether the fraction of the number of tardy jobs in percentage is the predetermined value. If it is not the predetermined value, take a different value for the due date coefficient and goto 1, else terminate.

Again the due date determination method is a trial and error method since the fraction of the number of tardy jobs in percentage can be determined after running the heuristic. The due date coefficients corresponding to the predetermined values for the fraction of the number of tardy jobs in percentage represent different tightness levels of the due date. However, as can be noticed, the due date cannot be calculated if the release date information is not available. Therefore, the release date determination method is employed first and the release date coefficients are designated for each predetermined value for the utilization level of the bottleneck shelter, and then the due date determination method is employed. Because of this, for each release date coefficient the due date determination method has to be employed. In other words, for each tightness level of the shop load, the due date coefficients are to be determined for each level of the fraction of the number of tardy jobs in percentage. In fact, this is an expected result, since the utilization level of the bottleneck shelter affects the fraction of the number of tardy jobs in percentage. We take the following values for the fraction of the number of tardy jobs in percentage:

i. 30%

ii. 40%

ii. 60%

iv. 70%

v. 80%

After employing the due date determination method explained above, we get the due date coefficient versus utilization level of the bottleneck shelter diagram figured in Figure 4.5 for each of the release date coefficients. Then the values of the due date coefficients corresponding to the predetermined utilization level of the bottleneck shelter are the following. It is important to mention here that, these release date coefficients are valid for our problem setting, for other problem settings different values will be obtained.

i. when the utilization level of the bottleneck shelter is 80% (that corresponds to rdc = 8.5 in Figure 4.4)

   1.1, 1.05, 0.92, 0.85, and 0.78 corresponding to the utilization levels of the bottleneck shelter 30%, 40%, 60%, 70%, and 80% respectively.

ii. when the utilization level of the bottleneck shelter is 85% (then rdc becomes 7.35 as shown in Figure 4.4)

   1.12, 1.07, 0.95, 0.865, and 0.8 corresponding to the utilization levels of the bottleneck shelter 30%, 40%, 60%, 70%, and 80% respectively.

iii. when the utilization level of the bottleneck shelter is 90% (then rdc becomes 7.3 as shown in Figure 4.4)

   1.2, 1.07, 0.94, 0.88, and 0.8 corresponding to the utilization levels of the bottleneck shelter 30%, 40%, 60%, 70%, and 80% respectively.

iv. when the utilization level of the bottleneck shelter is 95% (then rdc becomes 7.1 as shown in Figure 4.4)

   1.25, 1.1, 0.97, 0.9, and 0.83 corresponding to the utilization levels of the bottleneck shelter 30%, 40%, 60%, 70%, and 80% respectively.

v. when the utilization level of the bottleneck shelter is 97% (then rdc becomes 6.3 as shown in Figure 4.4)

   1.25, 1.1, 0.97, 0.9, and 0.83 corresponding to the utilization levels of the bottleneck shelter 30%, 40%, 60%, 70%, and 80% respectively.

As noticed, there are 25 different release and due date tightness level combinations. In addition, the due date coefficient value in the first items stands for the loose due date level where the values in the last item stands for the tight due date level.

We also took runs for the following due date coefficients for all release date coefficients and call the set below as the second due date coefficient set. As noticed, the largest due date coefficient in the main set mentioned above, that is 1.25, is below the tight due date coefficient in the second set. By using larger due date coefficients, we will get larger total project slack. We will also analyze the performance of the $\bar{t}_{ji}$ estimation methods for larger total project slack.

i. 1.3

ii. 1.5

ii. 1.7

iv. 1.9

v. 2

Having explained the release and the due date determination methods and stated the release and the due date coefficient levels representing different tightness levels of the shop load and the fraction of the number of tardy jobs in percentage, now we will analyze the effects of these different tightness levels on the objectives total weighted tardiness and total incurred cost. Moreover, we will criticize the performance of the $\bar{t}_{ji}$ estimation methods and the success of the improvement phase under tight and loose release and due date conditions. We will begin with analyzing the release date tightness levels. With the release date coefficient representing tight shop load, the scarcity of the number of docks in the shelters, especially in common shelters will come into scene. The data of the number of the docks and the workers for each skill level in the shelters reflect the fact that the docks are the restricted resources in case of high work load. This is because the total number of workers of all skill levels is greater than the number of docks in all of the shelters. In the view of the fact that the bounding constraint is the dock usage and capacity constraints under tight shop load, there will be considerable increase in the number of aircrafts waiting in the queues for an assignment to the docks in the shelters and so in the waiting times. The increase in the waiting times will lead to an increase in the completion times of the projects. As expected the tardiness of the projects will increase because of the increase in the completion times of the projects. Additionally, because the due date of the aircraft formulation involves the release date, the tight release date will result in tight due date. As a result of the increase in the the completion times of the projects and decrease in the due date of the project i, the total weighted tardiness will increase drastically. The limitation introduced by the number of docks also causes an increase in the worker utilizations of all skill levels. Because, the workers are assigned to the activities when the dock assignment takes place. The worker assignment rule used in the phase 1 strengthens this, since it does not postpone the resource assignment in any condition. In addition, the increase in the utilizations of the workers of all skill levels is more evident in the former shelters. Another consequence of high utilization of the workers of all skill levels, especially the lower skill levels, is that the activities being performed by workers of lower skill levels increase. As expected, this leads to a decrease in the total incurred cost. In other words, the congested shop load due to tight release dates will incur lower cost.

Finally, there will also be more alternatives that are satisfying the conditions mentioned in Section 3.4.2 in the improvement phase for the mode selection exchange of the activities since we will have more and long idle time blocks in the schedule when we are to schedule aircrafts that have tight interarrival times inbetween. Meanwhile, these long idle blocks are the waiting times of the activities. The increase in the number and the length of idle time blocks will increase the number of mode selection exchange candidates. However, we have to analyze the changes on the conditions checked for the mode selection exchange under congested shop load to find out whether these candidates will successfully be exchanged. To recall, the mode selection exchanges are employed in the PAC type shelters. As noticed, there are too many docks in the PAC type shelters, so the probability of finding an available dock is high. Then, the most important condition of mode selection exchange is satisfied. The next condition is to find an available worker of lower skill level in that time block. Meanwhile, the heuristic searches for an available dock in the time interval starting from the start time of the activity under consideration till the finish time of the idle time block, that is the start time of the succeeding activity of the same project. As mentioned before, the number of workers is greater than the number of docks in the shelters. Again due to the fact that there are many docks in the PAC type shelters, the probability of finding available worker of lower skill level is high. Furthermore, this probability also increases due to the fact that the workers of higher skill levels are assigned first while constructing the initial schedule. As a result, under congested shop load, which is the case of tight release date, the mode exchanges in the improvement phase will result with lower total incurred cost values.

Therefore, the release dates of the aircrafts to be maintained is an important experimental factor to test with which $\bar{t}_{ji}$ estimation method that the heuristic we have proposed performs well both in congested systems and in less utilized ones from both the MSP and the fleets of views.

After having noted the interpretations on the effect of the different release date tightness levels on the objectives total weighted tardiness and total incurred cost, now we proceed to analyzing the effect of the due date coefficient tightness levels on these objectives. When we increase the due date coefficient we will get looser due dates of the aircrafts. Then, intuitively the total weighted tardiness will decrease. The increase in the due dates of the projects results with larger total project slacks. Larger slacks will result in larger $\bar{t}_{ji}$ values. Meanwhile, the success of the ATC rule is dependent on the success of estimating the $\bar{t}_{ji}$ values. Then, the tightness of the due dates affect the ATC calculation results, so this affects the order of the activities to be performed in the common shelters. In addition, the activities to be performed in the PAC type shelters are ordered according to the Earliest Due Date rule. As a result, the tightness of the due dates affect the resultant schedule, so the total incurred cost. In addition, the increase in the due dates of the aircrafts enlarges the scheduling horizon, so the number of idle time blocks will increase. The criticism mentioned above for the congested shop load is valid for the loose due dates. Therefore, we evaluate the performance of the $\bar{t}_{ji}$ estimation methods and the success of the improvement phase by using this factor.

In addition to the release and due date tightness levels, the weight matrix of the aircraft configurations is an important input to our problem and our heuristic handles this factor. Moreover, there are two different points of view weighting the aircraft configurations. For the scheduler in the MSP, the utilization of the resources is important and for the scheduler in the fleet, who makes the flight plans, the ability to battle is important. Although TUAF is aware of the fact that the aircraft configurations have different importance, TUAF does not take this fact into account during scheduling of the FLPM of the aircrafts. Therefore, two different weight figures were obtained considering the grading made by 20 officers in the MSP and by 20 officers in the fleets. To calculate the weight values, the Analytic Hierarchy Process of Thomas Saaty [59] is used since it provides a tool that can be used to make decisions in situations involving multiple objectives. A pairwise comparison matrix is formed with the values indicating how much more important the aircraft type i is than the aircraft type j with the i the row and the j the column. Meanwhile, the importance is measured on an integer-valued 1-9 scale, 1 showing equal importance, 3 showing weakly importance, 5 showing strongly important, 7 showing strongly more important, 9 showing absolutely more important and the intermediate value show a importance between the lower and the higher evaluation. We have 5 aircraft types which are F4, F5, F16, T37, and T38. The following weight values are obtained:

i- F4; 0.364, F5; 0.098, F16; 0.407, T37; 0.074, T38; 0.058 by the officers in the MSP,

ii- F4; 0.308, F5; 0.105, F16; 0.519, T37; 0.029, T38; 0.039 by the officers in the fleets

We will study the effect of different release and due date tightness levels on the total weighted tardiness, the incurred cost and the CPU time required to run the proposed heuristic with the weight matrices stated above separately. We will also solve the problem experienced by TUAF with our heuristic in which all of the aircraft configurations have equivalent weights, 0.2.

To sum up, we used a four-factorial experimental design to determine the best performing $\bar{t}_{ji}$ estimation method in terms of total weighted tardiness and total incurred cost for each of the weight matrix of the aircraft configurations that is determined by the fleets and the MSP. These experimental factors are the release and the due date of the aircrafts, the weight figures of the aircrafts, and the total project slack. The release date tightness levels are determined from the relation of the arrival rate and the utilization level of the bottleneck shelter whereas the due date tightness levels are determined from the due date and the percentage fraction of the number of tardy projects. For the predetermined 5 utilization level of the bottleneck shelter and 10 percentage fraction of the number of tardy projects the corresponding levels are found out. Then, there are 50 different release and due date tightness level combinations. For each factor combination we took 5 replications using 5 different seeds. In addition, six $\bar{t}_{ji}$ estimation methods are employed for each of these runs, resulting with 1500 different schedules. The second phase is applied to these 1500 different schedules resulting with 4500 objective value triplets which is total weighted tardiness, total incurred cost, and the CPU time required for the execution of the proposed heuristic. Firstly in the next section, the proposed heuristic is run with the values determined by TUAF. Then a comparison is made among the $\bar{t}_{ji}$ estimation methods respecting the total weighted tardiness, the percentage fraction of the number of tardy projects and the total incurred cost for all weight figures.

4.3 Results for the FLPM Problem Experienced by TUAF

The data of the FLPM problem experienced by TUAF is presented in Section 4.1. For this data set, we run the proposed solution procedure and in this section, we present the total weighted tardiness, $\Sigma\overline{z_i}$, the total incurred cost, ΣB_i, and the percentage fraction of the number of tardy projects results. We compare the results of the problem in which the weights of all of the aircraft configurations are equivalent with the results of the problem in which the weights are determined by the MSP and the fleets.

The results of the proposed heuristic to this problem are stated in Table 4.6. Meanwhile, ES, BS, CES, PCS, VM, and RPCS are the abbreviations of the $\bar{t}_{ji}$ estimation methods stated in Subsection 3.4.1. The first thing that attracts attention is that, for all $\bar{t}_{ji}$ estimation methods, the percentage fraction of the number of tardy projects resulted from the proposed heuristic to the problem with the weight matrix being used by TUAF is below the results for the problem with the weight figures stated in the preceding section. Although this is the case, the total weighted tardiness obtained for the TUAF weight figure is greater than the total weighted tardiness for the weight figures of the MSP and the fleets. To recall, the objective of the TUAF is the latter one.

	ES			BS			CES		
Obj.	MSP	Fleet	TUAF	MSP	Fleet	TUAF	MSP	Fleet	TUAF
$\Sigma\overline{z_i}$	3816.9	2800.4	6556.6	3798.1	2789.6	6535.6	3815.9	2800.6	6556.6
% Tardy Prj.	0.97	0.97	0.93	0.95	0.95	0.93	0.97	0.97	0.93
ΣB_i	41194	41414	42403	40983	41122	42231	41215	41404	42403
CPU	1000	578	656	875	594	578	547	578	609
	PCS			VM			RPCS		
Obj.	MSP	Fleet	TUAF	MSP	Fleet	TUAF	MSP	Fleet	TUAF
$\Sigma\overline{z_i}$	3815.9	2800.4	6556.6	3637.4	2682.3	6224.7	3815.9	2800.6	6556.6
% Tardy Prj.	0.97	0.97	0.93	0.96	0.96	0.93	0.97	0.97	0.93
ΣB_i	41215	41414	42403	40227	40150	41109	41215	41404	42403
CPU	579	625	609	703	625	578	563	562	703

Table 4.6: The results at initial schedule for the FLPM problem experienced by TUAF

When the results are analyzed, it is noticed that the shop load is very congested, the bottleneck shelter's utilization levels are 0.97178406, 0.9762996, and 0.9597213 for the weight figures of the MSP, the fleets, and TUAF respectively. The common shelter BLS is the bottleneck for all weight figures. The BLS shelter has only one dock and there is no worker of skill level 7 as stated in Table 4.3. Because of the mode preference logic during assignment of the worker, all of the activities are performed by the worker of skill level 5 in the BLS shelter.

Having noted the first noticeables, let us analyze the results. The ATC calculations for the assignment to the common shelters helps us to identify the reason of these results. In the case of aircraft configurations weighted equivalently, the weight parameter is not effective. In other words, the ATC formulation turns out from a combination of Weighted Shortest Processing Time and Minimum Slack Rule to the combination of Shortest Processing Time and Minimum Slack Rule. When the ATC calculations of all of three weight figures are analyzed, it is noticed that the exponential term in the ATC formulation mostly results with 1. The reason behind this is the tightness of the due dates TUAF designated as stated in Table 4.1. As a result, the ATC rule turns to the Shortest Processing Time rule. Again, the data shows that this is very evident starting from the activities performed in the BLS shelter. Employing the Shortest Processing Time rule results with assigning the aircrafts in the F16, T37, T38, F5, and F4 order to the common shelters for the equivalent weight case and and F16, F4, F5, T37 and

T38 order for the weights determined by the AHP method. Supporting this claim, when the aircraft configurations which are not tardy in the case of equivalent weights are investigated, it is noticed that more than half of the aircrafts are F16. Because of assigning a F16 first in all of three cases, the probability of a F16 being not tardy is higher than all of the other aircraft configurations. Nearly half of the aircrafts that are not tardy are F16 for all of three cases in spite of there are only 9 F16s scheduled whereas there are 132 aircrafts of remaining configurations. This result, in fact, also explains why the percentage fraction of the number of tardy projects resulted from the proposed heuristic to the problem with the weight matrix of TUAF is the minimum. Because, the aircrafts wait for an assignment to the shelters so long that very few aircrafts' project finish before their due date. The long waiting times result with larger completion times of F4 and F5 than the T37 and T38 for the equivalent case since the latter configurations have precedence with respect to the former ones. This is the opposite for the weights determined by the AHP. As recalled, the weight of the F4 is nearly three multiples of the F5, T37 and T38 and this causes larger total weighted tardiness values in which the weights are equivalent than the total weighted tardiness values obtained for the other two weight matrices. It is important to mention that this result supports the known fact that the Shortest Processing Time rule does not perform well under tight shop load conditions where the jobs are weighted and the objective is to minimize the total weighted tardiness.

The second objective which is minimizing the total incurred cost results worse for the case where all the aircraft configurations have equivalent weights than the other two weight figures. That is the equivalent case incurs larger cost. This is due to the fact that the workers of higher skill levels that cost more are utilized more than the workers of lower skill levels in the resultant schedule for the equivalent weight figure. As stated just before, for the TUAF's weight figure the prioritization order in the assignment of the activities to the common shelters is F16, T37, T38, F5, and F4 and this is the ascending processing times required in these corresponding common shelters order. So, the workers of higher skill levels do the activities that require shorter processing times since the configurations requiring shorter processing times are assigned first and the available workers of higher skill levels are assigned first. This means as soon as a dock becomes available, the probability of assigning a worker of higher skill level increases. Then, the number of activities performed by workers of higher skill levels is greater, so the number of working time units the workers of higher skill levels work is higher in the equivalent weight case. In other words, the possibility of a worker of higher skill level being idle is smaller for the equivalent case than the other two weight figures. As a result, the equivalent case incurs larger cost than the other two weight figures.

Having interpreted the two objectives, now let us analyze the performance of the $\bar{t}_{ji}$ estimation methods. For all of the weight figures, the Vepsailanen-Morton (VM) method outperforms the others in terms of the total weighted tardiness and the Backward Scheduling (BS) method follows it. On the other hand, for the two weight figures determined by the AHP, the BS is the outperformer in terms of the percentage fraction of the number of tardy projects and the VM follows this time. The order does not change for the equivalent weight case, namely the VM is the outperformer and the BS follows it. The other four methods result with equivalent or very close total weighted tardiness and the percentage fraction of the number of tardy projects values. To recall, all of the six competing rules estimate the $\bar{t}_{ji}$, by distributing the total project slack by different logics. However, in the case of the FLPM problem of TUAF, the due dates are very tight. Moreover, the system is highly loaded so that the number of activities waiting in the queues, especially for an assignment to the common shelters, and their waiting time are very large values. Especially, this is very evident for the BLS shelter. Most of the time, the waiting times in the queues of the common shelters exceed the slacks assigned for all of the $\bar{t}_{ji}$ estimation methods since the time that the resource assignment takes place is later than the due date of the corresponding activity to be performed at the corresponding shelter. Then, the exponential term results with 1 for all of the six methods. So, it is expected that the method of the slack distribution will not make sense resulting equivalent objective values. However,

	ES			BS			CES		
Obj.	MSP	Fleet	TUAF	MSP	Fleet	TUAF	MSP	Fleet	TUAF
ΣB_i	40219	40469	41296	40087	40248	41040	40225	40454	41296
CPU	328	282	328	297	343	359	313	313	313
	PCS			VM			RPCS		
Obj.	MSP	Fleet	TUAF	MSP	Fleet	TUAF	MSP	Fleet	TUAF
ΣB_i	40225	40469	41296	39313	39240	40031	40225	40454	41296
CPU	297	359	328	265	297	344	359	297	359

Table 4.7: The results after improvement for the FLPM problem experienced by TUAF

this is not the case according to the total weighted tardiness results in Table 4.6, for all weight figures, the BS and the VM outperforms the others. When the data log is examined, it is noticed that when the VM and the BS methods are employed, the activities enter the waiting list of the shelters earlier than the other four competing methods. Therefore, the schedules obtained by these two methods end up with smaller completion times and hence, smaller total weighted tardiness and the percentage fraction of the number of tardy projects than the other four methods.

Table 4.7 denotes the cost values obtained after phase 2 and the CPU time required in milliseconds. According to the results when compared to the total incurred cost results in Table 4.6, for all of the $\bar{t}_{ji}$ estimation methods and weight figures, the improvement phase is successful. For all weight figures, after the employment of the improvement phase the cost is decreased for small additional CPU time.

To sum up, the heuristic we propose for the FLPM problem experienced by TUAF ends up with large total weighted tardiness and total incurred cost values when the aircraft configurations are weighted equivalently. The VM and the BS methods are the outperformers due to congested shop load and tight due dates for all of the weight figures. The improvement phase decreases the cost sufficiently for small additional CPU. In the next section, we will analyze the performance of the $\bar{t}_{ji}$ estimation methods in terms of total weighted tardiness, total incurred cost and CPU required according to the results obtained at initial schedule.

	ES			BS			CES		
Obj.	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
$\Sigma\overline{z_i}$	83.4	1455.4	591.3	77.1	1325.1	548.71	82.6	1454.6	590.4
ΣB_i	88971	96458	92788.6	86820	96348	92161.3	88969	96456	92792.3
CPU	343	1360	536.2	328	782	532.3	344	1469	534.7
	PCS			VM			RPCS		
Obj.	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
$\Sigma\overline{z_i}$	82.7	1454.6	589.9	69.4	1439.9	569	82.7	1454.6	590.3
ΣB_i	88969	96336	92792.3	86620	96039	91570.7	88969	96336	92794
CPU	344	1875	544	328	719	530.2	359	672	526.5

Table 4.8: Summary of the objective values at initial schedule with the weight matrix determined by the MSP

4.4 Results for Initial Scheduling Phase

In the previous section, the data of the release and the due date of the aircrafts were determined by TUAF. In this section, we solve the FLPM problems using the release and the due dates generated by the corresponding coefficients stated in Section 4.2 and the rest of the required data is the TUAF's data stated in Section 4.1. Then, we investigate the performance of the $\bar{t}_{ji}$ estimation methods in terms of the total weighted tardiness, the total incurred cost, and the computational effort required.

While constructing the initial schedule, we use the heuristic proposed in Chapter 3. This heuristic uses the six $\bar{t}_{ji}$, activity due date, estimation methods that were described in Subsection 3.4.1. There are 5 release date tightness levels and for each of these levels, there are 10 due date tightness levels resulting in 50 different combinations. For each factor combination, we take 5 replications using 5 different seeds. Therefore, a total of 250 runs are taken for each $\bar{t}_{ji}$ estimation method. Meanwhile, these 250 runs are taken with the weight matrices of the aircraft configurations determined by the MSP and the fleets separately that are stated in Section 4.2. Minimum, maximum, and average values for the total weighted tardiness, the incurred cost and computation time (CPU in milliseconds) results when the main due date coefficient set is used, are summarized in Tables 4.8 and 4.9 respectively for the MSP and the fleets.

When the Tables 4.8 and 4.9 are analyzed, it is noticed that on the average the Backward Scheduling (BS) method performs the best in terms of total weighted

	ES			BS			CES		
Obj.	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
$\Sigma\overline{z_i}$	48.1	864.1	370.7	43.9	797.8	346.8	48.6	864.1	370.6
ΣB_i	89267	96224	93102.6	87614	96071	92466	89312	96245	93104.7
CPU	343	687	530.1	328	704	540.9	328	687	533.1
	PCS			VM			RPCS		
Obj.	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
$\Sigma\overline{z_i}$	48.6	864.1	370.6	38.6	872.7	357.1	48.5	864.1	370.6
ΣB_i	89306	96245	93104.8	87177	96094	91984.2	89273	96224	93104.2
CPU	343	719	518.4	343	719	531.4	344	672	532.1

Table 4.9: Summary of the objective values at initial schedule with the weight matrix determined by the fleets

tardiness. To recall, the BS is expected to give better total weighted tardiness for the FLPM problem. Because, the FLPM problem is a dynamic job shop problem. Let us clarify this claim: Under congested shop load, the waiting times in the queues are very long and so the jobs can be performed very close to its due date and most of the time the completion time exceeds the due date. So the best estimate for the due date of the job is the possible latest due date which is the logic behind the BS method.

The Vepsailanen-Morton (VM) method gives very close results to the BS. However, we see that VM is the one that obtains the minimum total weighted tardiness for both weight figures. Nevertheless, for the fleets weight figure, in all cases the maximum total weighted tardiness that the VM finds is greater than the other $\bar{t}_{ji}$ estimation methods obtain whereas is very close to the results of the other methods for the MSP weight figure. We should investigate the reason of this situation. It might be due to some replications of these methods with considerably bad results with respect to very good results. Since we normalize the objective values, we can measure the performance of the methods in terms of percentage difference from the best result by using deviations. The formula for the deviation, dev_p, of the result of a single run, r_p, is written by using the best and worst results, max_r, min_r, achieved by any other algorithms in the same run for the same factor combination, as follows:

$$dev_p = \frac{max_r - r_p}{max_r - min_r}$$

In addition, among the other FLPM specific $\bar{t}_{ji}$ estimation methods, the ES performs the worst in terms of average total weighted tardiness for both weight figures. Furthermore, the minimum and the maximum values are greater than the other methods. However, it is important to notice that the differences between these methods are very small.

On the other hand, when we look at the summary of total incurred cost values in Tables 4.8 and 4.9, we see that the VM surpasses the other methods for both weight figures. The BS follows the VM and the rest of the methods obtain results that are away from the VM and the BS. Among them, the ES incurs, on the average, the minimum cost whereas the PCS incurs the maximum. Again the differences between them are very small.

The computational effort used by the $\bar{t}_{ji}$ estimation methods, which are stated in milliseconds in Tables 4.8 and 4.9, show that all of the methods require very close CPU time and so none of them have superiority over each other. In fact, these values are so small that the CPU time is not a criteria in determining the best performing $\bar{t}_{ji}$ estimation method.

Having interpreted the raw results of the runs, let us look for the deviation values. This analysis may let us understand the experiment more clearly. The average of the deviations for all factor combinations, are presented in Table 4.10. We observe that the BS provides better total weighted tardiness values for both of the weight figures. Furthermore, we also see that the VM performs the best in terms of total incurred cost. In addition, none of the methods have significant superiority over the others in terms of computational effort efficiency. Hence, at this stage we cannot conclude which method would be more beneficial.

	MSP			Fleet		
Method	$\Sigma\overline{z_i}$	ΣB_i	CPU	$\Sigma\overline{z_i}$	ΣB_i	CPU
ES	0.48234290	0.65933508	0.52112616	0.50018997	0.64722213	0.55556854
BS	0.38556505	0.52072520	0.52646115	0.39747797	0.50906274	0.59819930
CES	0.47959200	0.66005166	0.52043581	0.49982506	0.64758213	0.57049668
PCS	0.47824672	0.66047595	0.53835543	0.49987234	0.64817269	0.51467648
VM	0.42407986	0.38482088	0.52011578	0.42997140	0.39762592	0.56135774
RPCS	0.47939657	0.66085492	0.51274444	0.49983259	0.64840760	0.56631039

Table 4.10: Deviation averages in percentages at initial schedule

	ES			BS			CES		
Obj.	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
$\Sigma\overline{z_i}$	1.1	832.1	228.6	0	791.2	129	0.74	826.6	223.6
ΣB_i	88562	96550	92916.6	88721	97168	94117.1	88756	96593	93095.7
CPU	344	2094	587	328	1938	558.4	328	2562	560.7
	PCS			VM			RPCS		
Obj.	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
$\Sigma\overline{z_i}$	0.1	818.9	218.3	1.7	837.9	233.9	0.7	818.7	222.5
ΣB_i	88724	96665	93143.3	87592	96066	92048.1	88803	96416	93034.1
CPU	359	2172	561.3	344	781	535.6	328	2797	555.7

Table 4.11: Summary of the objective values at initial schedule with the weight matrix determined by the MSP using the second due date coefficient set

Let us analyze the minimum, maximum, and average values for the total weighted tardiness, the incurred cost, and the required computation time results that are summarized in Table 4.11 when the second due date coefficient set is used. Table 4.11 proves our claim that with larger total project slack, the FLPM specific $\overline{t}_{ji}$ estimation methods come to the fore, namely BS, PCS, RPCS, CES, and ES outperform the VM in terms of total weighted tardiness, on the average. The BS surpasses all the methods by obtaining about half of the total weighted tardiness values of the other methods. Furthermore, the BS obtains a schedule with 0 total weighted tardiness. PCS, RPCS, CES and ES is the order of the methods which have the descending total weighted tardiness. This is the expected order. The logic employed during the development of these methods is to estimate the most suitable value of the due date of the activity j of project i. We first thought to distribute the total project slack equally to all activities of the project. Then, benefiting from the information that the common shelters are highly utilized, we thought that reserving the total project slack to the activities to be performed in the common shelters would be more beneficial resulting smaller total weighted tardiness. Taking care of the variety of the processing time required for the activities to be performed in the common shelters leads us to distribute the total project slack to these activities in direct proportion to their processing time required values. To sum up, we expect the PCS to outperform the CES and the CES to outperform the ES. The RPCS method distributes the total project slack in reverse proportion to their processing time required values. We expect this method to give worse results than the PCS since the logics employed are the opposite of each other. We observe from the Table 4.11 that RPCS obtains larger total weighted tardiness than the PCS.

On the other hand, we see from Table 4.11 that the VM incurs the smallest cost. Furthermore, the BS obtains the largest total incurred cost. Among the other FLPM specific methods, ES incurs the smallest and PCS incurs the largest cost. As noticed, the performance of the methods turns to the other way around. Meanwhile, again the computational effort required by each method is not noteworthy to analyze.

Having noted the observations from the raw results for the large total project slack, let us investigate the standard deviation values. The average of the deviations for all factor combinations, is presented in Table 4.12. The results support our observations made for the Table 4.11.

Method	$\Sigma\overline{z_i}$	ΣB_i	CPU
ES	0.48211849	0.47682536	0.44993360
BS	0.17782426	0.74829610	0.43546826
CES	0.46340047	0.51545565	0.43048458
PCS	0.44566287	0.52382585	0.43205251
VM	0.49721062	0.28766655	0.41178882
RPCS	0.45932028	0.50131594	0.42049010

Table 4.12: Deviation averages in percentages at initial schedule with large total project slack

To sum up, the BS performs the best in terms of total weighted tardiness for the small and the large total project slack cases. The VM obtains very close results to BS for the former case whereas the other FLPM specific methods follow the BS for the latter case. The VM gives better total incurred cost for both cases. The BS is the second best performer in terms of total incurred cost for the main due date coefficient set, however it performs the worst for the large total project slack case. The order of the FLPM specific methods except the BS that results descending total weighted tardiness is PCS, RPCS, CES, and ES for both of the due date coefficient sets as we expected. The reverse order is valid for the total incurred cost objective. Meanwhile, the CPU required for all methods are so small that it is not a criterion in determining the overall best performer. However, at this stage, we cannot know how well the schedules proposed by these methods can be improved, or whether this proposal will be the $\bar{t}_{ji}$ estimation method that we will suggest at the end of this study. In order to figure out the answers to these questions, we will investigate the improvement algorithm, which is the phase 2, in the next section.

4.5 Results for Improvement Phase

This stage of our experimental design is utilized to figure out the improvement algorithm, which is the phase 2, that will yield good incurred cost values in considerable computation times, given the initial schedule. Before utilizing the phase 2, we have an initial schedule that is constructed by the algorithm of phase 1. We will improve all initial schedules obtained by the employment of six $\bar{t}_{ji}$ estimation methods which we explained in Chapter 3. In order to test the improvement algorithm, a total of 250 runs were taken for each $\bar{t}_{ji}$ estimation method. Meanwhile, these 125 runs were taken with the weight matrices of the aircraft configurations determined by the MSP and the fleets separately. As remembered, the total weighted tardiness does not change after the employment of the improvement algorithm. This is due to the the conditions used during the selection of the activities for which the mode selection exchange is applied and the reassignment of the dock and the worker to these activities, mentioned in Subsection 3.4.2. Therefore, in this section, the effect of the improvement phase on the total weighted tardiness is not examined. Minimum, maximum, and average values for the incurred cost and computation time results are summarized in Tables 4.13 and 4.14 respectively for the MSP and the fleets.

We observe from Tables 4.13 and 4.14 that the initial schedules constructed by the method VM incurs the minimum cost after the improvement on the average for both weight figures. The method BS gives very close results. The initial schedules constructed by the PCS incurs less cost than the CES and the initial schedules constructed by the CES incurs less cost than the ES after improvement. As noticed, this is the same order obtained from the total incurred cost results

	ES			BS			CES		
Obj.	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
ΣB_i	86172	94171	90411.4	84255	94170	89771.5	86152	94159	90406.5
CPU	250	563	311	234	453	302.5	250	391	307.8
	PCS			VM			RPCS		
Obj.	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
ΣB_i	86152	94159	90404.3	84177	93716	89264.1	86152	94159	90408
CPU	250	391	304.1	234	375	294.7	250	421	309.1

Table 4.13: Summary of the objective values after improvement with the weight matrix determined by the MSP

	ES			BS			CES		
Obj.	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
ΣB_i	87246	93743	90904.1	85079	93833	90252.8	87308	93729	90906.7
CPU	250	406	301.7	219	391	294.7	250	390	298.8
	PCS			VM			RPCS		
Obj.	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
ΣB_i	87284	93729	90826.1	85088	93899	89820	87308	93729	90827.7
CPU	250	406	300.6	204	359	285	235	406	299.1

Table 4.14: Summary of the objective values after improvement with the weight matrix determined by the fleets

of the inial schedules. The computational effort required by the phase 2 requires is very close to the amount used in the phase 1. However, it is not noteworthy.

For a better evaluation of the experiment, let us analyze the standard deviation results of the improvement phase. The average total incurred cost and the computational time (CPU) results obtained by each factor combination is stated in Table 4.15 with the weight matrices of the aircraft configurations determined by the MSP and the fleets. All the observations for the raw results are same for the deviation results according to the Table 4.15 except that the deviation average for the CES is smaller than the PCS. Although the CES outperforms the PCS according to the deviation average results, it is important to mention that the difference between them is very small. In fact, the differences between the deviation averages of the FLPM specific methods except the BS are very close.

To investigate the performance of the $\bar{t}_{ji}$ estimation methods in terms of total incurred cost results after improvement when larger total project slack is used, we run the heuristic for the second due date coefficient set. Minimum,

	MSP		Fleet	
Method	ΣB_i	CPU	ΣB_i	CPU
ES	0.64847559	0.42712457	0.64589769	0.44787914
BS	0.50521481	0.35475806	0.64618191	0.41283517
CES	0.64687061	0.41989364	0.52043581	0.49982506
PCS	0.64740068	0.38257813	0.64619145	0.43272624
VM	0.38486669	0.30254276	0.41378724	0.29037127
RPCS	0.64826479	0.41517596	0.64693037	0.41497032

Table 4.15: Deviation averages in percentages after improvement

	ES			BS			CES		
Obj.	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
ΣB_i	85698	93965	90395.3	86291	94195	91274.8	85925	93871	90562.2
CPU	250	547	315.4	265	484	322.4	234	469	317.1
	PCS			VM			RPCS		
Obj.	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
ΣB_i	85828	93890	90562.3	84734	93911	89682.6	86118	94026	90514.6
CPU	250	438	311.8	250	516	307.4	235	625	315.9

Table 4.16: Summary of the objective values after improvement with the weight matrix determined by the MSP for the large total project slack

maximum, and average values for the incurred cost and computation time results are summarized in Table 4.16 for the MSP. The VM surpasses the others and the BS performs the worst in terms total incurred cost after improvement for the large total project slack. The differences between the FLPM specific methods except the BS gets close after improvement compared to the initial schedule. We provide the deviations of the average total incurred cost and the computational time (CPU) results obtained by each factor combination in Table 4.17 with the weight figure of MSP. Table 4.17 supports the observations made for Table 4.16.

Method	ΣB_i	CPU
ES	0.50444229	0.31860905
BS	0.72339027	0.38476624
CES	0.54260504	0.34472946
PCS	0.54025357	0.30544713
VM	0.33227033	0.26969879
RPCS	0.53027734	0.32062101

Table 4.17: Deviation averages in percentages after improvement with large total project slack

To sum up, all of the initial schedules constructed by all $\bar{t}_{ji}$ estimation methods are improved successfully, namely the cost they incur decrease for small additional computational effort. The order of the methods that results with descending cost does not change after improvement. However, the differences between the deviation averages obtained for the FLPM specific methods except the BS are very small. In addition, for large total project slack, the deviation averages of the FLPM specific methods except the BS gets very close after improvement compared to the deviation averages at initial schedule. According to these two observations, we can conclude that the improvement phase reduces the outstandingness of the FLPM specific methods except the BS in terms of total incurred cost.

In this section, we evaluate the $\bar{t}_{ji}$ estimation methods in terms of total incurred cost obtained after the employment of improvement phase to the schedules constructed by these methods. However, this evaluation is on the general capabilities of the $\bar{t}_{ji}$ estimation methods. In the next section, we will realize a detailed analysis of the results we presented in this section. According to the analysis, we will select the appropriate $\bar{t}_{ji}$ estimation method with or without improvement phase for different tightness levels of the release and the due dates to be a part of our single-pass heuristic algorithm. This analysis will be made for the MSP and the fleets weight figures and for small and large total project slack separately.

4.6 Analysis of Results

In this section, we will make a detailed analysis of the results that we obtained in the previous sections. Firstly, in order to understand the capabilities of the improvement algorithm, we need to investigate the percentage decrease in the total incurred cost and the additional CPU used to obtain the improvement in percentages. The corresponding results are given in Table 4.18 for the MSP and the fleets.

Table 4.18 shows that the maximum decrease in total incurred cost occurs for

	MSP		Fleet	
Method	ΣB_i	CPU	ΣB_i	CPU
ES	0.025644039	0.595275997	0.023620985	0.581871855
BS	0.02595259	0.579437997	0.023951661	0.55850273
CES	0.025736072	0.593629838	0.023615515	0.575344802
PCS	0.025759237	0.578201754	0.023640414	0.593661046
VM	0.02520643	0.569416972	0.023025631	0.547795627
RPCS	0.025736629	0.598801208	0.023616553	0.574420868

Table 4.18: Averages of additional CPU used to obtain a lower incurred cost value and the cost decrease, in percentages

	Phase 1			Phase 2		
Method	SL 7	SL 5	SL 3	SL 7	SL 5	SL 3
ES	9779.76	12124.24	238.76	9377.124	11650.28	1717.312
BS	9744.42	11940.08	222.504	9336.72	11480.384	1694.348
CES	9782.5	12115.872	239.268	9378.368	11644.296	1719.432
PCS	9782.376	12116.24	239.476	9377.632	11645.12	1720.708
VM	9680.316	11903.28	208.64	9289.928	11443.032	1649.808
RPCS	9782.996	12114.32	239.492	9378.7	11643.472	1719.188

Table 4.19: Average working time units required

the initial schedule constructed by the BS whereas the minimum decrease belongs to the VM for both of the weight figures. To recall, the total incurred cost, on the average at initial schedule obtained by the BS is greater than the VM. This means that the number of working hours of workers of higher skill levels used in the schedule constructed by the BS is greater than the VM. Table 4.19 proves this claim. Another consequence of the having a large number of working time units of higher skill levels used in the schedule constructed by the BS is that the number of candidates for the mode selection exchange is more for the BS and less for the VM. Nevertheless, the difference between the decrease in total incurred cost results of the $\bar{t}_{ji}$ estimation methods is not noteworthy. About 2.5 % improvement is achieved for all of the $\bar{t}_{ji}$ estimation methods. Between 55 and 60 % of the computational effort used in phase 1 is required for the phase 2. Although the values of the additional CPU required for phase 2 in percentages are very large, the improvement phase is successful for all methods since the CPU time required for all of the methods are not noteworthy showing the success of the phase 2. We also calculate the percentage decrease in the total incurred cost, the additional CPU used to obtain the improvement in percentage, for the larger total project slack case. In Table 4.20, we provide a summary of these results for the MSP weight figure. For the large total project slack, the decrease in the total cost after improvement of the schedule constructed by the BS is again larger than the decrease in cost after improvement of the schedules obtained by the other methods and the minimum improvement is achieved for the VM similar to the small total project slack. This is again because of the fact that the number of working hours of workers of higher skill levels used in the schedule constructed by the BS is larger than the VM. The average working time units required is given in Table 4.21 proving our claim. On the other hand, the difference between the improvement percentage for the BS and the other methods are now significant. This is expected since the idle time blocks in the schedules for the large total project slack are more and long. Then, the number of mode selection exchanges satisfying the conditions stated in Subsection 3.4.2 is more for the large case.

Method	ΣB_i	CPU
ES	0.027147921	0.580624408
BS	0.030203973	0.608303835
CES	0.027224048	0.594677973
PCS	0.027720783	0.580643062
VM	0.025719861	0.589686434
RPCS	0.027092738	0.601515374

Table 4.20: Averages of additional CPU used to obtain a lower incurred cost value and the cost decrease, in percentages, for the MSP using the second due date coefficient set

When we look at the Table 4.22 and 4.23, we can see the characteristics of the $\bar{t}_{ji}$ estimation methods in a better way. It is important to mention that the cost of performing an activity by a worker of higher skill level is greater than the cost of performing by a lower skill level for all activities. Here, the cost refers to the multiplication of the number of working time units by the cost of a working time unit of that skill level. First of all, it is clear that the labor cost of the skill level 7 constitute the largest cost item for all methods. However, this percentage is the

	Phase 1			Phase 2		
Method	SL 7	SL 5	SL 3	SL 7	SL 5	SL 3
ES	9797.064	12098.24	232.124	9374.348	11590.216	1793.552
BS	10035.516	11818.936	206.98	9570.68	11235.544	1909.868
CES	9817.908	12074.48	230.048	9391.52	11564.184	1796.184
PCS	9829.96	12059.256	229.264	9395.788	11548.736	1814.764
VM	9723.96	11995.536	223.752	9321.776	11544.584	1671.388
RPCS	9808.268	12090.736	229.608	9385.128	11581.784	1787.92

Table 4.21: Average working time units required for the large total project slack

greatest when we use the method BS at initial schedule and after improvement. This is reasonable since the number of working time units of skill level 7 required in the schedules constructed by the BS is larger than the schedules constructed by the other methods. Furthermore, the smallest percentage is realized by the schedule constructed by the VM.

	Phase 1			Phase 2		
Method	SL 7	SL 5	SL 3	SL 7	SL 5	SL 3
ES	0.73621073	0.261211891	0.00257738	0.723664917	0.257369741	0.018965342
BS	0.738603973	0.258978258	0.002417769	0.7257479	0.25540438	0.018847721
CES	0.736395042	0.261022268	0.00258269	0.723771436	0.257239085	0.018989479
PCS	0.736384949	0.261030131	0.00258492	0.723733417	0.257262618	0.019003966
VM	0.738059377	0.25966149	0.002279133	0.725749126	0.255812109	0.018438765
RPCS	0.736428944	0.260985876	0.002585181	0.723795857	0.257217865	0.018986278

Table 4.22: Averages percentages of cost items in total incurred cost

	Phase 1			Phase 2		
Method	SL 7	SL 5	SL 3	SL 7	SL 5	SL 3
ES	0.73702506	0.260470544	0.002504396	0.723980691	0.25619789	0.019821419
BS	0.746306475	0.251488854	0.002204671	0.732886297	0.246194462	0.020919241
CES	0.737823306	0.259697046	0.002479648	0.724737222	0.255427331	0.019835447
PCS	0.738306884	0.259223521	0.002469596	0.724926927	0.255036482	0.020036592
VM	0.737275687	0.26029092	0.002433393	0.724556519	0.256852877	0.018590604
RPCS	0.737379644	0.260144474	0.002475882	0.724389283	0.255863769	0.019746947

Table 4.23: Averages percentages of cost items in total incurred cost for the large total project slack

Having concluded that the improvement phase is successful for all of the $\bar{t}_{ji}$ estimation methods, let us analyze these methods by tightness levels of the release and the due date in terms of the total weighted tardiness and the total incurred cost. In Tables A.1 and A.2, we provide descriptive statistics of the total weighted tardiness results by tightness levels of the release date, A_i, for the $\bar{t}_{ji}$ estimation methods, with which the weight matrices of the aircraft configurations determined by the MSP and the fleets, respectively. Meanwhile, release date level 1 corresponds to the release dates generated when the utilization level of the bottleneck shelter is 80%, 3 corresponds to 90%, and 5 corresponds to 97%. To remind, the total weighted tardiness values do not change in the second phase, thus, the results at initial schedule are stated in these tables.

We can see from Tables A.1 and A.2 that as the release date gets tighter, the total weighted tardiness gets larger for all of the $\bar{t}_{ji}$ estimation methods. For the tight release date case, the BS outperforms the others whereas for the loose release date case, the VM outperforms the others. Although the total project slack is so small, the PCS outperforms the CES and the CES outperforms the ES as claimed for all release date tightness levels for the MSP weight figure. This is also valid for the fleets weight figure except for the release date level 3 for which the CES outperforms the PCS. However, the differences are very small. In order to strengthen our claim that with larger total project slack, the FLPM specific $\bar{t}_{ji}$ estimation methods will show their real performance, let us analyze the descriptives in terms of total weighted tardiness with the second due date coefficient set. In Table A.3, we provide descriptive statistics of the total weighted tardiness results by levels of A_i for the $\bar{t}_{ji}$ estimation methods using the second set of the due date coefficient set for the MSP weight figure. We observe from Table A.3 that the BS surpasses all of the remaining five methods in terms of total weighted tardiness for all of the release date tightness levels. Moreover, some of the schedules when the BS is employed results with 0 for the release date level 1 and 3 for which the minimum values are 0. In addition, the largeness of the total project slack causes the PCS to outperform the CES and the CES to outperform the ES as claimed for all release date tightness levels. In other words, our aim in developing these methods specific to the FLPM problem are realized.

Having compared the $\bar{t}_{ji}$ estimation methods in terms of total weighted tardiness by tightness levels of release date, let us compare them in terms of total incurred cost. Tables A.4 and A.5 summarize the descriptive statistics of the incurred cost results by levels of A_i. We see from Tables A.4 and A.5 that for all of the methods, the cost decreases as the release date gets tighter. This is expected since as the interrarrival times get tighter, the work load in unit time gets larger so all of the resources are utilized more. This means that the workers of lower skill levels are utilized more resulting with smaller total incurred cost. Furthermore, the total incurred cost values after the improvement phase decreases as the release date gets tighter. This is because of the logic employed in the second phase that is the mode selection exchange is realized if the exchange decreases the cost. The VM results with smaller total incurred cost than the other methods both at initial schedule and after improvement for all release date tightness levels. Nevertheless, the difference between the VM and the BS is very small for the tight release date especially after improvement. At initial schedule, for the loose release date, the ES gives better results than the CES which gives better results than the PCS whereas for the tight release date the order is the vice versa except for the fleets weight figure for which the ES gives better results than the PCS and the CES. Again, the differences are very small. The situation is similar after the improvement for the MSP weight figure. For the fleets weight figure, the ES outperforms the CES which outperforms the PCS for the loose case and the PCS outperforms the ES which outperforms the CES for the tight case. Meanwhile, the BS outperforms all these three methods for all release date tightness levels both at initial schedule and after improvement. Till now, we have compared the $\bar{t}_{ji}$ estimation methods in terms total incurred cost by the tightness levels of the release date for both phases when the total project slack is small. Let us investigate the total incurred cost by the levels of the release date when total project slack is larger. In Table A.6, we provide descriptive statistics of the total incurred cost results by levels of A_i for the $\bar{t}_{ji}$ estimation methods using the second set of the due date coefficients with the MSP weight figure. We observe from Table A.6 that for all of the methods, the cost decreases as the release date gets tighter for the large total project slack similar to the small total project slack case. This observation is also valid for the cost values obtained after the improvement phase. Again, the VM obtains smaller total incurred cost at initial schedule than the other methods. However, contrary to the small total project slack, the BS does not follow the VM, rather it performs the worst for all tightness levels of the release date. For the loose release date, the ES outperforms the CES which outperforms the PCS similar to the main due date coefficient set. However, the ES outperforms the CES which outperforms the PCS contrary to the main due date coefficient set for the tight release date. In other words, for large total project slack, ES, CES, and PCS is the best performing order. In addition, the differences between the total incurred cost results of these three methods are greater than the main due date coefficient set. The performance order in terms of total incurred cost differs after the improvement phase. For the tight release date, the PCS outperforms the CES whereas the the same order is valid for the level 1 that represents the loose release date. Meanwhile, the VM again surpasses all of the other methods according to the results obtained after improvement.

Till now, we have analyzed the performance of the $\bar{t}_{ji}$ estimation methods, in terms of total weighted tardiness and the total incurred cost by the tightness levels of the release date for small and large total project slack. From now on, we will examine these two objectives by the tightness levels of the due date using the main and the second due date coefficient set. The descriptive statistics of the total weighted tardiness and the incurred cost results by the tightness levels of the due date, $\overline{T_i}$, are summarized for the MSP and the fleets in Tables A.7, A.8, A.9, A.10, A.11, and A.12, respectively. Meanwhile, in Tables A.7, A.8, A.10, and A.11 due date level 1 corresponds to the due dates generated when the fraction of the tardy projects in percentages is 30%, 3 corresponds to 60%, and 5 corresponds to 80%. In Tables A.9 and A.12, the due date level 1 corresponds to the due dates generated when the due date coefficient is 1.3, 3 corresponds to 1.7, and 5 corresponds to 2. Let us first analyze the total weighted tardiness. Tables A.7 and A.8 show that for all $\bar{t}_{ji}$ estimation methods as the due date gets tighter, the total weighted tardiness increases as expected. For the tight due date, the VM is the outperformer while the BS is the outperformer for the due date levels 1 and 3 that represent loose and medium due date. Especially for the level 3, the BS surpasses all of the methods, deviating nearly 20% from the total weighted tardiness of the other methods. In addition, for the loose due date, the difference between the total weighted tardiness results of the VM and the BS is very small. Furthermore, the PCS gives smaller total weighted tardiness results than the CES which gives smaller total weighted tardiness results than the ES. However, the differences are very small and for the tight due date, the CES and the PCS result with equivalent total weighted tardiness values. This is expected because of the smallness of the total project slack. To recall, due to the small total project slack, the ATC rule turns to the WSPT rule and the logic behind the $\bar{t}_{ji}$ estimation methods are not of use. In other words, these methods end up with similar schedules. According to our results, for the due date levels 3 and 5, this situation exists resulting equivalent or very close total weighted tardiness values for different methods of $\bar{t}_{ji}$ estimation. Let us investigate what happens to the performance of the $\bar{t}_{ji}$ estimation methods in terms of total weighted tardiness for different levels of the due date when the total project slack is large. In Table A.9, we provide descriptive statistics of the total weighted tardiness results by levels of $\overline{T_i}$ for the $\bar{t}_{ji}$ estimation methods using the second set of the due date coefficients for the MSP weight figure. We observe from Table A.9 that for all $\bar{t}_{ji}$ estimation methods as the due date gets looser, the total weighted tardiness decreases as expected for the large total project slack. The BS surpasses all of the methods in terms of total weighted tardiness. Especially for the medium and the loose due date, that are level 3 and 5, it gives results nearly half and one sixths of the second best method. For the tight due date, the VM outperforms the PCS and PCS, CES and ES is the performance order in terms of total weighted tardiness. On the other hand for the levels 3 and 5, that represent the medium and the loose due date, the VM performs the worst but again PCS, CES and ES is the performance order in terms of total weighted tardiness.

Having compared the $\bar{t}_{ji}$ estimation methods, in terms of total weighted tardiness by the levels of the due date, let us compare them in terms of total incurred cost. We see from Table A.10 that the VM outperforms the other methods for the tight due date at initial schedule whereas the PCS outperforms the others for the loose due date. The PCS is followed by the VM and the VM is followed by the BS for the loose and the tight due date respectively. Although the PCS performs better than the VM at initial schedule for the loose due date, the VM performs better after improvement. Furthermore, the VM also performs better than the other methods after improvement for the tight due date. The PCS gives smaller total incurred cost than the CES which gives smaller results than the ES after the improvement phase. On the other hand, for the fleets weight figure, the VM outperforms the others for both the tight and the loose due dates according to Table A.11. The ES, the CES, and the PCS result with equivalent or close total incurred cost for the level 5 and the descending total incurred cost order is PCS, CES, ES similar to the MSP case. For all of the $\bar{t}_{ji}$ estimation methods, after improvement the total incurred cost decreases as expected for both weight figures.

Let us analyze the total incurred cost by tightness levels of the due date when there is large total project slack. In Table A.12, we provide descriptive statistics of the total incurred cost results by the tightness levels of $\overline{T_i}$ for all $\bar{t}_{ji}$ estimation methods using the second set of the due date coefficients for the MSP weight figure. We see from Table A.12 that the VM outperforms all the other methods and the BS performs the worst for all due date tightness levels for the large total project slack at initial schedule and after improvement. ES, PCS, and CES is the best performing order for due date level 1 and 3 whereas the order is ES, CES, and PCS for the level 5. The order between the FLPM problem specific methods does not change after improvement.

After analyzing the total weighted tardiness and the total incurred cost results by levels of the release and the due date tightness levels, let us propose one of the $\bar{t}_{ji}$ estimation methods to the different combinations of these two factors by the help of the t-paired sample test. Tables B.1 and B.2 provide paired samples statistics for the total weighted tardiness results of all $\bar{t}_{ji}$ estimation methods for the MSP and the fleets respectively. Meanwhile, the first number in the combination corresponds to the release date level and the second one corresponds to the due date level. The levels 1 and 5 are the equivalences of the levels in the previous tables. For some of the pairs, the correlation and t can not be computed because the standard error of the difference is 0. In other words, some pairs give equivalent results. The superiority of the VM for the loose release and due date combination is observed more clearly by looking at Tables B.1 and B.2 in terms of total weighted tardiness. In addition, the FLPM specific methods the PCS and the CES outperform the ES for 1-1 combination for the MSP weight figure. On the other hand, the BS is superior to these three methods for both weight figures. For the loose release date and tight due date case, again the PCS and the CES outperform the ES. This relation still holds for the tight release and due dates case, that is combination 5-5. For the tight release date and loose due date, the BS outperforms the other FLPM specific methods. As expected for the tight due date case, the method which gives the best performance cannot be obtained since with small total project slack the methods cannot demonstrate their capabilities. Then, let us analyze Table B.3 where the total project slack is larger. We observe from Table B.3 that the BS surpasses the VM for all combinations. In addition, the BS outperforms all of the other FLPM specific methods for the large total project slack. The VM performs worse than the FLPM specific methods for the loose due date and the superiority of the PCS over the CES and the CES over the ES comes to the fore.

Let us analyze the results of the t-paired sample tests of the total incurred cost. Tables B.4 and B.5 summarize the paired samples statistics for the incurred cost results of all $\bar{t}_{ji}$ estimation methods and the release and the due date tightness level combinations after improvement for the MSP and the fleets respectively. For some of the pairs, the correlation and t can not be computed because the standard error of the difference is 0. We observe from Tables B.4 and B.5 that the VM surpasses all the other methods and the difference between the FLPM specific methods is not evident for the loose release and due dates. For the loose release and tight due date combination, the CES and the PCS result with smaller cost than the ES for the MSP weight figure. None of the methods have outstanding performance compared to the others for the tight release and due dates for both weight figures. The 5-1 combination, that represents tight release and loose due dates, again none of the methods gives better cost values. Tables B.6 and B.7 summarize the paired samples statistics for the incurred cost results of all $\bar{t}_{ji}$ estimation methods at initial schedule and after improvement for all release and due date tightness level combinations for the MSP and the fleets respectively. For all release and due date combinations, the improvement phase performs well except the ES for the 5-5 combination.

The total incurred cost results of the t-paired sample tests for the second due date coefficient set is provided in Table B.8 for the MSP case. To recall, the due date coefficients are greater than the coefficients in the main due date coefficient set enabling large total project slack. For the 1-1 combination again the VM performs better, but the significance of the superiority of the VM over the FLPM specific methods decreases compared to the small total project slack. In other words, the FLPM specific methods give results closer to the VM when the total project slack increases. Nevertheless, the PCS, the RPCS, the CES, and the ES give results very close to the BS which performs the worst with respect to the VM. For the 1-5 combination, the PCS, the RPCS, the CES, and the ES, especially the ES, outperform the BS. The superiority of the VM has no significance for the 1-5 combination compared to 1-1 combination. In other words, for the loose due date, none of the methods surpasses the others. For the 5-5 combination, that is the tight release date and the loose due date, the ES outperforms the other FLPM specific methods. In addition, the PCS, the RPCS, the CES, and the ES give better results than the BS for the tight release date compared to the loose release date. Again, the VM has no significance for the 5-5 combination. For the 5-1 combination, the VM surpasses all the other methods. As a result, for the large total project slack, the FLPM specific methods except the BS give better total incurred cost results for the loose due date and the VM performs well for the tight due date. In addition, the ES surpasses the other FLPM specific methods for the loose due date.

Table B.9 summarizes the paired samples statistics for the incurred cost results of all $\bar{t}_{ji}$ estimation methods at initial schedule and after improvement when the total project slack is large for all release and due date combinations for the MSP weight figure. For all release and due date combinations the improvement phase performs well according to the results in Table B.9.

In order to understand how much our experimental factors are effective on the total weighted tardiness and the total cost incurred objectives, we performed Univariate ANOVA tests on the $\bar{t}_{ji}$ estimation methods using the SPSS. There are two factors, namely the release and due date of the aircrafts. Recall that, there are 5 levels for each factor. We used the weight matrix determined by the MSP. In addition, the Univariate ANOVA tests for the main and second due date coefficient sets are made separately. The significance level is 0.05. The results in Tables 4.24 and 4.25 provide the results of the Univariate ANOVA tests. Table 4.24 shows that the release and the due date are significant factors on the total weighted tardiness for all $\bar{t}_{ji}$ estimation methods. We observe from Table 4.25 that the release date is a significant factor on the total incurred cost for all methods whereas due date is significant for the BS and the VM. Tables 4.26 and 4.27 provide the Univariate ANOVA tests for the large total project slack. The conclusions made for the small total project slack is also valid for the large total project slack.

	Model			A_i			$\overline{T_i}$		
Method	df	F	Sig.	df	F	Sig.	df	F	Sig.
(ES)	24	11.593	0	4	28.239	0	4	41.184	0
(BS)	24	11.241	0	4	22.832	0	4	42.377	0
(CES)	24	11.550	0	4	27.936	0	4	41.232	0
(PCS)	24	11.583	0	4	27.817	0	4	41.538	0
(VM)	24	11.590	0	4	28.202	0	4	40.990	0
(RPCS)	24	11.553	0	4	27.934	0	4	41.254	0

Table 4.24: ANOVA test results for the total weighted tardiness results of all $\bar{t}_{ji}$ estimation methods

According to the analysis we realized in this section, we observe that the performance of the $\bar{t}_{ji}$ estimation method is dependent on the release and the

	Model			A_i			$\overline{T_i}$		
Method	df	F	Sig.	df	F	Sig.	df	F	Sig.
(ES)	24	5.534	0	4	33.119	0	4	0.028	0.998
(BS)	24	9.276	0	4	40.659	0	4	7.742	0
(CES)	24	5.666	0	4	33.908	0	4	0.027	0.999
(PCS)	24	5.796	0	4	34.704	0	4	0.007	1
(VM)	24	6.700	0	4	26.464	0	4	2.471	0.049
(RPCS)	24	5.751	0	4	34.408	0	4	0.030	0.998

Table 4.25: ANOVA test results for the incurred cost results of all $\bar{t}_{ji}$ estimation methods

	Model			A_i			$\overline{T_i}$		
Method	df	F	Sig.	df	F	Sig.	df	F	Sig.
(ES)	24	7.212	0	4	38.652	0	4	4.313	0.003
(BS)	24	9.224	0	4	26.645	0	4	22.844	0
(CES)	24	7.286	0	4	38.624	0	4	4.759	0.001
(PCS)	24	7.321	0	4	38.289	0	4	5.240	0.001
(VM)	24	7.673	0	4	42.055	0	4	3.725	0.007
(RPCS)	24	7.290	0	4	38.652	0	4	4.768	0.001

Table 4.26: ANOVA test results for the total weighted tardiness results of $\bar{t}_{ji}$ estimation methods using the second due date coefficient set

due date tightness levels and the total project slack. In addition, different $\bar{t}_{ji}$ estimation methods are proposed for the objectives total weighted tardiness and the total incurred cost. The improvement algorithm is successful since it decreases the cost for small additional computational effort for all conditions.

4.7 Conclusion

According to the results we obtained in the experiments we have performed, our single-pass heuristic algorithm improves the objective function value at every step.

In this chapter, the logistic and the financial information experienced during the FLPM of the aircrafts belonging to TUAF in one of the past years are provided

	Model			A_i			$\overline{T_i}$		
Method	df	F	Sig.	df	F	Sig.	df	F	Sig.
(ES)	24	6.998	0	4	41.607	0	4	0.168	0.954
(BS)	24	8.220	0	4	45.429	0	4	2.604	0.040
(CES)	24	6.878	0	4	40.728	0	4	0.145	0.965
(PCS)	24	7.547	0	4	44.587	0	4	0.311	0.870
(VM)	24	6.012	0	4	33.120	0	4	2.581	0.042
(RPCS)	24	7.366	0	4	43.703	0	4	0.247	0.911

Table 4.27: ANOVA test results for the incurred cost results of all $\bar{t}_{ji}$ estimation methods using the second due date coefficient set

firstly. The release and the due dates of the FLPM of the aircrafts are also within this data. We find out that the method which is used by TUAF for determining these two data, is insufficient, so we propose a determination method for each of the release and the due dates. The method that we propose aims finding the tightness levels of these two parameters. The release date determination method that we propose relates the arrival rate of the aircrafts with the utilization of the bottleneck shelter whereas the due date determination method that we propose relates the due dates of the aircrafts with the fraction of the number of tardy jobs in percentages. Following the methods that we propose, we find out the corresponding release and the due date coefficients for the predetermined utilization of the bottleneck shelter and the fraction of the number of tardy jobs in percentages. We also find out the weight matrices representing the MSP and the fleets points of view by the help of the Analytic Hierarchy Process. Then, we present the total weighted tardiness, the percentage fraction of the number of tardy projects, and the total incurred cost results of the heuristic that we propose to the experienced problem setting. We compare the results for the problem where the weights of all of the aircraft configurations are equivalent with the results for the problem where the weights are determined by the MSP and the fleets. Then, we solve the FLPM problems using the release and the due dates generated by the corresponding coefficients determined by the release and the due date determination methods that we propose. We investigate the performance of the

$\bar{t}_{ji}$ estimation methods in terms of the total weighted tardiness, the total incurred cost, and the computational effort required. This analysis is performed for the initial schedule and after the improvement separately. Furthermore, we analyze these methods by levels of release and due date tightness levels in terms of total weighted tardiness and the total incurred cost. In order to propose one of the $\bar{t}_{ji}$ estimation methods to the different combinations of the release and the due date tightness levels, we analyze the results of the t-paired sample tests. Meanwhile, all the analysis are also realized for the large total project slack because the due date coefficients determined are so small that the the superiority between the FLPM specific methods except the BS does not come to the fore. On the hand, the PCS outperforms the CES which outperforms the ES when the total project slack is large, as expected. Lastly, we prove the effects of our experimental factors on the objectives by the help of the ANOVA tests.

In the next chapter, we will present the conclusions that we come up with in our study. The contributions and the future research directions are also discussed.

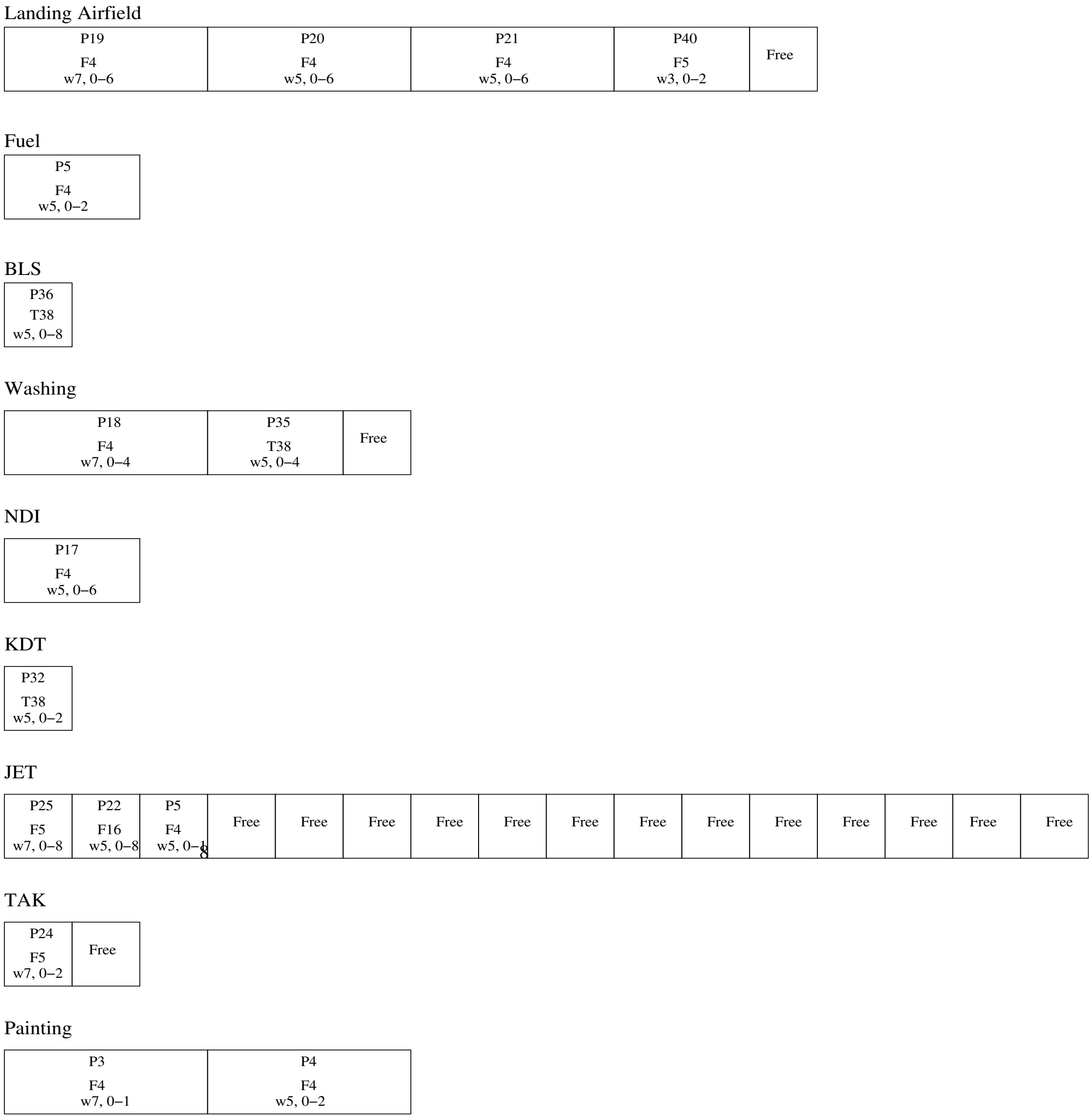


Figure 4.2: Existing work load in the common shelters

F4D

P2 F4 w7, 0–6	P6 F4 w5, 0–34	P7 F4 w5, 0–34	P8 F4 w5, 0–34	P9 F4 w5, 0–34	P10 F4 w5, 0–40	P11 F4 w5, 0–74	P12 F4 w5, 0–18	P13 F4 w5, 0–18	P14 F4 w5, 0–28	P15 F4 w3, 0–34	P16 F4 w3, 0–34	P22 F16 w3, 0–4	Free	Free	Free

F4H

P11 F4 w7, 0–2	P23 F16 w5, 0–2	Free	Free

F5D

P26 F5 w7, 0–38	P27 F5 w5, 0–54	P28 F5 w5, 0–12	P29 F5 w5, 0–26	P25 F5 w5, 0–8	Free	Free	Free	Free	Free	Free	Free

F5H

Free	Free	Free	Free

T37D

P37 T37 w7, 0–22	P38 T37 w5, 0–22	Free	Free	Free	Free	Free	Free	Free	Free	Free	Free

T37H

P39 T37 w7, 0–2	Free	Free	Free	Free	Free

T38D

P30 T38 w7, 0–14	P31 T38 w5, 0–14	P33 T38 w5, 0–10	P34 T38 w5, 0–10	Free	Free	Free	Free	Free	Free	Free	Free

T38H

Free	Free	Free	Free

Figure 4.3: Existing work load in the PAC type shelters

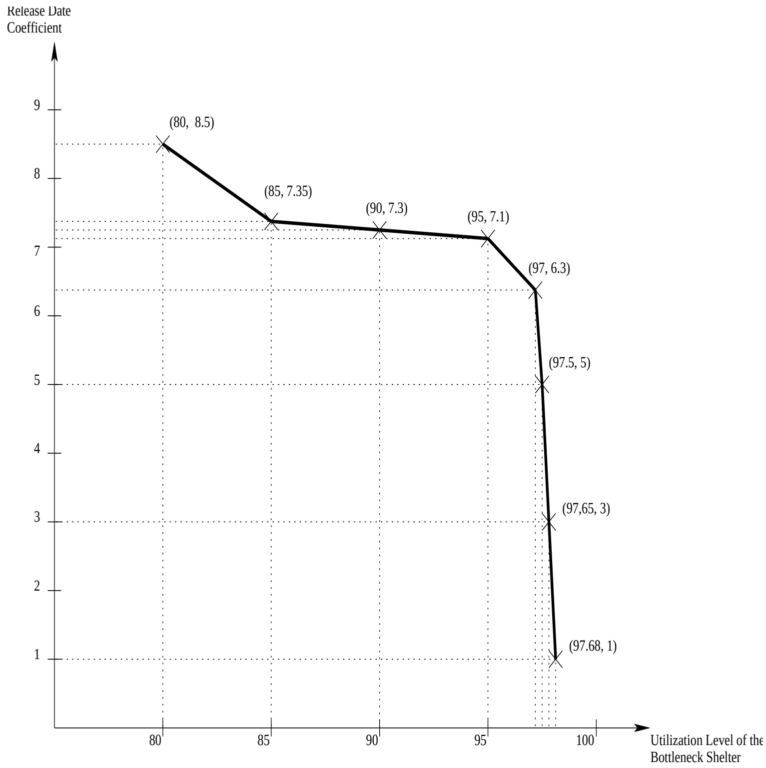
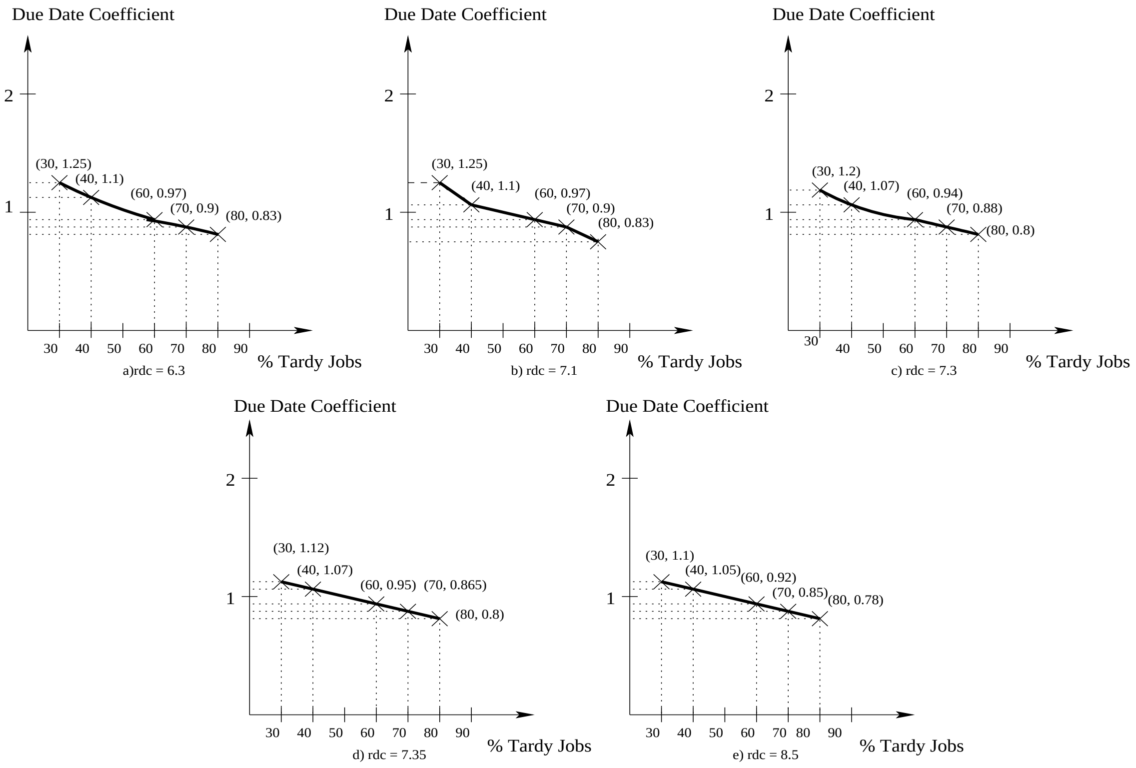


Figure 4.4: Release date coefficient versus utilization level of the bottleneck shelter diagram



a)rdc = 6.3

b) rdc = 7.1

c) rdc = 7.3

d) rdc = 7.35

e) rdc = 8.5

Figure 4.5: Due date coefficient versus fraction of the number of tardy projects in percentage diagram

Chapter 5

Conclusion

In this study we consider the Factory Level Preventive Maintenance (FLPM) of the aircrafts belonging to the fleets of Turkish Air Force (TUAF) which is a well fit real life application of Nonpreemptive Resource Constrained Multiple Project Scheduling with Mode Selection (NRCMPSMS).

The aircrafts of different aircraft configurations, are maintained in predetermined periods in the Military Supply Point (MSP). The arriving time to the MSP and the due date for the completion of the FLPM for each aircraft are determined by TUAF somehow in an adhoc manner without considering the implications of the scheduling decisions of the limited resources on the project completion times. An aircraft configuration specific task plan exists for the FLPM where the order of the operations, the time, and the resources required to perform each operation are gathered in. The resources are the workers and the docks in the shelter. Meanwhile, there are two types of shelters, the first type shelters are used only by one aircraft configuration and the second type shelters are used by all aircraft configurations. The operations can be processed by a worker of multiple possible skill levels. The cost of performing an operation increases as the skill level increases. In addition, a ranking is made between the aircraft configurations from the availability point of view. TUAF aims minimizing the time elapsed to complete the FLPM and secondarily aims minimizing the total incurred cost that is composed of the labor cost only. Here, the aircraft configurations are the project types, the FLPM of each arriving aircraft is the project, the operations of the FLPM indicated in the task plans are the activities of the projects, and the worker skill levels are the modes. The primary objective is minimizing the total weighted tardiness and the secondary objective is minimizing the total incurred cost.

In Chapter 3, we proposed a new solution procedure to this real life problem that is composed of two phases. In the first phase, an initial feasible schedule is obtained with the objective of minimum total weighted tardiness and in the second phase, this schedule is modified by mode selection exchanges to obtain a smaller total incurred cost value for a fixed total weighted tardiness, if possible.

In the proposed heuristic, we use different chain of rules for different shelter types in prioritization of the activities. We adapted the known ATC rule to capture the existence of multiple projects and availability of the mode selection and use this modified rule in prioritization of the activities that are to be processed in the commonly used shelters. This is achieved by using time dependent duration variable and introducing activity and project indices to the parameters in the ATC formula. Furthermore, the modified ATC rule requires the activity due date information which is not available in the FLPM problem. Therefore, five activity due date estimation methods were developed considering the properties of the FLPM problem and the method developed by Vepsailanen and Morton (VM) [58] was also used as an activity due date estimation method. In the first method, the tightness due to work load in all shelters is relaxed by introducing equal slacks in addition to the duration variable of the activity. In the second method, the possible latest due date values are set to the activity due date parameters. Due to this property, we expected this method to give minimum total weighted tardiness for the FLPM problem under congested shop load. Because, under congested shop load, the waiting times in the queues are very long and so the jobs can be performed very close to its due date and most of the time the completion time exceeds the due date. So the best estimate for the due date of the job is the possible latest due date. The logic used in the third method, distributing the slack among the common shelters, is because of the fact that the common shelters are the most utilized shelters. By introducing larger slacks to the activities to be performed in those common shelters, this tightness is to be eliminated insofar as it is possible. However, the processing time required for the corresponding activities in the common shelters are not close values. Therefore, the work congestion due to the processing times in these common shelters vary. The fourth method, which is distributing the slack among the activities that are performed in common shelters in proportion to the processing time required for the corresponding activities if a worker of skill level 5 is assigned, was proposed to normalize this variety. The fifth method employs the opposite of logic used in the fourth method, that is the slack is distributed to the common shelters in reverse proportion to the processing time required for the activities. ES, BS, CES, PCS, and RPCS are the abbreviations of the methods respectively.

The activities to be performed in the shelters that are peculiar to the aircraft configurations ordered firstly in ascending release time for that specific shelter. Then, the ones that have equivalent activity release time values are grouped and they are ordered in ascending project release time. Again the ones that have equivalent activity and project release time are ordered in ascending the due date.

After prioritizing the activities to be performed, the dock and the worker assignment process begins. Firstly, the availability of the dock(s) is checked. If there is enough dock(s), the assignment takes place and then the worker assignment is carried out. While assigning worker to the activity among the available workers, the worker with highest qualification is assigned first. It is logical to utilize the available worker of highest level as much as possible to come up with a schedule that has the minimal tardiness values.

To find out a schedule incurring smaller cost value than the value incurred by the feasible schedule obtained in the first phase which is the secondary objective of TUAF, we changed the modes of the activities performed only in the PAC shelters with the lower ones in the second phase. The logic followed was making the aircraft being in process in the PAC shelter before the common shelter instead of waiting for the common shelter, because of the fact that the common shelters are highly utilized and the waiting times in the queues of them are very large. While this operation is made, the order of the activities in the succeeding common shelter is not changed. The second phase starts processing after the termination of the first phase and continues till there is no activity satisfying the conditions required to apply the second phase.

In Chapter 4, we first compare the results of the heuristic that we proposed for the FLPM problem experienced by TUAF where the weights of all of the aircraft configurations are equivalent, that is the weight figure used by TUAF, with the results for the problem where the weights are determined by the MSP and the fleets. Meanwhile, the MSP and the fleets weight figures were determined by the help of Analytic Hierarchy Process method. The equivalent weight case ends up with large total weighted tardiness and total incurred cost values than the other two weight figures. The VM and the BS methods are the outperformers due to congested shop load and tight due dates for all of the weight figures. In addition, the improvement phase decreases the cost sufficiently for small additional CPU.

In this chapter, we also propose a determination method for each of the release and the due dates because we found out that the method which is used by TUAF for determining these two parameter, is insufficient. These methods aims finding the tightness levels of these two parameters. The release date determination method relates the arrival rate of the aircrafts with the utilization of the bottleneck shelter whereas the due date determination method relates the due dates of the aircrafts with the fraction of the number of tardy jobs in percentages. By considering the shop load of the system with the help of the utilization of the bottleneck shelter, we can determine when the aircrafts arrive to the MSP. By this consideration, the unnecessary waiting times due to the shop load is eliminated insofar as it is possible. With the release dates set by TUAF, the aircrafts may arrive to the MSP early and have to wait much for an assignment to the shelters. Again, by considering the fraction of number of tardy maintenances in percentage, we can set more reliable due dates. This leads to decrease in the deviations from the estimates of the number of available aircrafts at some time instance. Following these methods, we found out the corresponding release and the due dates for the predetermined utilization of the bottleneck shelter and the fraction of the number of tardy jobs in percentages. Then, with the release and the due dates obtained, we solved the FLPM problem. According to the results, the Backward Scheduling (BS) method performs the best in terms of total weighted tardiness and the Vepsailanen-Morton (VM) gives very close results to the BS. On the other hand, when we analyzed the summary of total incurred cost values, we saw that the VM surpasses the other methods for both weight figures and the BS follows the VM. We expected all of the FLPM specific methods which are BS, PCS, CES, ES, and RPCS to outperform the VM. However, only the BS gives better results than the VM. We thought that this may be due to the fact that the assumption made in the development of these methods, which is the existence of sufficient total project slack, is not satisfied. This leaded us to use larger total project slack. With larger total project slack, the FLPM specific methods come to the fore, namely BS, PCS, RPCS, CES, and ES outperforms the VM in terms of total weighted tardiness. PCS, RPCS, CES and ES is the order of the methods which have the descending total weighted tardiness. Again, the VM gives better total incurred cost for the large total project slack. However, the BS performs the worst for this case. The reverse of the order for the total weighted tardiness between the FLPM specific methods except the BS is valid for the total incurred cost objective. We evaluated these methods in terms of total incurred cost obtained after the employment of improvement phase to the schedules constructed in the first phase. All of the initial schedules constructed by all activity due date estimation methods are improved successfully. The order of the methods that results with descending cost does not change after improvement. We also concluded that the improvement phase reduces the outstandingness of the FLPM specific methods except the BS in terms of total incurred cost. Meanwhile, the CPU required for all methods for constructing the initial schedule and employment of the improvement are so small that it should not be a criterion in determining the overall best performer method.

We made a detailed analysis on the performance of the activity due date estimation methods and the success of the improvement phase for different tightness levels of the release and the due dates determined by the release and due date determination methods that we propose. Our first conclusion was that, as the release date gets tighter, the total weighted tardiness gets larger for all of the methods as expected. For the tight release date case, the BS outperforms the others whereas for the loose release date case, the PCS, RPCS, CES, and ES to give better results than the VM. Meanwhile, the PCS outperforms the CES which outperforms the ES for all release date tightness levels. In addition, the cost decreases as the release date gets tighter. This was expected since as the interrarrival times get tighter, the work load in unit time gets larger so all of the resources are utilized more. The VM results with smaller total incurred cost than the other methods both at initial schedule and after improvement for all release date tightness levels. However, contrary to the small total project slack, the BS does not follow the VM, rather it performs the worst for all tightness levels of the release date. For the small total project slack the differences between the FLPM specific methods except the BS are very small. For large total project slack, at initial schedule, ES, CES, and PCS is the best performing order in terms of total incurred cost. The performance order in terms of total incurred cost differs after the improvement phase. For the tight release date, the PCS outperforms the CES whereas the the same order is valid for the loose release date.

Another consequence of the analysis was that as the due date gets tighter, the total weighted tardiness increases as expected for both of the small and the large total project slack cases. For the tight due date, the VM is the outperformer while the BS is the outperformer for the loose and the medium due date when the total project slack is small. Again, the differences between the FLPM specific methods except the BS are very small. The BS surpasses all of the methods for large total project slack. For the medium and the loose due date, the VM performs the worst but again PCS, CES and ES is the ascending total weighted tardiness order. The behavior of the total incurred cost for different tightness levels of the due date cannot be determined. The ANOVA results support this, namely the due date is an insignificant factor on the total incurred cost for all methods except the BS and the VM according to the ANOVA results. Nevertheless, the VM outperforms the other methods for the tight due date at initial schedule whereas the PCS outperforms the others for the loose due date in terms of total incurred cost. The VM performs better after improvement for the loose due date. For all of the methods, after improvement the total incurred cost decreases. The VM outperforms all the other methods and the BS performs the worst for all due date tightness levels for the large total project slack at initial schedule and after improvement. ES, PCS, and CES is the best performing order for the tight and the medium due date whereas the order is ES, CES, and PCS for the loose due date. The order between the FLPM problem specific methods does not change after improvement. We also analyze the superiority of $\bar{t}_{ji}$ estimation methods over each other for different tightness level combinations of the release and the due date by the help of the t-paired sample test. Lastly, we proved the effects of our experimental factors on the objectives by the help of the ANOVA tests.

Possible topics for future research is to handle the problem as a multi criteria decision making problem. As noticed, for different objectives, different activity due date estimation methods are proposed. In addition, the tightness levels of the release and the due dates enlarge the solution variety. Then, weighting the objectives will enable to choose the activity due date estimation method easily. The outsourcing possibility is also important to analyze. Meanwhile, the airlines, outsource the preventive maintenances of the aircrafts in general. The airlines set a penalty cost for tardy maintenances and also aim minimizing the cost of the maintenance. Then, for this problem definition, different from the FLPM problem of TUAF there are two cost items which are the penalty cost and the labor cost. The heuristic we proposed has to be modified by treating outsourcing as one of the execution modes. In addition to the outsourcing possibility, the maintenance services serving for the civilian airlines prioritize the maintenances considering the airline that the aircraft belongs to. For instance, an airline having a smaller fleet wants the maintenance of its aircraft to be completed as soon as possible. This can be handled by airline dependent weighting of the maintenance projects.

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Appendix A

Results, Descriptive Statistics

Method	A_i	run#	Mean	95% CI for Mean		Minimum	Maximum
				Lower	Upper		
ES-1	1	25	445.5912	359.0410	532.1415	124.99	802.35
	3	25	593.5463	455.1487	731.9439	83.39	1233.64
	5	25	879.8482	781.7473	977.9490	530.87	1455.37
BS-1	1	25	440.7198	355.3403	526.0994	123.51	798.72
	3	25	562.7506	428.3498	697.1515	77.05	1210.34
	5	25	797.5382	699.7738	895.3026	499.07	1325.12
CES-1	1	25	444.9445	358.4714	531.4175	124.19	801.78
	3	25	592.6397	454.1055	731.1739	82.58	1233.07
	5	25	877.7308	779.3402	976.1214	527.83	1454.59
PCS-1	1	25	444.8546	358.3391	531.3700	123.90	801.78
	3	25	592.3872	453.8160	730.9583	82.65	1233.07
	5	25	876.3415	777.4549	975.2281	525.96	1454.59
VM-1	1	25	433.5584	349.5114	517.6054	117.80	798.72
	3	25	558.3162	424.9812	691.6512	69.42	1196.92
	5	25	848.8546	753.8342	943.8750	529.10	1439.86
RPCS-1	1	25	444.8589	358.3445	531.3733	124.19	801.78
	3	25	592.3872	454.0008	731.1046	82.65	1233.07
	5	25	877.7206	779.3299	976.1113	527.83	1454.59

Table A.1: Descriptives for total weighted tardiness results by levels of release date with the weight matrix determined by the MSP

Method	A_i	run#	Mean	95% CI for Mean		Minimum	Maximum
				Lower	Upper		
ES-1	1	25	310.0857	241.3932	378.7782	80.89	572.39
	3	25	374.7236	287.1767	462.2706	48.06	791.94
	5	25	499.6021	430.7824	568.4219	262.03	864.05
BS-1	1	25	307.3564	239.5903	375.1225	80.27	571.94
	3	25	356.7093	271.8362	441.5824	43.88	775.77
	5	25	458.8334	392.0531	525.6138	253.22	797.76
CES-1	1	25	310.0857	241.3932	378.7782	80.89	572.39
	3	25	374.7233	287.1666	462.2801	48.62	791.94
	5	25	499.4704	430.5792	568.3616	261.93	864.05
PCS-1	1	25	310.0857	241.3932	378.7782	80.89	572.39
	3	25	374.8397	287.3523	462.3270	48.62	791.94
	5	25	499.4577	430.5513	568.3641	261.93	864.05
VM-1	1	25	302.3156	234.6472	369.9840	76.96	572.14
	3	25	353.0802	268.3924	437.7681	38.60	775.10
	5	25	484.0625	416.4670	551.6581	259.78	872.72
RPCS-1	1	25	310.0424	241.3312	378.7536	80.89	572.39
	3	25	374.7047	287.1406	462.2689	48.45	791.94
	5	25	499.5145	430.6556	568.3734	261.93	864.05

Table A.2: Descriptives for total weighted tardiness results by levels of release date with the weight matrix determined by the fleets

Method	A_i	run#	Mean	95% CI for Mean		Minimum	Maximum
				Lower	Upper		
ES-1	1	25	77.4465	55.2726	99.6205	1.13	196.15
	3	25	225.6023	133.2553	317.9493	1.33	618.00
	5	25	499.5089	445.7398	553.2779	336.79	832.06
BS-1	1	25	35.0520	14.5687	55.5353	0.00	174.57
	3	25	135.8947	63.0824	208.7070	0.00	577.15
	5	25	303.2294	220.8055	385.6534	31.84	791.21
CES-1	1	25	74.1258	51.7831	96.4686	0.81	194.74
	3	25	221.6557	130.1687	313.1427	0.74	612.25
	5	25	492.4624	438.2329	546.6919	320.90	826.61
PCS-1	1	25	70.8596	48.5192	93.2000	0.78	194.73
	3	25	216.6213	126.2973	306.9454	0.07	607.42
	5	25	482.8708	428.0822	537.6593	314.91	818.91
VM-1	1	25	78.3892	57.3294	99.4490	1.65	197.77
	3	25	223.0409	133.3942	312.6876	2.70	585.06
	5	25	510.6804	456.2494	565.1114	314.73	837.87
RPCS-1	1	25	73.4116	50.9991	95.8241	0.75	193.52
	3	25	221.1942	129.9874	312.4009	0.74	610.73
	5	25	490.6858	436.8926	544.4791	320.26	818.71

Table A.3: Descriptives for total weighted tardiness results by levels of release date with the weight matrix determined by the MSP using the second due date coefficient set

Method	A_i	run#	Mean	95% CI for Mean		Minimum	Maximum
				Lower	Upper		
ES-1	1	25	94655.28	94256.14	95054.42	93241.00	96092.00
	3	25	92455.28	91526.60	93383.96	89933.00	96348.00
	5	25	90651.24	90238.61	91063.87	88971.00	92244.00
BS-1	1	25	94537.96	94122.90	94953.02	92560.00	96313.00
	3	25	91783.56	90857.59	92709.53	88186.00	96348.00
	5	25	89920.48	89359.45	90481.51	86820.00	92041.00
CES-1	1	25	94659.40	94256.15	95062.65	93234.00	96091.00
	3	25	92489.68	91564.85	93414.51	89932.00	96456.00
	5	25	90622.64	90221.89	91023.39	88969.00	92176.00
PCS-1	1	25	94667.04	94269.87	95064.21	93425.00	96091.00
	3	25	92466.36	91545.16	93387.56	89932.00	96336.00
	5	25	90588.64	90192.79	90984.49	88969.00	92099.00
VM-1	1	25	93424.32	92940.86	93907.78	91365.00	95783.00
	3	25	91247.88	90318.68	92177.08	87105.00	96039.00
	5	25	89575.40	89077.31	90073.49	86620.00	91578.00
RPCS-1	1	25	94660.84	94260.50	95061.18	93234.00	96091.00
	3	25	92485.24	91564.25	93406.23	89932.00	96336.00
	5	25	90615.08	90216.56	91013.60	88969.00	92166.00
ES-2	1	25	92473.92	92075.52	92872.32	90978.00	94029.00
	3	25	90095.96	89148.42	91043.50	87524.00	94171.00
	5	25	88141.40	87682.83	88599.97	86172.00	89750.00
BS-2	1	25	92310.24	91895.03	92725.45	90388.00	94170.00
	3	25	89449.24	88562.92	90335.56	85945.00	93809.00
	5	25	87363.68	86774.45	87952.91	84255.00	89680.00
CES-2	1	25	92478.00	92071.18	92884.82	90938.00	94019.00
	3	25	90114.88	89175.02	91054.74	87517.00	94159.00
	5	25	88103.88	87665.16	88542.60	86152.00	89674.00
PCS-2	1	25	92486.16	92085.15	92887.17	91117.00	94019.00
	3	25	90078.64	89144.32	91012.96	87517.00	94159.00
	5	25	88085.64	87660.44	88510.84	86152.00	89604.00
VM-2	1	25	91251.80	90758.81	91744.79	89181.00	93716.00
	3	25	88974.12	88060.42	89887.82	84752.00	93714.00
	5	25	87141.80	86617.30	87666.30	84177.00	89057.00
RPCS-2	1	25	92468.00	92065.93	92870.07	90938.00	94019.00
	3	25	90108.36	89177.16	91039.56	87517.00	94159.00
	5	25	88096.92	87660.49	88533.35	86152.00	89654.00

Table A.4: Descriptives for incurred cost results by levels of release date with the weight matrix determined by the MSP

Method	A_i	run#	Mean	95% CI for Mean		Minimum	Maximum
				Lower	Upper		
ES-1	1	25	94680.7200	94335.2842	95026.1558	93139.00	95839.00
	3	25	92998.9200	92210.7958	93787.0442	90575.00	96224.00
	5	25	91133.0000	90687.0090	91578.9910	89267.00	92306.00
BS-1	1	25	94539.4800	94175.2192	94903.7408	92874.00	96048.00
	3	25	92414.6400	91595.3586	93233.9214	88932.00	96071.00
	5	25	90341.2000	89782.3165	90900.0835	87614.00	92794.00
CES-1	1	25	94681.9200	94336.9764	95026.8636	93142.00	95835.00
	3	25	92987.2000	92196.8890	93777.5110	90575.00	96245.00
	5	25	91151.7200	90712.3486	91591.0914	89312.00	92378.00
PCS-1	1	25	94681.1600	94336.2361	95026.0839	93142.00	95835.00
	3	25	92962.5200	92173.1227	93751.9173	90575.00	96245.00
	5	25	91183.3200	90734.2991	91632.3409	89306.00	92804.00
VM-1	1	25	93459.0800	93018.7103	93899.4497	91541.00	95951.00
	3	25	91867.7600	90997.0149	92738.5051	87177.00	96094.00
	5	25	90229.3200	89725.6787	90732.9613	87383.00	92146.00
RPCS-1	1	25	94680.6800	94334.3671	95026.9929	93139.00	95879.00
	3	25	92966.0400	92182.6280	93749.4520	90575.00	96224.00
	5	25	91157.5600	90705.4181	91609.7019	89273.00	92832.00
ES-2	1	25	92666.96	92307.4815	93026.4385	91019.00	93743.00
	3	25	90778.96	90064.8543	91493.0657	88488.00	93511.00
	5	25	88911.8	88487.6717	89335.9283	87246.00	90124.00
BS-2	1	25	92519.08	92162.9680	92875.1920	90878.00	93833.00
	3	25	90168.52	89409.8753	90927.1647	86944.00	93461.00
	5	25	88057.64	87487.8643	88627.4157	85079.00	90553.00
CES-2	1	25	92667.32	92308.4096	93026.2304	91021.00	93729.00
	3	25	90776.96	90060.7469	91493.1731	88488.00	93533.00
	5	25	88933.76	88520.0421	89347.4779	87308.00	90178.00
PCS-2	1	25	92666.88	92308.0236	93025.7364	91021.00	93729.00
	3	25	90746.36	90033.5039	91459.2161	88488.00	93533.00
	5	25	88958.32	88533.8458	89382.7942	87284.00	90582.00
VM-2	1	25	91506.2	91066.1335	91946.2665	89681.00	93899.00
	3	25	89652.28	88845.3033	90459.2567	85088.00	93396.00
	5	25	88100.4	87617.4483	88583.3517	85555.00	89954.00
RPCS-2	1	25	92666.16	92307.3427	93024.9773	91044.00	93749.00
	3	25	90754.4	90045.6170	91463.1830	88488.00	93511.00
	5	25	88937.76	88511.9292	89363.5908	87308.00	90579.00

Table A.5: Descriptives for incurred cost results by levels of release date with the weight matrix determined by the fleets

Method	A_i	run#	Mean	95% CI for Mean Lower	Upper	Minimum	Maximum
ES-1	1	25	94775.68	94442.89	95108.47	92953.00	96125.00
	3	25	92617.32	91714.62	93520.02	89985.00	96550.00
	5	25	90751.64	90382.60	91626.71	88562.00	92008.00
BS-1	1	25	95886.40	95565.39	96167.41	94213.00	97168.00
	3	25	93866.88	93149.34	94584.42	90901.00	96694.00
	5	25	92169.60	91626.71	92712.49	88721.00	94024.00
CES-1	1	25	94940.48	94636.92	95244.04	93625.00	96176.00
	3	25	92854.52	91956.86	93752.18	89904.00	96593.00
	5	25	90868.92	90462.88	91274.96	88756.00	92181.00
PCS-1	1	25	94993.40	94702.34	95284.46	93704.00	96173.00
	3	25	92930.04	92042.58	93817.50	90089.00	96665.00
	5	25	90910.84	90481.86	91339.82	88724.00	92560.00
VM-1	1	25	94048.28	93562.63	94533.93	92304.00	95995.00
	3	25	91667.20	90661.64	92672.76	87970.00	96066.00
	5	25	89912.52	89492.52	90332.52	87592.00	91842.00
RPCS-1	1	25	94875.80	94603.86	95147.74	93921.00	96193.00
	3	25	92800.08	91934.92	93665.24	89932.00	96416.00
	5	25	90778.36	90386.00	91170.72	88803.00	92211.00
ES-2	1	25	92425.80	92076.12	92775.48	90705.00	93965.00
	3	25	90072.36	89218.16	90926.56	87479.00	93828.00
	5	25	88119.88	87736.83	88502.93	85698.00	89503.00
BS-2	1	25	93132.64	92856.21	93409.07	91558.00	94195.00
	3	25	91026.92	90353.81	91700.03	88362.00	93783.00
	5	25	89224.84	88721.71	89727.97	86291.00	90625.00
CES-2	1	25	92581.36	92252.38	92910.34	91123.00	93871.00
	3	25	90286.20	89428.44	91143.96	87199.00	93717.00
	5	25	88279.72	87867.01	88692.43	85925.00	89596.00
PCS-2	1	25	92572.80	92277.37	92868.23	91452.00	93734.00
	3	25	90361.24	89528.87	91193.61	87620.00	93890.00
	5	25	88216.76	87820.91	88612.61	85828.00	89478.00
VM-2	1	25	91858.40	91362.94	92353.86	90189.00	93911.00
	3	25	89316.16	88316.32	90316.00	85711.00	93715.00
	5	25	87421.80	86988.77	87854.83	84734.00	89316.00
RPCS-2	1	25	92500.92	92196.07	92805.77	91443.00	94026.00
	3	25	90282.48	89462.61	91102.35	87258.00	93717.00
	5	25	88166.12	87749.07	88583.17	86118.00	89620.00

Table A.6: Descriptives for incurred cost results by levels of release date with the weight matrix determined by the MSP using the second due date coefficient set

Method	$\overline{T_i}$	run#	Mean	95% CI for Mean Lower	Upper	Minimum	Maximum
ES-1	1	25	358.2229	273.3755	443.0703	83.39	854.39
	3	25	583.0235	490.0154	676.0315	298.03	1132.71
	5	25	878.5594	784.6743	972.4445	557.00	1455.37
BS-1	1	25	337.7623	255.9217	419.6030	77.05	820.57
	3	25	480.5443	412.2556	548.8331	282.68	850.34
	5	25	849.3084	760.5436	938.0731	526.78	1325.12
CES-1	1	25	356.2206	271.4040	441.0371	82.58	852.96
	3	25	582.4052	489.4848	675.3256	297.46	1131.94
	5	25	877.8921	784.1186	971.6655	556.43	1454.59
PCS-1	1	25	354.27546	270.3360	438.2151	82.65	840.64
	3	25	582.4052	489.4848	675.3256	297.46	1131.94
	5	25	877.8921	784.1186	971.6655	556.43	1454.59
VM-1	1	25	344.2254	259.9786	428.4722	69.42	863.30
	3	25	559.2477	471.8066	646.6889	286.77	1129.50
	5	25	847.4755	758.0281	936.9228	535.14	1439.86
RPCS-1	1	25	356.0207	271.1650	440.8764	82.65	852.96
	3	25	582.4052	489.4848	675.3256	297.46	1131.94
	5	25	877.8921	784.1186	971.6655	556.43	1454.59

Table A.7: Descriptives for total weighted tardiness results by levels of due date with the weight matrix determined by the MSP

Method	$\overline{T_i}$	run#	Mean	95% CI for Mean		Minimum	Maximum
				Lower	Upper		
ES-1	1	25	184.5302	144.6204	224.4401	48.06	412.62
	3	25	361.5086	317.7459	405.2713	219.17	613.18
	5	25	606.5060	562.3645	650.6475	439.36	864.05
BS-1	1	25	179.3306	139.8415	218.8198	43.88	408.51
	3	25	306.7927	273.5196	340.0659	204.76	490.83
	5	25	587.7909	545.5320	630.0498	408.23	797.76
CES-1	1	25	184.3541	144.4414	224.2668	48.62	411.86
	3	25	361.5227	317.7548	405.2907	219.17	613.18
	5	25	606.4730	562.3133	650.6326	439.36	864.05
PCS-1	1	25	184.3883	144.5465	224.2301	48.62	411.85
	3	25	361.5227	317.7548	405.2907	219.17	613.18
	5	25	606.4730	562.3133	650.6326	439.36	864.05
VM-1	1	25	177.1811	137.7430	216.6192	38.60	413.56
	3	25	348.1170	307.1979	389.0362	209.45	608.78
	5	25	587.8888	544.3136	631.4639	416.70	872.72
RPCS-1	1	25	184.2744	144.3478	224.2009	48.45	411.86
	3	25	361.5227	317.7548	405.2907	219.17	613.18
	5	25	606.4730	562.3133	650.6326	439.36	864.05

Table A.8: Descriptives for total weighted tardiness results by levels of due date with the weight matrix determined by the fleets

Method	$\overline{T_i}$	run#	Mean	95% CI for Mean		Minimum	Maximum
				Lower	Upper		
ES-1	1	25	310.2018	219.4227	400.9809	54.75	832.06
	3	25	216.6274	136.9059	296.3488	8.86	688.02
	5	25	173.0660	100.6910	245.4111	1.13	611.68
BS-1	1	25	278.3339	191.2703	365.3976	45.89	791.21
	3	25	100.8162	48.1674	153.4651	0.41	466.20
	5	25	37.7242	9.6958	65.7526	0.00	294.81
CES-1	1	25	308.5577	218.1444	398.9709	52.80	826.61
	3	25	211.8506	132.2455	291.4556	8.52	684.09
	5	25	165.5083	94.0692	236.9473	0.74	605.92
PCS-1	1	25	306.2965	216.5649	396.0280	52.18	818.91
	3	25	206.8926	128.1742	285.6110	7.96	682.38
	5	25	156.4243	88.0124	224.8361	0.07	574.15
VM-1	1	25	304.7211	215.8429	393.5994	55.14	837.87
	3	25	227.8932	146.6394	309.1469	11.02	716.49
	5	25	180.5902	108.0793	253.1011	1.65	645.80
RPCS-1	1	25	307.1690	217.4843	396.8537	54.63	818.71
	3	25	211.3186	131.7109	290.9262	8.52	683.78
	5	25	164.4661	93.2598	235.6724	0.74	602.01

Table A.9: Descriptives for total weighted tardiness results by levels of due date with the weight matrix determined by the MSP using the second due date coefficient set

Method	$\overline{T_i}$	run#	Mean	95% CI for Mean		Minimum	Maximum
				Lower	Upper		
ES-1	1	25	92839.56	92082.14	93596.98	89459.00	96458.00
	3	25	92781.32	91995.68	93566.96	88993.00	96337.00
	5	25	92810.20	92032.50	93587.00	88971.00	96337.00
BS-1	1	25	92933.88	92155.16	93712.60	89258.00	96313.00
	3	25	91831.04	90921.23	92740.85	87655.00	95181.00
	5	25	92046.56	91203.87	92889.25	87841.00	95813.00
CES-1	1	25	92847.64	92093.30	93601.98	89372.00	96456.00
	3	25	92781.72	91995.42	93568.02	88991.00	96336.00
	5	25	92810.60	92032.32	93588.88	88969.00	96336.00
PCS-1	1	25	91392.36	90753.72	92031.00	88721.00	95096.00
	3	25	92781.72	91995.42	93568.02	88991.00	96336.00
	5	25	92810.60	92032.32	93588.88	88969.00	96336.00
VM-1	1	25	92815.40	92044.21	93586.59	89315.00	96301.00
	3	25	92207.36	91413.97	93000.75	87105.00	94761.00
	5	25	91749.40	90960.35	92538.45	87821.00	95783.00
RPCS-1	1	25	92855.800	92099.69	93611.91	89375.00	96306.00
	3	25	92781.72	91995.42	93568.02	88991.00	96336.00
	5	25	92810.60	92032.32	93588.88	88969.00	96336.00
ES-2	1	25	90467.08	89687.30	91246.86	87114.00	94083.00
	3	25	90403.68	89580.26	91227.10	86204.00	94171.00
	5	25	90435.44	89621.92	91248.96	16707.2	342628.2
BS-2	1	25	90509.28	89720.94	91297.62	87008.00	94170.00
	3	25	89313.20	88342.74	90283.66	84647.00	93035.00
	5	25	89757.68	88906.06	90609.30	16707.2	342628.2
CES-2	1	25	90481.72	89700.32	91263.12	87028.00	93987.00
	3	25	90392.44	89567.89	91216.99	86184.00	94159.00
	5	25	90424.28	89609.65	91238.91	16707.2	342628.2
PCS-2	1	25	90417.16	89623.58	91210.74	86957.00	93984.00
	3	25	90392.44	89567.89	91216.99	86184.00	94159.00
	5	25	90424.28	89609.65	91238.91	16707.2	342628.2
VM-2	1	25	89128.68	88419.39	89837.97	85909.00	92946.00
	3	25	89855.40	89052.51	90658.29	84752.00	92699.00
	5	25	89418.16	88616.63	90219.69	16707.2	342628.2
RPCS-2	1	25	90474.04	89703.04	91425.04	87032.00	93987.00
	3	25	90392.44	89567.89	91216.99	86184.00	94159.00
	5	25	90424.28	89609.65	91238.91	16707.2	342628.2

Table A.10: Descriptives for incurred cost results by levels of due date with the weight matrix determined by the MSP

Method	$\overline{T_i}$	run#	Mean	95% CI for Mean		Minimum	Maximum
				Lower	Upper		
ES-1	1	25	93165.5600	92488.7239	93842.3961	89381.00	96202.00
	3	25	93100.7200	92409.4708	93791.9692	89346.00	96224.00
	5	25	93075.6800	92398.6058	93752.7542	89346.00	95833.00
BS-1	1	25	92932.9600	92188.1060	93677.8140	88383.00	96071.00
	3	25	92007.6800	91119.0876	92896.2724	87614.00	95360.00
	5	25	92590.4400	91845.6108	93335.2692	88734.00	95886.00
CES-1	1	25	93155.9200	92478.1853	93833.6547	89401.00	96245.00
	3	25	93102.7200	92413.1062	93792.3338	89346.00	96224.00
	5	25	93077.6800	92402.2505	93753.1095	89346.00	95833.00
PCS-1	1	25	93163.1600	92498.6239	93827.6961	89394.00	96245.00
	3	25	93102.7200	92413.1062	93792.3338	89346.00	96224.00
	5	25	93077.6800	92402.2505	93753.1095	89346.00	95833.00
VM-1	1	25	91753.2000	91187.9962	92318.4038	89025.00	95062.00
	3	25	92571.5600	91812.3913	93330.7287	87177.00	95169.00
	5	25	92148.3600	91395.8881	92900.8319	88742.00	95951.00
RPCS-1	1	25	93154.5600	92487.9166	93821.2034	89401.00	96002.00
	3	25	93102.7200	92413.1062	93792.3338	89346.00	96224.00
	5	25	93077.6800	92402.2505	93753.1095	89346.00	95833.00
ES-2	1	25	90954.8400	90268.8479	91640.8321	87367.00	93743.00
	3	25	90905.2800	90209.9573	91600.6027	87308.00	93727.00
	5	25	90885.4000	90197.3408	91573.4592	87308.00	93729.00
BS-2	1	25	90656.0400	89902.0548	91410.0252	86358.00	93637.00
	3	25	89694.2400	88755.2008	90633.2792	85079.00	92997.00
	5	25	90455.4800	89685.1662	91225.7938	86473.00	93833.00
CES-2	1	25	90946.5600	90258.3302	91634.7898	87387.00	93729.00
	3	25	90907.6000	90214.1620	91601.0380	87308.00	93727.00
	5	25	90887.8000	90201.6833	91573.9167	87308.00	93729.00
PCS-2	1	25	90941.4400	90267.9306	91614.9494	87379.00	93729.00
	3	25	90907.6000	90214.1620	91601.0380	87308.00	93727.00
	5	25	90887.8000	90201.6833	91573.9167	87308.00	93729.00
VM-2	1	25	89693.0400	89115.0808	90270.9992	87002.00	92573.00
	3	25	90405.7600	89639.8288	91171.6912	85088.00	93053.00
	5	25	90043.7600	89271.7131	90815.8069	86690.00	93899.00
RPCS-2	1	25	90944.4400	90270.7490	91618.1310	87387.00	93749.00
	3	25	90907.6000	90214.1620	91601.0380	87308.00	93727.00
	5	25	90887.8000	90201.6833	91573.9167	87308.00	93729.00

Table A.11: Descriptives for incurred cost results by levels of due date with the weight matrix determined by the fleets

Method	$\overline{T_i}$	run#	Mean	95% CI for Mean Lower	Upper	Minimum	Maximum
ES-1	1	25	92857.36	92101.45	93613.27	89334.00	96314.00
	3	25	92985.04	92224.10	93745.98	89563.00	96550.00
	5	25	92953.24	92179.99	93726.49	88562.00	95711.00
BS-1	1	25	93251.84	92471.92	94031.76	88721.00	96098.00
	3	25	94130.28	93433.87	94826.69	89522.00	96819.00
	5	25	94628.40	94011.35	95245.45	91789.00	96922.00
CES-1	1	25	92942.60	92183.01	93702.19	89528.00	96318.00
	3	25	93024.28	92231.78	93816.78	88756.00	95934.00
	5	25	93270.76	92532.32	94009.20	88854.00	96284.00
PCS-1	1	25	92936.76	92150.14	93723.38	89315.00	96665.00
	3	25	93006.64	92248.65	93764.63	88724.00	96002.00
	5	25	93455.12	92690.92	94219.32	89046.00	96514.00
VM-1	1	25	91525.88	90754.90	92296.86	87592.00	95257.00
	3	25	92580.20	91756.13	93404.27	88916.00	96066.00
	5	25	91830.04	91048.00	92612.08	88487.00	95894.00
RPCS-1	1	25	92856.80	92088.74	93624.86	89358.00	96318.00
	3	25	93037.16	92256.44	93817.88	88803.00	95937.00
	5	25	93346.44	92631.72	94061.16	89489.00	95957.00
ES-2	1	25	90460.76	89682.87	91238.65	86941.00	93965.00
	3	25	90531.20	89787.60	91274.80	87366.00	93780.00
	5	25	90300.16	89519.59	91080.73	85698.00	9329.00
BS-2	1	25	90686.04	89893.24	91478.84	86291.00	93680.00
	3	25	91269.48	90575.64	91963.32	86537.00	93933.00
	5	25	91528.84	90911.72	92145.96	88873.00	93785.00
CES-2	1	25	90537.16	89760.07	91314.25	86998.00	93773.00
	3	25	90443.44	89639.12	91247.76	86105.00	93702.00
	5	25	90629.40	89868.17	91390.63	85925.00	93803.00
PCS-2	1	25	90521.52	89723.65	91319.39	86957.00	93888.00
	3	25	90385.68	89631.19	91140.17	85828.00	93141.00
	5	25	90709.48	89915.11	91503.85	86377.00	93674.00
VM-2	1	25	89168.84	88375.77	89961.91	84734.00	92929.00
	3	25	90138.96	89277.55	91000.37	86108.00	93911.00
	5	25	89487.08	88679.83	90294.33	86419.00	93813.00
RPCS-2	1	25	90453.32	89672.67	91233.97	86999.00	94026.00
	3	25	90502.52	89710.31	91294.73	86118.00	93684.00
	5	25	90728.00	89994.72	91461.28	86468.00	93327.00

Table A.12: Descriptives for incurred cost results by levels of due date with the weight matrix determined by the MSP using the second set of due date coefficient set

Appendix B

Results, t-paired Sample Test

		Paired Differences					
Pairs		Mean	Std. Dev.	95% CI		t	Sig.
				Lower	Upper		
ES-BS	1-1	6.1018	4.0512	1.0716	11.1320	3.368	0.028
ES-CES		1.8064	1.0995	0.4413	3.1716	3.674	0.021
ES-PCS		2.3184	1.7041	0.2025	4.4343	3.042	0.038
ES-VM		9.2425	1.2265	7.7196	10.7654	16.850	0.000
ES-RPCS		2.0599	1.2981	0.4481	3.6717	3.548	0.024
BS-CES		-4.2954	4.1743	-9.4784	0.8876	-2.301	0.083
BS-PCS		-3.7834	4.0323	-8.7901	1.2234	-2.098	0.104
BS-VM		3.1407	3.7874	-1.5620	7.8434	1.854	0.137
BS-RPCS		-4.0419	4.1307	-9.1709	1.0871	-2.188	0.094
CES-PCS		0.5120	1.0342	-0.7722	1.7962	1.107	0.330
CES-VM		7.4361	0.9636	6.2397	8.6325	17.256	0.000
CES-RPCS		0.2535	0.3349	-0.1623	0.6693	1.693	0.166
PCS-VM		6.9241	1.6777	4.8410	9.0072	9.229	0.001
PCS-RPCS		-0.2585	0.7428	-1.1808	0.6638	-0.778	0.480
VM-RPCS		-7.1826	1.0795	-8.5230	-5.8423	-14.878	0.000
ES-BS	1-5	11.5078	18.5862	-11.5701	34.5856	1.384	0.238
ES-CES		0.8138	0.3957	0.3224	1.3051	4.598	0.010
ES-PCS		0.8138	0.3957	0.3224	1.3051	4.598	0.010
ES-VM		18.6038	40.4310	-31.5979	68.8056	1.029	0.362
ES-RPCS		0.8138	0.3957	0.3224	1.3051	4.598	0.010
BS-CES		-10.6940	18.5413	-33.7161	12.3280	-1.290	0.267
BS-PCS		-10.6940	18.5413	-33.7161	12.3280	-1.290	0.267
BS-VM		7.0961	42.3323	-45.4664	59.6586	0.375	0.727
BS-RPCS		-10.6940	18.5413	-33.7161	12.3280	-1.290	0.267
CES-PCS		None	None	None	None	None	None
CES-VM		17.7901	40.5387	-32.5453	68.1255	0.981	0.382
CES-RPCS		None	None	None	None	None	None
PCS-VM		17.7901	40.5387	-32.5453	68.1255	0.981	0.382
PCS-RPCS		None	None	None	None	None	None
VM-RPCS		17.7901	40.5387	-32.5453	68.1255	0.981	0.382
ES-BS	5-5	30.9160	55.5505	-38.0591	99.8911	1.244	0.281
ES-CES		1.7383	1.3998	0.0002364	2.777	7.96	0.050
ES-PCS		1.7383	1.3998	0.0002364	2.777	7.96	0.050
ES-VM		60.0362	89.8156	-51.4846	171.5569	1.495	0.209
ES-RPCS		1.7383	1.3998	0.0002364	2.777	7.96	0.050
BS-CES		-29.1776	56.0760	-98.8052	40.4499	-1.163	0.309
BS-PCS		-29.1776	56.0760	-98.8052	40.4499	-1.163	0.309
BS-VM		29.1202	118.9408	-118.5643	176.8047	0.547	0.613
BS-RPCS		-29.1776	56.0760	-98.8052	40.4499	-1.163	0.309
CES-PCS		None	None	None	None	None	None
CES-VM		58.2978	90.2525	-53.7654	170.3611	1.444	0.222
CES-RPCS		None	None	None	None	None	None
PCS- VM		58.2978	90.2525	-53.7654	170.3611	1.444	0.222
PCS-RPCS		None	None	None	None	None	None
VM-RPCS		-58.2978	90.2525	-170.3611	53.7654	-1.444	0.222
ES-BS	5-1	33.8284	3.7910	29.1213	38.5355	19.953	0.000
ES-CES		2.7964	.9396	1.6298	3.9630	6.655	0.003
ES-PCS		9.2594	7.3157	0.1758	18.3431	2.830	0.047
ES-VM		15.8631	28.7227	-19.8008	51.5271	1.235	0.284
ES-RPCS		2.6532	1.0906	1.2990	4.0074	5.440	0.006
BS-CES		-31.0320	3.4937	-35.3700	-26.6940	-19.861	0.000
BS-PCS		-24.5690	4.7326	-30.4453	-18.6927	-11.608	0.000
BS-VM		-17.9653	30.3668	-55.6707	19.7401	-1.323	0.256
BS-RPCS		-31.1752	3.2643	-35.2284	-27.1220	-21.355	0.000
CES-PCS		6.4630	7.4744	-2.8177	15.7437	1.933	0.125
CES-VM		13.0667	28.3544	-22.1399	48.2733	1.030	0.361
CES-RPCS		-.1432	0.3413	-0.5670	0.2806	-0.938	0.401
PCS- VM		6.6037	34.4573	-36.1807	49.3882	0.429	0.690
PCS-RPCS		-6.6062	7.3240	-15.7001	2.4877	-2.017	0.114
VM-RPCS		-13.2099	28.5292	-48.6336	22.2137	-1.035	0.359

Table B.1: Paired Samples Statistics for the total weighted tardiness results of different $\bar{t}_{ji}$ estimation methods with the weight matrix determined by the MSP

		Paired Differences					
Pairs		Mean	Std. Dev.	95% CI		t	Sig.
				Lower	Upper		
ES-BS	1-1	0.7931	0.3979	0.2991	1.2871	4.457	0.011
ES-CES		None	None	None	None	None	None
ES-PCS		None	None	None	None	None	None
ES-VM		5.1466	1.3451	3.4764	6.8168	8.555	0.001
ES-RPCS		0.1557	0.3482	-0.2766	0.588	1	0.374
BS-CES		-0.7931	0.3979	-1.2871	-0.2991	-4.457	0.011
BS-PCS		-0.7931	0.3979	-1.2871	-0.2991	-4.457	0.011
BS-VM		4.3535	1.2166	2.8429	5.8641	8.001	0.001
BS-RPCS		-0.6374	0.6395	-1.4315	0.1567	-2.229	0.09
CES-PCS		None	None	None	None	None	None
CES-VM		5.1466	1.3451	3.4764	6.8168	8.555	0.001
CES-RPCS		0.1557	0.3482	-0.2766	0.588	1	0.374
PCS-VM		5.1466	1.3451	3.4764	6.8168	8.555	0.001
PCS-RPCS		0.1557	0.3482	-0.2766	0.588	1	0.374
VM-RPCS		-4.9909	1.5373	-6.8997	-3.0821	-7.26	0.002
ES-BS	1-5	6.5613	10.5682	-6.5608	19.6834	1.388	0.237
ES-CES		None	None	None	None	None	None
ES-PCS		None	None	None	None	None	None
ES-VM		8.0221	14.0481	-9.4209	25.4651	1.277	0.271
ES-RPCS		None	None	None	None	None	None
BS-CES		-6.5613	10.5682	-19.6834	6.5608	-1.388	0.237
BS-PCS		-6.5613	10.5682	-19.6834	6.5608	-1.388	0.237
BS-VM		1.4608	18.6182	-21.6568	24.5783	0.175	0.869
BS-RPCS		-6.5613	10.5682	-19.6834	6.5608	-1.388	0.237
CES-PCS		None	None	None	None	None	None
CES-VM		8.0221	14.0481	-9.4209	25.4651	1.277	0.271
CES-RPCS		None	None	None	None	None	None
PCS-VM		8.0221	14.0481	-9.4209	25.4651	1.277	0.271
PCS-RPCS		None	None	None	None	None	None
VM-RPCS		-8.0221	14.0481	-25.4651	9.4209	-1.277	0.271
ES-BS	5-5	17.4313	27.4435	-16.6442	51.5069	1.42	0.229
ES-CES		-0.00197	0.00440	-0.00744	0.00350	-1	0.374
ES-PCS		-0.00197	0.00440	-0.00744	0.00350	-1	0.374
ES-VM		26.3867	48.83	-34.2437	87.0172	1.208	0.293
ES-RPCS		-0.00197	0.00440	-0.00744	0.00350	-1	0.374
BS-CES		-17.451	27.4285	-51.508	16.6059	-1.423	0.228
BS-PCS		-17.451	27.4285	-51.508	16.6059	-1.423	0.228
BS-VM		8.9554	63.9713	-70.4754	88.3862	0.313	0.77
BS-RPCS		-17.451	27.4285	-51.508	16.6059	-1.423	0.228
CES-PCS		None	None	None	None	None	None
CES-VM		26.4064	48.8159	-34.2066	87.0194	1.21	0.293
CES-RPCS		None	None	None	None	None	None
PCS- VM		26.4064	48.8159	-34.2066	87.0194	1.21	0.293
PCS-RPCS		None	None	None	None	None	None
VM-RPCS		-26.4064	48.8159	-87.0194	34.2066	-1.21	0.293
ES-BS	5-1	7.6175	3.004	3.8876	11.3474	5.67	0.005
ES-CES		0.6702	0.8638	-0.4023	1.7427	1.735	0.158
ES-PCS		0.8073	0.9411	-0.3612	1.9758	1.918	0.128
ES-VM		8.6991	11.8428	-6.0056	23.4038	1.643	0.176
ES-RPCS		0.2202	0.5234	-0.4297	0.8701	0.941	0.4
BS-CES		-6.9473	3.285	-11.0262	-2.8684	-4.729	0.009
BS-PCS		-6.8102	2.9141	-10.4285	-3.1919	-5.226	0.006
BS-VM		1.0816	12.8844	-14.9165	17.0797	0.188	0.86
BS-RPCS		-7.3973	2.9467	-11.0561	-3.7385	-5.613	0.005
CES-PCS		0.1371	0.5006	-0.4845	0.7587	0.612	0.573
CES-VM		8.0289	11.9653	-6.828	22.8858	1.5	0.208
CES-RPCS		-0.45	0.9227	-1.5956	0.6957	-1.091	0.337
PCS- VM		7.8918	12.2158	-7.2761	23.0597	1.445	0.222
PCS-RPCS		-0.5871	0.8084	-1.5908	0.4166	-1.624	0.18
VM-RPCS		-8.4789	12.3167	-23.772	6.8142	-1.539	0.199

Table B.2: Paired Samples Statistics for the total weighted tardiness results of different $\bar{t}_{ji}$ estimation methods with the weight matrix determined by the fleets

		Paired Differences					
Pairs		Mean	Std. Dev.	95% CI		t	Sig.
				Lower	Upper		
ES-BS	1-1	24.3428	14.5306	6.3007	42.3849	3.746	0.020
ES-CES		0.6514	1.7273	-1.4933	2.7962	0.843	0.447
ES-PCS		2.2938	2.2111	-.4517	5.0393	2.320	0.081
ES-VM		3.8672	12.0652	-11.1137	18.8481	0.717	0.513
ES-RPCS		1.0300	1.2649	-0.5406	2.6006	1.821	0.143
BS-CES		-23.6914	16.0146	-43.5761	-3.8067	-3.308	0.030
BS-PCS		-22.0490	15.1023	-40.8010	-3.2970	-3.265	0.031
BS-VM		-20.4756	19.5684	-44.7730	3.8218	-2.340	0.079
BS-RPCS		-23.3128	14.5547	-41.3848	-5.2408	-3.582	0.023
CES-PCS		1.6424	1.7963	-0.5880	3.8728	2.044	0.110
CES-VM		3.2158	12.8120	-12.6924	19.1240	0.561	0.605
CES-RPCS		0.3786	1.6180	-1.6304	2.3876	0.523	0.628
PCS-VM		1.5734	13.5876	-15.2979	18.4447	0.259	0.808
PCS-RPCS		-1.2638	1.9386	-3.6709	1.1433	-1.458	0.219
VM-RPCS		-2.8372	12.9626	-18.9323	13.2580	-0.489	0.650
ES-BS	1-5	39.7938	33.2075	-1.4387	81.0263	2.680	0.055
ES-CES		5.7070	5.8702	-1.5818	12.9958	2.17	0.095
ES-PCS		9.6308	8.2829	-0.6538	19.9154	2.600	0.060
ES-VM		-0.8312	15.6697	-20.2877	18.6253	-0.119	0.911
ES-RPCS		6.9550	6.7801	-1.4636	15.3736	2.29	0.084
BS-CES		-34.0868	28.6164	-69.6188	1.4452	-2.664	0.056
BS-PCS		-30.1630	26.2392	-62.7433	2.4173	-2.570	0.062
BS-VM		-40.6250	25.8319	-72.6996	-8.5504	-3.517	0.025
BS-RPCS		-32.8388	28.3909	-68.0907	2.4131	-2.586	0.061
CES-PCS		3.9238	2.6935	0.5794	7.2682	3.257	0.031
CES-VM		-6.5382	12.7184	-22.3302	9.2538	-1.150	0.314
CES-RPCS		1.2480	1.4567	-0.5607	3.0567	1.916	0.128
PCS-VM		-10.4620	12.8113	-26.3693	5.4453	-1.826	0.142
PCS-RPCS		-2.6758	2.1873	-5.3917	0.0004010	-2.735	0.052
VM-RPCS		7.7862	13.5972	-9.0969	24.6693	1.280	0.270
ES-BS	5-5	306.6324	16.3930	286.2778	326.9870	41.826	0.000
ES-CES		10.0284	6.2684	2.2451	17.8117	3.577	0.023
ES-PCS		29.4818	6.1759	21.8135	37.1501	10.674	0.000
ES-VM		-2.6630	34.4175	-45.3980	40.0720	-0.173	0.871
ES-RPCS		12.0822	5.4935	5.2611	18.9033	4.918	0.008
BS-CES		-296.6040	13.3072	-313.1271	-280.0809	-49.840	0.000
BS-PCS		-277.1506	13.2192	-293.5644	-260.7368	-46.881	0.000
BS-VM		-309.2954	38.1751	-356.6960	-261.8948	-18.117	0.000
BS-RPCS		-294.5502	13.2540	-311.0072	-278.0932	-49.693	0.000
CES-PCS		19.4534	9.4327	7.7411	31.1657	4.612	0.010
CES-VM		-12.6914	34.4737	-55.4962	30.1134	-0.823	0.457
CES-RPCS		2.0538	1.8856	-0.2875	4.3951	2.435	0.072
PCS- VM		-32.1448	35.2206	-75.8769	11.5874	-2.041	0.111
PCS-RPCS		-17.3996	8.3743	-27.7976	-7.0016	-4.646	0.010
VM-RPCS		14.7452	35.6277	-29.4924	58.9828	0.925	0.407
ES-BS	5-1	421.960	31.355	383.028	460.893	30.092	0.000
ES-CES		25.734	22.740	-0.2501	53.969	2.530	0.065
ES-PCS		82.890	74.624	-0.9768	175.549	2.484	0.068
ES-VM		65.958	254.485	-250.027	381.944	0.580	0.593
ES-RPCS		72.252	74.330	-20.041	164.546	2.174	0.095
BS-CES		-396.226	36.293	-441.290	-351.162	-24.412	0.000
BS-PCS		-339.070	56.986	-409.828	-268.312	-13.305	0.000
BS-VM		-356.002	268.354	-689.208	-22.796	-2.966	0.041
BS-RPCS		-349.708	57.907	-421.609	-277.808	-13.504	0.000
CES-PCS		57.156	70.448	-30.317	144.629	1.814	0.144
CES-VM		40.224	267.816	-292.313	372.762	0.336	0.754
CES-RPCS		46.518	68.048	-37.974	131.010	1.529	0.201
PCS- VM		-16.932	308.810	-400.369	366.506	-0.123	0.908
PCS-RPCS		-10.638	0.9826	-22.839	0.1563	-2.421	0.073
VM-RPCS		0.6294	306.753	-374.590	387.177	0.046	0.966

Table B.3: Paired Samples Statistics for the total weighted tardiness results of different $\bar{t}_{ji}$ estimation methods with the weight matrix determined by the MSP using the second due date coefficient set

		Paired Differences					
Pairs		Mean	Std. Dev.	95% CI		t	Sig.
				Lower	Upper		
ES2-BS2	1-1	-151.0000	333.5806	-565.1950	263.1950	-1.012	0.369
ES2-CES2		-49.2000	103.8398	-178.1341	79.7341	-1.059	0.349
ES2-PCS2		-44.6000	100.3982	-169.2608	80.0608	-.993	0.377
ES2-VM2		1647.2000	495.8641	1031.5034	2262.8966	7.428	0.002
ES2-RPCS2		-32.8000	66.1717	-114.9631	49.3631	-1.108	0.330
BS2-CES2		101.8000	396.8749	-390.9853	594.5853	0.574	0.597
BS2-PCS2		106.4000	390.0299	-377.8860	590.6860	0.610	0.575
BS2-VM2		1798.2000	284.3127	1445.1792	2151.2208	14.143	0.000
BS2-RPCS2		118.2000	355.9083	-323.7185	560.1185	0.743	0.499
CES2-PCS2		4.6000	7.1972	-4.3365	13.5365	1.429	0.226
CES2-VM2		1696.4000	568.4147	990.6199	2402.1801	6.673	0.003
CES2-RPCS2		16.4000	61.0844	-59.4463	92.2463	0.600	0.581
PCS2-VM2		1691.8000	561.9917	993.995	2389.6049	6.731	0.003
PCS2-RPCS2		11.8000	58.0491	-60.2775	83.8775	0.455	0.673
VM2-RPCS2		-1680.0000	542.2859	-2353.3369	-1006.6631	-6.927	0.002
ES2-BS2	1-5	126.2000	190.8526	-110.7748	363.1748	1.479	0.213
ES2-CES2		11.6000	7.4027	2.4083	20.7917	3.504	0.025
ES2-PCS2		11.6000	7.4027	2.4083	20.7917	3.504	0.025
ES2-VM2		741.2000	889.4224	-363.1638	1845.5638	1.863	0.136
ES2-RPCS2		11.6000	7.4027	2.4083	20.7917	3.504	0.025
BS2-CES2		-114.6000	190.9353	-351.6775	122.4775	-1.342	0.251
BS2-PCS2		-114.6000	190.9353	-351.6775	122.4775	-1.342	0.251
BS2-VM2		615.0000	1059.4130	-700.4350	1930.4350	1.298	0.264
BS2-RPCS2		-114.6000	190.9353	-351.6775	122.4775	-1.342	0.251
CES2-PCS2		None	None	None	None	None	None
CES2-VM2		729.6000	888.5982	-373.7404	1832.9404	1.836	0.140
CES2-RPCS2		None	None	None	None	None	None
PCS2-VM2		729.6000	888.5982	-373.7404	1832.9404	1.836	0.140
PCS2-RPCS2		None	None	None	None	None	None
VM2-RPCS2		-1680.0000	542.2859	-2353.3369	-1006.6631	-6.927	0.002
ES2-BS2	5-5	1218.6000	3225.3139	-2786.1562	5223.3562	0.845	0.446
ES2-CES2		973.2000	3118.3217	-2898.7078	4845.1078	0.698	0.524
ES2-PCS2		973.2000	3118.3217	-2898.7078	4845.1078	0.698	0.524
ES2-VM2		1632.6000	2741.9362	-1771.9635	5037.1635	1.331	0.254
ES2-RPCS2		973.2000	3118.3217	-2898.7078	4845.1078	0.698	0.524
BS2-CES2		-245.4000	338.8846	-666.1809	175.3809	-1.619	0.181
BS2-PCS2		-245.4000	338.8846	-666.1809	175.3809	-1.619	0.181
BS2-VM2		414.0000	1104.7780	-957.7631	1785.7631	0.838	0.449
BS2-RPCS2		-245.4000	338.8846	-666.1809	175.3809	-1.619	0.181
CES2-PCS2		None	None	None	None	None	None
CES2-VM2		659.4000	863.0662	-412.2383	1731.0383	1.708	0.163
CES2-RPCS2		None	None	None	None	None	None
PCS2-VM2		659.4000	863.0662	-412.2383	1731.0383	1.708	0.163
PCS2-RPCS2		None	None	None	None	None	None
VM2-RPCS2		-659.4000	863.0662	-1731.0383	412.2383	-1.708	0.163
ES2-BS2	5-1	180.0000	912.9439	-953.5695	1313.5695	0.441	0.682
ES2-CES2		10.8000	259.6627	-311.6138	333.2138	0.093	0.930
ES2-PCS2		194.8000	414.2363	-319.5423	709.1423	1.052	0.352
ES2-VM2		1208.4000	1032.3601	-73.4443	2490.2443	2.617	0.059
ES2-RPCS2		12.4000	261.8631	-312.7460	337.5460	0.106	0.921
BS2-CES2		-169.2000	798.3387	-1160.4684	822.0684	-0.474	0.660
BS2-PCS2		14.8000	905.4365	-1109.4479	1139.0479	0.037	0.973
BS2-VM2		1028.4000	608.1330	273.3031	1783.4969	3.781	0.019
BS2-RPCS2		-167.6000	789.1177	-1147.4191	812.2191	-0.475	0.660
CES2-PCS2		184.0000	207.1859	-73.2553	441.2553	1.986	0.118
CES2-VM2		1197.6000	1048.4871	-104.2687	2499.4687	2.554	0.063
CES2-RPCS2		1.6000	11.4586	-12.6278	15.8278	0.312	0.770
PCS2-VM2		1013.6000	1205.6796	-483.4490	2510.6490	1.880	0.133
PCS2-RPCS2		-182.4000	210.2399	-443.4473	78.6473	-1.940	0.124
VM2-RPCS2		-1196.0000	1038.7748	-2485.8092	93.8092	-2.575	0.062

Table B.4: Paired Samples Statistics for the incurred cost results of different $\bar{t}_{ji}$ estimation methods with the weight matrix determined by the MSP

		Paired Differences					
Pairs		Mean	Std. Dev.	95% CI		t	Sig.
				Lower	Upper		
ES2-BS2	1-1	29.6	324.8666	-373.7751	432.9751	0.204	0.849
ES2-CES2		-0.2	8.3785	-10.6033	10.2033	-0.053	0.96
ES2-PCS2		2	6.9282	-6.6025	10.6025	0.645	0.554
ES2-VM2		1802.8	460.3235	1231.2329	2374.3671	8.757	0.001
ES2-RPCS2		1.4	10.5736	-11.7288	14.5288	0.296	0.782
BS2-CES2		-29.8	322.9353	-430.7771	371.1771	-0.206	0.847
BS2-PCS2		-27.6	323.9264	-429.8077	374.6077	-0.191	0.858
BS2-VM2		1773.2	660.8432	952.6548	2593.7452	6	0.004
BS2-RPCS2		-28.2	329.7805	-437.6766	381.2766	-0.191	0.858
CES2-PCS2		2.2	3.3466	-1.9554	6.3554	1.47	0.216
CES2-VM2		1803	456.0493	1236.74	2369.26	8.84	0.001
CES2-RPCS2		1.6	17.1114	-19.6466	22.8466	0.209	0.845
PCS2-VM2		1800.8	455.3907	1235.3577	2366.2423	8.842	0.001
PCS2-RPCS2		-0.6	14.1704	-18.1949	16.9949	-0.095	0.929
VM2-RPCS2		-1801.4	458.0478	-2370.1415	-1232.6585	-8.794	0.001
ES2-BS2	1-5	35.6	131.8647	-128.1317	199.3317	0.604	0.579
ES2-CES2		-0.4	0.8944	-1.5106	0.7106	-1	0.374
ES2-PCS2		-0.4	0.8944	-1.5106	0.7106	-1	0.374
ES2-VM2		601.4	1150.9083	-827.6413	2030.4413	1.168	0.308
ES2-RPCS2		-0.4	0.8944	-1.5106	0.7106	-1	0.374
BS2-CES2		-36	132.2365	-200.1933	128.1933	-0.609	0.576
BS2-PCS2		-36	132.2365	-200.1933	128.1933	-0.609	0.576
BS2-VM2		565.8	1216.6549	-944.8766	2076.4766	1.04	0.357
BS2-RPCS2		-36	132.2365	-200.1933	128.1933	-0.609	0.576
CES2-PCS2		None	None	None	None	None	None
CES2-VM2		601.8	1150.7672	-827.0662	2030.6662	1.169	0.307
CES2-RPCS2		None	None	None	None	None	None
PCS2-VM2		601.8	1150.7672	-827.0662	2030.6662	1.169	0.307
PCS2-RPCS2		None	None	None	None	None	None
VM2-RPCS2		-601.8	1150.7672	-2030.6662	827.0662	-1.169	0.307
ES2-BS2	5-5	175.4	396.2894	-316.6583	667.4583	0.99	0.378
ES2-CES2		-13.2	29.5161	-49.8491	23.4491	-1	0.374
ES2-PCS2		-13.2	29.5161	-49.8491	23.4491	-1	0.374
ES2-VM2		762.4	900.0341	-355.1399	1879.9399	1.894	0.131
ES2-RPCS2		-13.2	29.5161	-49.8491	23.4491	-1	0.374
BS2-CES2		-188.6	379.9649	-660.3887	283.1887	-1.11	0.329
BS2-PCS2		-188.6	379.9649	-660.3887	283.1887	-1.11	0.329
BS2-VM2		587	910.4005	-543.4115	1717.4115	1.442	0.223
BS2-RPCS2		-188.6	379.9649	-660.3887	283.1887	-1.11	0.329
CES2-PCS2		None	None	None	None	None	None
CES2-VM2		775.6	883.0257	-320.8212	1872.0212	1.964	0.121
CES2-RPCS2		None	None	None	None	None	None
PCS2-VM2		775.6	883.0257	-320.8212	1872.0212	1.964	0.121
PCS2-RPCS2		None	None	None	None	None	None
VM2-RPCS2		-775.6	883.0257	-1872.0212	320.8212	-1.964	0.121
ES2-BS2	5-1	645	837.2046	-394.5268	1684.5268	1.723	0.16
ES2-CES2		-40.2	161.979	-241.3235	160.9235	-0.555	0.608
ES2-PCS2		-169.8	310.1503	-554.9024	215.3024	-1.224	0.288
ES2-VM2		969.6	1125.7959	-428.2602	2367.4602	1.926	0.126
ES2-RPCS2		-89	251.7578	-401.5986	223.5986	-0.79	0.473
BS2-CES2		-685.2	724.5514	-1584.8494	214.4494	-2.115	0.102
BS2-PCS2		-814.8	719.1861	-1707.7875	78.1875	-2.533	0.064
BS2-VM2		324.6	1065.136	-997.9411	1647.1411	0.681	0.533
BS2-RPCS2		-734	893.5955	-1843.5454	375.5454	-1.837	0.14
CES2-PCS2		-129.6	188.9466	-364.2081	105.0081	-1.534	0.2
CES2-VM2		1009.8	1139.2606	-404.7789	2424.3789	1.982	0.119
CES2-RPCS2		-48.8	213.2034	-313.527	215.927	-0.512	0.636
PCS2-VM2		1139.4	1299.5039	-474.1472	2752.9472	1.961	0.121
PCS2-RPCS2		80.8	196.5851	-163.2926	324.8926	0.919	0.41
VM2-RPCS2		-1058.6	1336.8494	-2718.5178	601.3178	-1.771	0.151

Table B.5: Paired Samples Statistics for the incurred cost results of different $\bar{t}_{ji}$ estimation method with the weight matrix determined by the MSP

		Paired Differences					
Pairs		Mean	Std. Dev.	95% CI		t	Sig.
				Lower	Upper		
ES1-ES2	1-1	2202.4000	183.8948	1974.0644	2430.7356	26.780	0.000
BS1-BS2		2222.8000	201.6859	1972.3739	2473.2261	24.644	0.000
CES1-CES2		2135.4000	109.3769	1999.5907	2271.2093	43.655	0.000
PCS1-PCS2		2132.4000	107.5258	1998.8891	2265.9109	44.345	0.000
VM1-VM2		2017.4000	163.0255	1814.9772	2219.8228	27.671	0.000
RPCS1-PCS2		2205.4000	189.3906	1970.2405	2440.5595	26.038	0.000
ES1-ES2	1-5	2177.2000	198.2667	1931.0193	2423.3807	24.555	0.000
BS1-BS2		2219.4000	181.6007	1993.9130	2444.8870	27.328	0.000
CES1-CES2		2190.4000	200.8938	1940.9575	2439.8425	24.380	0.000
PCS1-PCS2		2190.4000	200.8938	1940.9575	2439.8425	24.380	0.000
VM1-VM2		2214.0000	179.5439	1991.0668	2436.9332	27.574	0.000
RPCS1-PCS2		2190.4000	200.8938	1940.9575	2439.8425	24.380	0.000
ES1-ES2	5-5	1573.2000	3242.7454	-2453.2002	5599.6002	1.085	0.339
BS1-BS2		2438.8000	179.0215	2216.5154	2661.0846	30.462	0.000
CES1-CES2		2538.2000	218.3957	2267.0259	2809.3741	25.988	0.000
PCS1-PCS2		2538.2000	218.3957	2267.0259	2809.3741	25.988	0.000
VM1-VM2		2406.6000	181.1251	2181.7035	2631.4965	29.711	0.000
RPCS1-PCS2		2538.2000	218.3957	2267.0259	2809.3741	25.988	0.000
ES1-ES2	5-1	2498.6000	252.9670	2184.5000	2812.7000	22.086	0.000
BS1-BS2		2493.4000	195.6050	2250.5244	2736.2756	28.503	0.000
CES1-CES2		2476.0000	218.7613	2204.3720	2747.6280	25.308	0.000
PCS1-PCS2		2453.0000	271.2130	2116.2446	2789.7554	20.224	0.000
VM1-VM2		2572.4000	244.9792	2268.2182	2876.5818	23.480	0.000
RPCS1-PCS2		2476.0000	216.6968	2206.9354	2745.0646	25.550	0.000

Table B.6: Paired Samples Statistics for the incurred cost results of $\bar{t}_{ji}$ estimation methods at initial schedule and after improvement with the weight matrix determined by the MSP

		Paired Differences					
Pairs		Mean	Std. Dev.	95% CI		t	Sig.
				Lower	Upper		
ES1-ES2	1-1	2002.2	122.0971	1850.5964	2153.8036	36.668	0.000
BS1-BS2		2101.6	206.4795	1845.2218	2357.9782	22.759	0.000
CES1-CES2		2005.6	124.0738	1851.5421	2159.6579	36.145	0.000
PCS1-PCS2		2004	123.9456	1850.1013	2157.8987	36.154	0.000
VM1-VM2		1900.8	230.9615	1614.0235	2187.5765	18.403	0.000
RPCS1-PCS2		2010.4	129.2838	1849.873	2170.927	34.771	0.000
ES1-ES2	1-5	2017.6	124.6688	1862.8033	2172.3967	36.188	0.000
BS1-BS2		1922.4	115.6581	1778.7915	2066.0085	37.167	0.000
CES1-CES2		2017.8	124.8567	1862.7699	2172.8301	36.137	0.000
PCS1-PCS2		2017.8	124.8567	1862.7699	2172.8301	36.137	0.000
VM1-VM2		1935.6	114.6704	1793.2179	2077.9821	37.744	0.000
RPCS1-PCS2		2017.8	124.8567	1862.7699	2172.8301	36.137	0.000
ES1-ES2	5-5	2213.6	233.0714	1924.2036	2502.9964	21.237	0.000
BS1-BS2		2262.6	226.2295	1981.6989	2543.5011	22.364	0.000
CES1-CES2		2211.8	232.0381	1923.6866	2499.9134	21.314	0.000
PCS1-PCS2		2211.8	232.0381	1923.6866	2499.9134	21.314	0.000
VM1-VM2		2135.6	175.1065	1918.1765	2353.0235	27.271	0.000
RPCS1-PCS2		2211.8	232.0381	1923.6866	2499.9134	21.314	0.000
ES1-ES2	5-1	2252.4	201.0381	2002.7783	2502.0217	25.053	0.000
BS1-BS2		2295.6	269.4389	1961.0475	2630.1525	19.051	0.000
CES1-CES2		2259	207.8172	2000.9608	2517.0392	24.306	0.000
PCS1-PCS2		2277.8	217.0696	2008.2725	2547.3275	23.464	0.000
VM1-VM2		2111.6	123.5751	1958.1613	2265.0387	38.209	0.000
RPCS1-PCS2		2267	203.9608	2013.7492	2520.2508	24.854	0.000

Table B.7: Paired Samples Statistics for the incurred cost results of $\bar{t}_{ji}$ estimation methods at initial schedule and after improvement with the weight matrix determined by the MSP

		Paired Differences					
Pairs		Mean	Std. Dev.	95% CI		t	Sig.
				Lower	Upper		
ES2-BS2	1-1	-211.6000	590.8894	-945.2861	522.0861	-0.801	0.468
ES2-CES2		-305.6000	562.0216	-1003.4420	392.2420	-1.216	0.291
ES2-PCS2		-249.4000	377.6140	-718.2697	219.4697	-1.477	0.214
ES2-VM2		1205.2000	943.5450	33.6341	2376.7659	2.856	0.046
ES2-RPCS2		-147.4000	502.1372	-770.8857	476.0857	-0.656	0.547
BS2-CES2		-94.0000	421.8531	-617.7998	429.7998	-0.498	0.644
BS2-PCS2		-37.8000	333.0183	-451.2969	375.6969	-0.254	0.812
BS2-VM2		1416.8000	946.5082	241.5549	2592.0451	3.347	0.029
BS2-RPCS2		64.2000	305.3477	-314.9392	443.3392	0.470	0.663
CES2-PCS2		56.2000	257.5601	-263.6031	376.0031	0.488	0.651
CES2-VM2		1510.8000	557.7331	818.2829	2203.3171	6.057	0.004
CES2-RPCS2		158.2000	345.2560	-270.4919	586.8919	1.025	0.363
PCS2-VM2		1454.6000	772.2780	495.6902	2413.5098	4.212	0.014
PCS2-RPCS2		102.0000	353.1020	-336.4340	540.4340	0.646	0.554
VM2-RPCS2		-1352.6000	768.9501	-2307.3777	-397.8223	-3.933	0.017
ES2-BS2	1-5	-1051.2000	929.2506	-2205.0170	102.6170	-2.530	0.065
ES2-CES2		-53.6000	441.3936	-601.6625	494.4625	-0.272	0.799
ES2-PCS2		-391.6000	548.3596	-1072.4784	289.2784	-1.597	0.186
ES2-VM2		660.4000	780.6064	-308.8508	1629.6508	1.892	0.131
ES2-RPCS2		-85.8000	410.7532	-595.8175	424.2175	-0.467	0.665
BS2-CES2		997.6000	1110.1823	-380.8734	2376.0734	2.009	0.115
BS2-PCS2		659.6000	665.9785	-167.3215	1486.5215	2.215	0.091
BS2-VM2		1711.6000	1703.9258	-404.1034	3827.3034	2.246	0.088
BS2-RPCS2		965.4000	840.4295	-78.1311	2008.9311	2.569	0.062
CES2-PCS2		-338.0000	608.3424	-1093.3569	417.3569	-1.242	0.282
CES2-VM2		714.0000	807.7899	-289.0036	1717.0036	1.976	0.119
CES2-RPCS2		-32.2000	413.3705	-545.4673	481.0673	-0.174	0.870
PCS2-VM2		1052.0000	1213.7139	-455.0249	2559.0249	1.938	0.125
PCS2-RPCS2		305.8000	368.2353	-151.4245	763.0245	1.857	0.137
VM2-RPCS2		-746.2000	1042.9167	-2041.1521	548.7521	-1.600	0.185
ES2-BS2	5-5	-1997.4000	682.3290	-2844.6233	-1150.1767	-6.546	0.003
ES2-CES2		-381.0000	383.2525	-856.8709	94.8709	-2.223	0.090
ES2-PCS2		-530.4000	350.4116	-965.4935	-95.3065	-3.385	0.028
ES2-VM2		651.4000	1017.8597	-612.4397	1915.2397	1.431	0.226
ES2-RPCS2		-473.6000	558.7972	-1167.4384	220.2384	-1.895	0.131
BS2-CES2		1616.4000	883.2029	519.7588	2713.0412	4.092	0.015
BS2-PCS2		1467.0000	693.2341	606.2362	2327.7638	4.732	0.009
BS2-VM2		2648.8000	503.6851	2023.3923	3274.2077	11.759	0.000
BS2-RPCS2		1523.8000	795.3821	536.2027	2511.3973	4.284	0.013
CES2-PCS2		-149.4000	226.0770	-430.1116	131.3116	-1.478	0.214
CES2-VM2		1032.4000	1205.5701	-464.5130	2529.3130	1.915	0.128
CES2-RPCS2		-92.6000	299.1251	-464.0128	278.8128	-0.692	0.527
PCS2-VM2		1181.8000	987.2627	-44.0486	2407.6486	2.677	0.055
PCS2-RPCS2		56.8000	269.6678	-278.0367	391.6367	0.471	0.662
VM2-RPCS2		-1125.0000	1129.0631	-2526.9170	276.9170	-2.228	0.090
ES2-BS2	5-1	124.8000	914.4346	-1010.6206	1260.2206	0.305	0.775
ES2-CES2		70.0000	476.3602	-521.4793	661.4793	0.329	0.759
ES2-PCS2		29.6000	481.2653	-567.9698	627.1698	0.138	0.897
ES2-VM2		1342.4000	680.4052	497.5653	2187.2347	4.412	0.012
ES2-RPCS2		189.2000	402.3894	-310.4324	688.8324	1.051	0.352
BS2-CES2		-54.8000	856.6783	-1118.5066	1008.9066	-0.143	0.893
BS2-PCS2		-95.2000	853.2885	-1154.6976	964.2976	-0.249	0.815
BS2-VM2		1217.6000	717.3488	326.8938	2108.3062	3.795	0.019
BS2-RPCS2		64.4000	1055.9679	-1246.7574	1375.5574	0.136	0.898
CES2-PCS2		-40.4000	93.9085	-157.0028	76.2028	-0.962	0.391
CES2-VM2		1272.4000	600.2744	527.0609	2017.7391	4.740	0.009
CES2-RPCS2		119.2000	289.1698	-239.8518	478.2518	0.922	0.409
PCS2-VM2		1312.8000	538.0225	644.7568	1980.8432	5.456	0.005
PCS2-RPCS2		159.6000	269.5224	-175.0562	494.2562	1.324	0.256
VM2-RPCS2		-1153.2000	697.3032	-2019.0162	-287.3838	-3.698	0.021

Table B.8: Paired Samples Statistics for the incurred cost results of different $\bar{t}_{ji}$ estimation method with the weight matrix determined by the MSP using the second due date coefficient set

		Paired Differences					
Pairs		Mean	Std. Dev.	95% CI		t	Sig.
				Lower	Upper		
ES1-ES2	1-1	2234.8000	49.0989	2173.8357	2295.7643	101.778	0.000
BS1-BS2		2482.4000	140.3756	2308.1007	2656.6993	39.543	0.000
CES1-CES2		2260.4000	168.8307	2050.7690	2470.0310	29.938	0.000
PCS1-PCS2		2204.6000	92.0804	2090.2671	2318.9329	53.536	0.000
VM1-VM2		2234.4000	174.3970	2017.8576	2450.9424	28.649	0.000
RPCS1-RPCS2		2270.0000	62.4940	2192.4035	2347.5965	81.222	0.000
ES1-ES2	1-5	2483.8000	143.6478	2305.4377	2662.1623	38.664	0.000
BS1-BS2		2918.6000	156.9086	2723.7723	3113.4277	41.592	0.000
CES1-CES2		2432.4000	77.3712	2336.3310	2528.4690	70.298	0.000
PCS1-PCS2		2503.6000	237.7841	2208.3520	2798.8480	23.543	0.000
VM1-VM2		2154.2000	86.5893	2046.6852	2261.7148	55.630	0.000
RPCS1-RPCS2		2527.8000	159.3603	2329.9281	2725.6719	35.469	0.000
ES1-ES2	5-5	2788.0000	240.6605	2489.1805	3086.8195	25.904	0.000
BS1-BS2		3190.4000	341.9785	2765.7776	3615.0224	20.861	0.000
CES1-CES2		2732.2000	119.7109	2583.5593	2880.8407	51.034	0.000
PCS1-PCS2		2949.0000	202.4784	2697.5899	3200.4101	32.567	0.000
VM1-VM2		2444.4000	397.9815	1950.2407	2938.5593	13.734	0.000
RPCS1-PCS2		2767.0000	178.8812	2544.8896	2989.1104	34.588	0.000
ES1-ES2	5-1	2521.2000	266.3132	2190.5285	2851.8715	21.169	0.000
BS1-BS2		2712.4000	176.9613	2492.6735	2932.1265	34.274	0.000
CES1-CES2		2499.0000	268.4642	2165.6577	2832.3423	20.814	0.000
PCS1-PCS2		2497.0000	319.6623	2100.0868	2893.9132	17.467	0.000
VM1-VM2		2540.8000	205.9738	2285.0498	2796.5502	27.583	0.000
RPCS1-PCS2		2484.0000	304.3329	2106.1208	2861.8792	18.251	0.000

Table B.9: Paired Samples Statistics for the incurred cost results of $\bar{t}_{ji}$ estimation methods at initial schedule and after improvement with the weight matrix determined by the MSP using the second due date coefficient set