AN ADAPTIVE SIMULATED ANNEALING METHOD FOR ASSEMBLY LINE BALANCING AND A CASE STUDY

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ABSTRACT

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Assembly line balancing problem is one of the most studied NP-Hard problems. NP-Hardness leads us to search for a good solution instead of the optimal solution especially for the big-size problems. Meta-heuristic algorithms are the search methods which are developed to find good solutions to the big-size and combinatorial problems. In this study, it is aimed at solving the multi-objective multi-model assembly line balancing problem of a company. A meta-heuristic algorithm is developed to solve the deterministic assembly line balancing problems. The algorithm developed is tested using the test problems in the literature and the the real life problem of the company as well. The results are analyzed and found to be promising and a solution is proposed for the firm.

Keywords: Assembly Line Balancing, Multi-Model Line, Multi-Objective, Meta-Heuristics, Adaptive Simulated Annealing

ÖZ

MONTAJ HATTI DENGELEMESİ İÇİN BİR UYARLANABİLİR TAVLAMA BENZETİMİ YÖNTEMİ VE BİR ÖRNEK ÇALIŞMA

Güden, Hüseyin
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Tez Yöneticisi: Y. Doç. Dr. Sedef Meral

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Montaj hattı dengeleme problemi en çok çalışılan NP-Zor problemlerden biridir. NP-Zorluk, özellikle büyük boyutlu problemlerde, en iyi çözüm yerine iyi bir çözümü araştırmamıza neden olur. Modern-sezgisel algoritmalar büyük boyutlu ve kombinatoryal problemlere iyi çözümler bulmak amacıyla geliştirilmiş yöntemlerdir. Bu çalışmada, bir şirketin çok-amaçlı çok-modelli montaj hattı dengeleme problemini çözmek amaçlanmıştır. Bir modern-sezgisel algoritma geliştirilmiş ve deterministik montaj hattı dengeleme problemlerini çözmek üzere sunulmuştur. Geliştirilen algoritma literatürdeki test problemleri ve şirketteki gerçek hayat problemi kullanılarak test edilmiştir. Sonuçlar analiz edilmiş ve umut verici bulunmuşlardır ve firma için bir çözüm önerilmiştir.

Anahtar Kelimeler: Montaj Hattı Dengeleme, Çok-Modelli Hat, Çok-Amaç, Modern-Sezgiseller, Uyarlanabilir Tavlama Benzetimi

To my family

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CHAPTER 1

INTRODUCTION

Assembly line production is a production type, which is especially suitable for mass production. The production system runs with a high production rate and it is assumed that there is enough demand that can consume this production.

Assembly line balancing offers many benefits such as increased productivity, production of high amount of standardized items at low costs, less work congestion, reduced material handling, etc.

In order to realize the production, there are some tasks that have to be performed. Assembly lines are the production lines through which these tasks are performed following the sequential stations. At the assembly lines, production parts flow from a previous station to the next one. Because of this fixed and directed flow, the tasks have to be assigned to the sequential stations such that no part goes back to be reprocessed. The precedence relationships between the tasks show the order of the tasks to be completed. Any task cannot be performed before the tasks that are located in front of itself on the precedence relationships diagram. The assembly line balancing is allocating the tasks to the stations on the line such that all precedence relationships are satisfied and the production is realized with the directed production flow.

Cycle time is the time between two parts' passing from one station to the next one. It can be assumed that each station has this time capacity which cannot be exceeded.

Assembly lines can be classified into three groups, namely, single-model lines which are dedicated to the production of a single product, multi-model lines on which two or more similar models of products are produced separately in batches and mixed-model lines on which two or more similar models of a product are produced simultaneously on the line where the batch sizes are very small or even one.

Real life problems are complex problems. When the problem includes more than one and conflicting objectives, it gets harder to solve the problem. Assembly line balancing problems, especially multi/mixed-model assembly line balancing problems, are complex problems and generally consist of more than one and conflicting objectives. Number of used stations, cycle time, idle times, common tasks between models, setup cost for switching from production of a model to another one's, etc. are some of the components that affect the solution of the assembly line balancing problems.

Especially for the multi-model assembly lines, the sequencing problem arises as another problem besides the balancing problem. Because the common tasks between the sequential models change with respect to the models, it becomes important to determine the best sequence. If so, without balancing the line for each model, determining the best sequence of the models arises as another problem.

In today's industries and global market, due to the increasing competitiveness, companies try to enhance production flexibility by reducing their batch sizes and increasing product varieties. Because of this competitiveness, single-model production is less common than multi/mixed model production.

Although, based on our limited observations, multi/mixed-model assembly lines are more preferred in real life, literature includes much more studies on the single-model line. Therefore, the main motivation of our study for working on multi/mixed-model assembly lines stems from these observations. During our study on a real life multi-model assembly line balancing problem, we have faced with many kinds of details, complexities and very flexible structures on the line. In real life, assembly line balancing problems proved to be much more difficult than in theory. We spent a lot of time and effort to deal with these difficulties but it somehow motivated us.

The firm in the study produces consumer durables. It is one of the companies that continue their production with different models. The firm develops new models and produces different models in a continuous manner. It also modifies its standard models according to customer specifications. But, the ratio of these modifications is very small. Recently, the firm especially produces four main models with high amounts.

There is no precedence relationships diagram in the firm. Assignments are made manually by trial and error approach based on personal experiences. Daily production is adjusted according to the production plans on some monthly periods. Then, the line is balanced such that it satisfies this production rate. Batch sizes of the different models are omitted. Similarities and common tasks between models and consequently, sequence of the models are also neglected.

Production seriously becomes inconsistent at the week that balancing is made. This is an important disadvantage of the current balancing procedure. Rarely, a few amount of products from a different model passes throughout the line among other models. But, generally system works with large batch sizes and as a multi-model assembly line. Balancing the multi-model assembly line as if it is a mixed-model assembly line is another disadvantage of the current procedure. Because of the lack of the objective functions goodness of the obtained solution is not known. Furthermore, due to the lack of evaluating functions and difficulty of the current method, better solutions may not be searched. This is another disadvantage of the current procedure.

Meta-heuristic approaches are recently developed general search strategies. When the problem sizes get larger, the computational times to solve an NP-Hard problem increase non-polinomially. Especially solving the big-size NP-Hard and combinatorial problems optimally becomes very hard, even impossible.

This study proposes a new approach which is based on the Simulated Annealing, one of the meta-heuristic approaches, to solve assembly line balancing problems. The developed algorithm solves the multi-objective single, mixed and multi-model assembly line balancing problems in a heuristic manner. For illustrative purposes, the algorithm is used to solve the real life multi-model assembly line balancing problem of the firm under consideration.

The proposed algorithm is tested on test problems from the literature and on the case problem. For each type of assembly line balancing problems the experimental results are analyzed separately and found to be promising. With this study, it is achieved to find very good solutions even optimal solutions, but it is not guaranteed, to complex assembly line balancing problems in reasonable computational times. For the specific case of the firm the method eradicated the disadvantages of the current method of the firm.

The thesis includes five chapters. The concepts related to Assembly Line Balancing and the techniques used to solve Assembly Line Balancing Problems are discussed in Chapter 2. The real life multi-model assembly line balancing problem under consideration and its environment are defined in Chapter 3. Besides, the difficulties related to the problem at hand and the process of the development of the solution method proposed are discussed in Chapter 3. In Chapter 4, the proposed solution method is explained. In

Chapter 5, the experimental results are analyzed and the study is concluded in Chapter 6.

CHAPTER 2

ASSEMBLY LINE BALANCING AND THE RELEVANT LITERATURE

2.1 Assembly Lines

When a product or a family of technologically similar products exhibits high volume and stable demand over lengthy periods of time, it becomes economical to design and layout a special facility dedicated exclusively to the product or family of products under consideration. In order to cut down work-in-process inventory and nonproductive times as loading, unloading and transportation between successive operations, the workstations are physically arranged in a contiguous sequence according to the technological ordering of the manufacturing stages. The resulting facility is called an *assembly line* if the production process is assembly or *fabrication line* if it is fabrication (Hax and Candea, 1984).

Assembly is a production system and it is defined as the aggregation of all necessary tasks in order to form a product.

Assembly is usually realized on assembly lines. *Assembly line* is a set of workstations which are sequentially arranged and connected by means of a transfer system.

Assembly lines can be classified with respect to the variety of models assembled and the batch sizes of the models as:

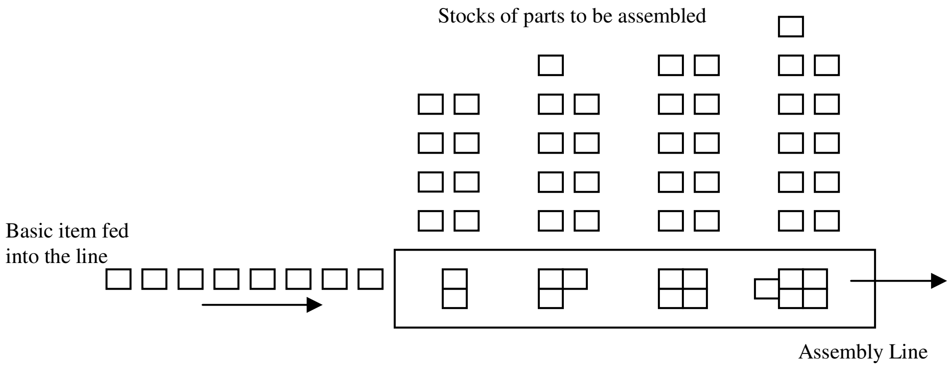
- Single-model Assembly Line
- Multi-model Assembly Line
- Mixed-model Assembly Line

Single-model assembly line is the line on which only one model product assembly is realized. The assembly line on which the batch production of more than one similar model of products is realized is called *multi-model assembly line*. *Mixed-model assembly* line is the line on which the simultaneous production of more than one model of products takes place (Wild, 1972). (See Figure 2.1).

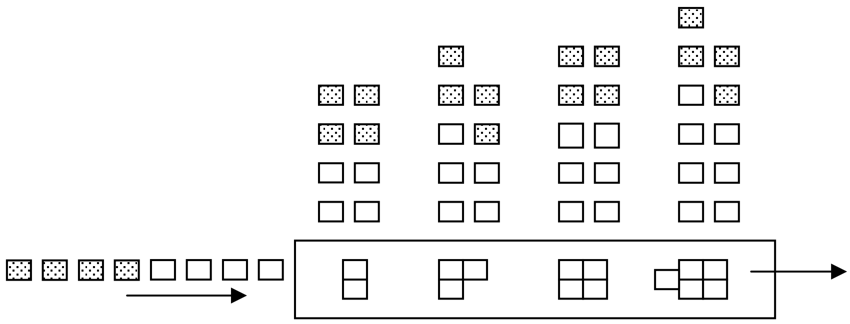
Manufacturing a product on an assembly line requires partitioning the total amount of work into a set of elementary operations named *tasks* (Scholl and Becker, 2004). A task is the smallest indivisible work element that adds value to the product. Performing a task requires certain equipment, machines and/or skills of workers and takes some time called *task time*.

A *workstation* (or just station) is a location along the assembly line where a subset of tasks is processed. To perform these set of tasks, a workstation consists of human and/or robotic operators and equipment.

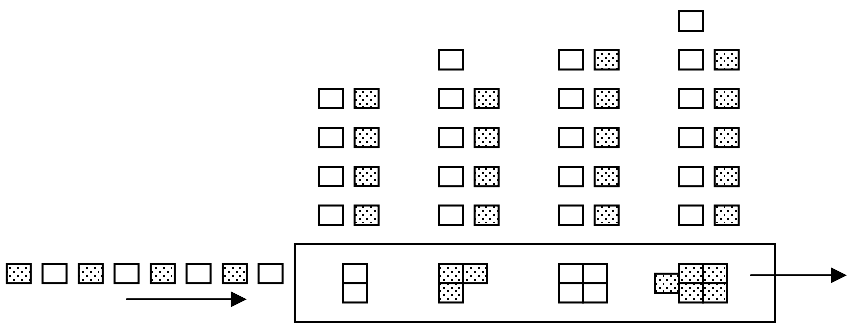
The sum of the task times of all tasks that are assigned to a workstation (i) is called *work content* (WCi) of the workstation. A predetermined amount of time allocated to each workstation to finish the tasks assigned to it is called the *cycle time* (C). Cycle time is equal to the biggest work content and it determines the time between two successive products passing from any fixed point of the assembly line. In other words, cycle time is the time between two successive products' completions. Hence, the production rate of the assembly line is 1/C. *Slack time (or idle time)* (ST_i) of a station (i) is the time difference between cycle time and the work content of that station. The sum of the work contents of all stations, or equivalently the sum of the task times of all tasks, is called the *total work content* (TWC) and the sum of slack times of all stations is called the *total slack time* (TST) or *balance delay* (BD). *Assembly time* (AT) is the maximum time that the line may use to complete a product. Assembly time is equal to multiplication of number of stations (m) and cycle time (Baybars, 1986; Held, Karp and Sareshian, 1963; Klein, 1963; Kilbridge and Wester, 1961; Kilbridge and Wester, 1962).



a) Single-Model Assembly Line



b) Multi-Model Assembly Line



c) Mixed-Model Assembly Line

Figure 2.1 Types of Assembly Lines (Wild, 1972)

In order to realize the production, all tasks have to be performed. At the assembly lines, products move from a previous station to the next station. Because of this fixed and directed flow, the operations have to be assigned to sequential stations such that no part goes back to be reprocessed. Some tasks can not be performed until some other tasks are completed. These *precedence relations* restrict the assignment of tasks to the workstations. A task can not be assigned to the previous stations of the station that any previous task of that task is assigned. The graph that shows precedence relations of tasks is called precedence graph. It contains a node for each task, node weights for the task times and arcs for the precedence constraints (Scholl and Becker, 2004).

Especially for the real life problems, *zoning restrictions* add further complexities to the problem. Sometimes, there can be such situations that a set of tasks has to be performed at the same station or different stations. Occasionally, because of particular equipment, a task would be made at any specific station or a task can not be performed at a particular station.

2.2 Assembly Line Balancing Problem

Assembly lines rely heavily on the *Principle of Interchangeability* and the *Division of Labor.* Principle of interchangeability suggests that individual components that make up a finished product should be interchangeable between product units. Division of labor includes the concepts of work simplification, standardization and specialization. These two concepts facilitated mass production, allowed replacement parts to be used to lengthen a product's useful life and made the development of assembly lines possible (Askin and Standridge, 1993).

The first assembly line is credited to Henry Ford in 1915 after which it has been widely used in various production systems (Erel, Sabuncuoğlu and Aksu, 2001).

Assembly line balancing is allocating the tasks, which have to be performed to manufacture the product, to workstations such that all precedence relations and zoning restrictions are satisfied, taking into account cycle time and/or number of workstations and task times. Assembly line balancing problem (ALBP) is finding an allocation that optimizes an objective function.

Minimizing the number of workstations given cycle time, and minimizing the cycle time given number of workstations are the two most commonly used objectives in ALBP literature. When the ALBP considers the first objective, it is called ***Type I problem***, and it is called ***Type II problem*** when it considers the second objective. There are some other objectives like minimizing balance delay, maximizing line efficiency, minimizing inventory, minimizing some costs, minimizing set-up time, etc..

Whether the objective is minimizing the number of workstations or minimizing the cycle time, the ALBP is referred to as the *General Assembly Line Balancing Problem (GALBP).* The subtypes of ALBP are considered in the next sections (Scholl and Becker, 2004).

2.2.1 Single-Model Deterministic ALBP

The line is dedicated to a single-model product and all task times are known with certainty. This is the simplest form of ALBP and it is called *Simple Assembly Line Balancing Problem (SALBP).*

The following assumptions are valid for SALBP (Baybars, 1986):

- All input parameters are given and known with certainty.
- All tasks have to be done.
- A task cannot be split among two or more stations.
- Because of the precedence relations, tasks cannot be done in an arbitrary sequence.

- There are no layout, zoning or positional restrictions, thus any task can be processed at any station.
- The fixed and the variable costs associated with all stations are the same and all stations under consideration are equipped and manned to process any one of the tasks.
- The task times are fixed and independent from the sequence.
- The line is serial with no feeder line or parallel subassembly lines.
- The line is designed for a unique model of a single product.

The problem is called as the SALBP-I if the simple assembly line balancing problem is Type-1 problem, and SALBP-II if the problem is Type-II problem.

Although the SALBP problem is easy to formulate, it is NP-hard. The enumeration of the feasible task sequence requires an enormous effort. The SALBP has a finite, but extremely large number of feasible solutions. The problem's inherent integer restrictions result in enormous computational difficulties. There are $n!$ different sequences of n tasks, without considering the precedence constraints. However, the precedence and cycle time constraints drastically reduce this number. For r precedence relations among n tasks, there are roughly $n!/2r$ distinct sequences; even this is too large to handle (Erel and Sarin, 1998).

Because of the complexity of the problem, to achieve an optimal or at least an acceptable solution, a lot of solution methodologies have been suggested in the literature.

2.2.1.1 Single-Model Deterministic Type-I ALBP

2.2.1.1.1 Optimal Seeking Methods

According to both Tonge (1961) and Prenting and Thomopoulos (1974), Bryton (1954) was the first to give an analytical statement of ALBP. However, the first published analytical statement of the problem is due to Salveson (1955) (Baybars, 1986). Salveson (1955) formulated Type-I ALBP as a linear programming problem. His model can result in split tasks and infeasible solution, because of the continuous definition of the decision variables. Bowman (1960) was the first researcher who suggested integer programming approaches for ALBP. By changing the LP formulation to IP formulation, he provided the “nondivisibility” constraint. He developed two different IP formulations to solve ALBPs. The first one uses decision variables which represent the amount of time that a task uses at a station. Then he uses other binary variables to prevent division of tasks. The second one uses decision variables which show the starting times of tasks. In this model the stations are not explicitly represented. Then he uses other binary variables to guarantee that tasks may not have the same starting time.

White (1961) modified Bowman’s model and used binary variables to represent the assignments. A variable is ‘1’ if a task is assigned to a station or ‘0’ otherwise. Bowman (1960) and White (1961) use a cost function to minimize the number of stations. Some other IP formulations have been presented that use different objective functions to minimize the number of stations. Thangavelu and Shetty (1971) and Patterson and Albracht (1975) are two of these studies.

Thangavelu and Shetty (1971) proposed a 0-1 IP formulation. They have used different precedence constraints and occurrence constraints from the Bowman’s model. They solve their 0-1 IP program by applying additive algorithm of Balas (1965), as presented by Geoffrion (1967). This method is a Branch and Bound (B&B) method which uses two subroutines, one for augmenting the partial solution if it may lead to a feasible completion better than the incumbent feasible solution, and the other one for backtracking and record-keeping, whenever a feasible completion better than the incumbent is obtained or when it can be shown that such a solution does not exist. Authors add a conditional feasibility test to the Geoffrion algorithm. The test permits ready augmentation of the partial solution retaining feasibility, so that the implicit enumeration process is expedited. They start with a feasible solution, obtained by the heuristic procedure of Helgeson and Birnie (1961), from which they determine the optimal solution (Baybars, 1986).

Patterson and Albracht (1975) suggested a 0-1 IP formulation with a Fibonacci Search method. Their method examines a sequence of 0-1 IP problems to obtain feasible solutions. In order to reduce the number of variables, they use the earliest and latest stations that the tasks can be assigned to. They eliminate the occurrence constraints and use conditional feasibility tests for the precedence constraints, and use a binary infeasibility test for the cycle time constraints. They use a dummy final task if necessary and try to minimize the number of the stations that the final task is assigned to.

Talbot and Patterson (1984) proposed a general IP algorithm to solve SALBP-I. Since the problem is not 0-1 IP, the number of integer variables is limited with the number of tasks. To expedite the backtracking in the problem they used network cuts and network chains and idle time tests. Their method systematically evaluates all possible task assignments to the stations and, like Thangavelu and Shetty (1971) it is based on the implicit enumeration algorithm of Balas (1965) (Baybars, 1986).

The general 0-1 IP for Type-I ALBP is formulated as follows:

Minimize $\sum_{j}^{m} m_j$ (1)

Subject to

$$\sum_{j=1}^{m} x_{ij} = 1 \qquad i = 1,...,n \qquad (2)$$

$$\sum_{j=1}^{m} jx_{ij} - \sum_{j=1}^{m} jx_{kj} \leq 0 \qquad i = 1,...,n \ \ and \ \ k \in S_i \qquad (3)$$

$$\sum_{i=1}^{n} t_i x_{ij} \leq C \qquad j = 1,...,m \qquad (4)$$

$$\sum_{i=1}^{n} x_{ij} - Mm_j \leq 0 \qquad j = 1,...,m \qquad (5)$$

$$x_{ij} \in \{0,1\} \qquad i = 1,...,n \ and \ j = 1,...,m \qquad (6)$$

where,

$$x_{ij} = \begin{cases} 1 & \text{if task } i \text{ is assigned to station } j \\ 0 & \text{otherwise} \end{cases}$$

$$m_j = \begin{cases} 1 & \text{if station } j \text{ is used} \\ 0 & \text{otherwise} \end{cases}$$

S_i is the set of immediate successors of task i

m is the maximum number of stations

n is the number of tasks

t_i is the task time of task i

C is cycle time

and M is a very large number.

In this model, the objective function (1) computes the number of used stations *m*. Constraint (2) is the assignment constraint and ensures that each task is assigned to exactly one station. Constraint (3) is known as the precedence constraint and states that all immediate successors of task *i* (S_i) have to be assigned to either stations that comes after the station that task *i* is assigned to or to the station that task *i* is assigned to. Constraint (4) is the cycle time constraint and prevents exceeding the cycle time for a station. Constraint

(5) states that station j is used if any task is assigned to it. Constraint (6) is the non-divisibility constraint and satisfies that any task can be assigned to a station as a whole or not.

The general 0-1 IP for Type-II ALBP is formulated as follows:

Minimize $\quad C \qquad (7)$

Subject to

$$\sum_{j=1}^{m} x_{ij} = 1 \qquad i = 1,\ldots,n \qquad (8)$$

$$\sum_{j=1}^{m} jx_{ij} - \sum_{j=1}^{m} jx_{kj} \leq 0 \qquad i = 1,\ldots,n \;\; and \;\; k \in S_i \qquad (9)$$

$$\sum_{i=1}^{n} t_i x_{ij} \leq C \qquad j = 1,\ldots,m \qquad (10)$$

$$x_{ij} \in \{0,1\} \qquad i = 1,\ldots,n \; and \; j = 1,\ldots,m \qquad (11)$$

where,

$$x_{ij} = \begin{cases} 1 & \text{if task } i \text{ is assigned to station } j \\ 0 & \text{otherwise} \end{cases}$$

S_i is the set of immediate successors of task i

m is the number of stations used

n is the number of tasks

t_i is the task time of task i

and C is cycle time

In this model, the objective function (7) minimizes the cycle time. Constraint (8), Constraint (9) and Constraint (10) are same with the Constraints (2), (3) and (4) in the previous model respectively. Constraint (11) is same with the Constraint (6) in the previous model.

It is possible to find the optimal solution of an ALBP by a Branch and Bound (B&B) algorithm. A feasible solution to an ALBP can be represented by a tree in which each path corresponds to a feasible solution, with each arc representing a workstation. Optimal solution can be found by evaluating the paths enumeratively.

Jackson (1956) presented the first branch and bound algorithm to solve the ALBP. In this algorithm, before any assignment is made to the last station, all assignments except for the last station are examined explicitly. Therefore, the algorithm is time consuming. Jackson (1956) showed that an optimal solution exists in a full enumeration tree whose arcs represent only maximal stations. A station is maximal, if no unassigned task can be added feasibly.

Hu (1961) and Mertens (1967) are some of the authors that present optimum tree-search procedures for solving ALBP in their studies.

Wee and Magazine (1981a) constructed a B&B algorithm. This enumerative method was formulated for the minimization of the number of workstations. They developed two heuristics, one of which is a variation of the bin packing problem and the other is basically a reverse application of the Ranked Positional Weight Technique due to Helgeson and Birnie (1961).

Wee and Magazine (1981b) developed another B&B algorithm by modifying the one in Wee and Magazine (1981a). This algorithm was formulated for the minimization of cycle time. They reported four different search methods. Two of them are search methods starting with lower and upper bounds. The others are a "binary search" and a "binary and Fibonacci search" procedures.

Johnson (1988) developed a B&B algorithm called **F**ast **A**lgorithm for **B**alancing **L**ines **E**ffectively (FABLE) to solve SALBP-I. Because of the fact that just one branch in the tree needs to be stored at any one time, the use of backtracking and re-use of the same computer memory locations allow minimal and predictable memory space to be used. Constructing the tree as one branch at a time is termed laser search by Johnson (1988). In other words, FABLE is a depth-first B&B algorithm. In the enumeration stage, eight fathoming rules are used in order to shorten the search time. Although FABLE is an effective algorithm it has some limitations. For example, some of the fathoming rules can not be applied if problem includes zoning restrictions.

Hoffmann (1992) proposed a single solution method called EUREKA. EUREKA makes depth-first laser search by using "theoretical minimum total slack time" fathoming rule. Since EUREKA is a depth oriented laser search algorithm, only the current branch needs to be recalled along with the precedence information and thus computer storage does not have to be allocated for alternate nodes. EUREKA uses the procedure that is described by Hoffmann (1963) to generate a set of tasks for a single station. Hoffmann Heuristic Technique uses this procedure and creates all alternative task sets for a single station and selects the set that has the smallest slack time. Then it passes to the next station. On the other hand, EUREKA uses this procedure to generate a set for a single station and then algorithm passes to the next station. As a new station combination is generated, the cumulative sum of station slack times is calculated. If this sum exceeds the theoretical minimum total slack time, all emanating branches are fathomed. The algorithm searches in an orderly manner for an alternative set at this station; if one is found that does not result in an excessive slack, it goes on to the next station; if not, it backtracks to the previous station and generates an alternative set of tasks there and continues. The algorithm continues until all the tasks have been assigned and the theoretical minimum total slack time has not been exceeded or all branches have been fathomed. If the algorithm can not find a feasible solution at the end of searching all the branches, it increases the theoretical minimum number of workstations by one and the theoretical minimum total slack time by cycle time, then searches all branches again. When problem size gets larger, it may take unreasonable time to search all branches. Therefore, Hoffmann sets a time limit for computation, and if the algorithm can not find a feasible solution at the end of this time limit, then the algorithm searches in the backward direction in the tree of branches. If the algorithm again can not find a feasible solution at the end of the time limit, it uses Hoffmann Heuristic Technique (1963) to find a feasible solution.

Klein and Scholl (1996) developed Simple Assembly Line Balancing Optimization Method (SALOME). The version of the algorithm that is developed to solve Type-I ALBP is called SALOME-I. This algorithm is a multiple solution method that performs bidirectional search. It integrates and improves the most promising components of FABLE and EUREKA and it uses some additional bounding and dominance rules. A local lower bound method is used in each node to dynamically decide on the planning direction. The branching scheme used is station oriented.

Dynamic programming (DP) is another technique in order to solve ALBPs optimally. The main problem of all dynamic programming methods is that the computations required grow at an exponential rate with the increasing problem size. Jackson (1956) developed the first algorithm based on dynamic programming (DP) to solve ALBPs. He starts by generating all feasible assignments to the first station. Then one generates all feasible assignments to the second station, given the first station assignments. Then, for all feasible first-second station combination, all feasible assignments are generated for the third station. The algorithm is then repeated by adding a new station and stops with the optimal solution (Baybars, 1986).

Held and Karp (1962) reported a new DP algorithm which was described in detail in Held, Karp and Sharessian (1963). They proposed a solution method in two parts: first part consists of a dynamic programming technique for the exact solution of small problems and the second part finds an approximate solution of large problems by an iterative procedure. Schrage and Baker (1978) proposed an efficient dynamic programming algorithm. They defined and used feasible subsets of tasks and enumerate all of them with a labeling scheme.

2.2.1.1.2 Heuristic Solution Approaches

Solving the ALBP optimally can not always be possible because of the problem size. When the problem size gets larger, solving the problem optimally becomes harder and even impossible in a reasonable computation time. Therefore, several heuristic approaches have been tried so far to find a good solution, maybe the optimal one, but they do not guarantee it, in a reasonable time.

The Ranked Positional Weight Technique (RPWT), due to Helgeson and Birnie (1961), is one of the best known heuristic methods proposed. The procedure constructs a single sequence. A task is prioritized based on the cumulative assembly time associated with itself and its successors. Tasks are then assigned in this order to the lowest numbered feasible station (Askin and Stanridge, 1993).

Hoffmann (1963) proposed the Successive Maximum Element Time Method (known as Hoffmann heuristic). This method uses precedence matrix to generate all feasible assignments and aims to make assignment with the least slack time.

Arcus (1966) presented COMSOAL (Computer Method of Sequencing Operations for Assembly Lines). Procedure constructs the set of available tasks that can be assigned to the current station and chooses and assigns any task from this set randomly. Then it updates the available task set and assigns another task randomly. The algorithm stops when all tasks are assigned. Because of this random selection, algorithm gives different solutions at the end of every run. It is a fast algorithm and offers a set of sequences to the researcher. It is especially useful for large problems.

Raouf and Tsui (1980) proposed Critical Path Approach to solve SALBP-I. Their method first determines the critical path, then gives priority to the tasks that are on the critical path while assigning tasks to the stations.

Baybars (1986a) proposed a heuristic method in which he first eliminates some tasks and reduces the size of the problem. Then he decomposes the problem into some smaller problems, searches their solutions and finally combines their solutions to construct the entire solution.

Heckman, Magazine and Wee (1989) developed several heuristic fathoming rules and proposed a fast and effective branch-and-bound method.

2.2.1.2 Single-Model Deterministic Type-II ALBP

While a large variety of exact solution procedures exists for Type-I problem, only few have been developed which directly solve SALBP-II. Most research has been devoted to search methods which are based on repeatedly solving SALBP-I.

Helgeson and Birnie (1961) proposed solving Type-II problems, for the first time, as a sequence of Type-I problems. For any value of cycle time, the Type-I problem is solved. If the minimum number of stations obtained from solution of Type-I problem is less than the given number of stations, then the cycle time is made smaller. If it is more than the specified number of stations, then the cycle time is made larger. At the end, the minimum cycle time is found for the given number of stations.

Klein and Scholl (1996) proposed a branch and bound algorithm, called SALOME-II, for the SALBP-II. SALOME-II is the adaptation of SALOME-I to SALBP-II. It solves Type-II problems by using a new enumeration technique, the Local Lower Bound Method, which is complemented by a number of bounding and dominance rules. It makes unidirectional and bidirectional search.

Uğurdağ, Rachamadugu and Papachristou (1997) presented a two-stage heuristic procedure to solve SALBP-II. Their approach is based on the integer formulation of the problem. The first stage, which is based on a heuristic procedure they have developed, provides an initial solution to the problem. The second stage improves the initial solution using a simplex like algorithm.

Recently, meta-heuristic approaches became very popular to solve many different NP-hard combinatorial problems. These brilliant approaches provide a way to construct efficient heuristic algorithms to solve a specific problem. It is possible to solve SALBP-I or many other variations of ALBP like SALBP-II, multi-objective, stochastic, multi/mixed-model, U-type or any other assembly line balancing problem with these meta-heuristics. Because these methods are general approaches to solve any kind of ALBP as well as SALBP, they are discussed in the last section of this chapter.

2.2.2 Mixed-Model ALBP

Mixed-model assembly line is the line on which the simultaneous production of more than one model is realized. On a mixed-model assembly line, the lot sizes are usually very small, like one. Although there are numerous studies published on the various aspects of the line balancing problem, the number of studies on mixed-model is relatively small. (Gökçen and Erel, 1998).

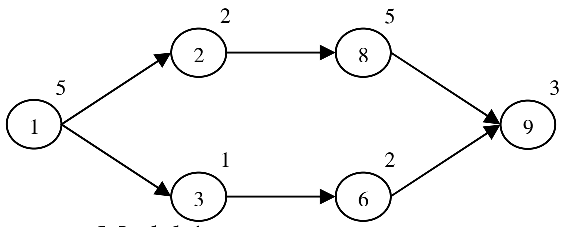
The most important difference between single-model and mixed-model assembly line balancing (MiALB) is seen in the precedence constraints. In SALB, there is only one model and precedence diagram. However, in MiALB, every model has its own precedence diagram and a solution (balance) can not violate any of these constraints.

The mixed-model assembly lines assume that both changeover times and changeover costs are negligible. This assumption allows to transform the problem into single-model assembly line balancing problem. There are mainly two methods used in this transformation: *combined precedence diagram* and *adjusted task times*. The first approach combines the precedence diagram of the different models into a single precedence diagram. The second approach is appropriate only when different models have the same precedence diagram, but with different task times. The combined precedence diagram method is more widely used in the literature.

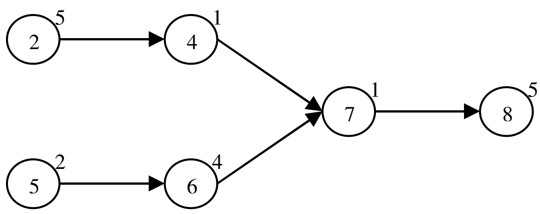
Combined Precedence Diagram Methods

Macaskill (1972) gives the formal definition of combining many single-models into a single precedence diagram. When the precedence diagram of model i is represented by a graph $G_i=(V_i,A_i)$, where V_i is the set of tasks of model i and A_i is the set of precedence relations, the combined graph is $G=(V,A)$, where $V=\cup_i V_i$ and $A=\cup_i A_i \setminus \{redundant\ arcs\}$. An arc (i,j) is redundant if there exists another path from i to j in G. The mixed-model defines the number of units to be produced from each model during a shift of T time units. The processing time of $i \in V$ is equal to the total time required for the processing of this task in a given mixed-model.

Figure 2.2 illustrates the combined precedence diagram method. The numbers above each node represent the task time of the corresponding task. Note that the redundant arcs are indicated with a dashed line.



Model 1
Number of units required: 2



Model 2
Number of units required: 1

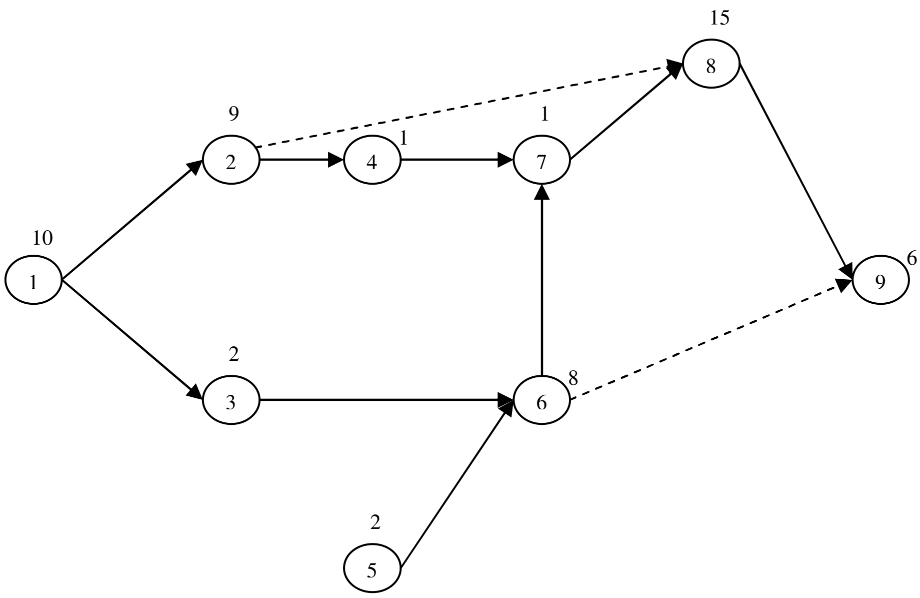


Figure 2.2 A combined precedence diagram constructed from two models

The balancing of the mixed-model line using the combined precedence diagram approach is similar to the balancing of a single-model assembly line. The only difference is that the tasks are assigned to the stations on shift, *T*, which is the basis in the combined precedence diagram method, instead of the cycle time, *C*.

Thomopoulos (1967) was the first researcher who used the combined precedence diagram to solve MiALBP. Thomopoulos and then Macaskill (1972) applied heuristics developed to solve SALBP to their combined precedence diagrams.

Fokkert and de Kok (1997) summarized the advantages and disadvantages of the combined precedence diagram method. According to their study, an advantage of this method is that every repetition of a task is performed by the same workstation, resulting in minimum learning costs. A disadvantage of this method is related to the balancing on shift basis. Another model mix can lead to another balance and this might create some confusion on the shop floor. Another disadvantage of the method is that it might lead to unequal distribution of the total work content of single-models among the workstations.

Gökçen and Erel (1998) developed a binary integer programming model for the MiALBP. They attempt to decrease the size of the model by using combined predecence diagram and lower and upper bounds that limit the increase in the number of decision variables and constraints. The results obtained with their model are significantly superior to the one in the literature with respect to the number of decision variables and constraints. But the suggested model is capable of solving problems with up to 40 tasks in the combined precedence diagram.

Gökçen and Erel (1997) proposed a goal programming approach to solve MiALBPs with conflicting objectives. They use their mathematical model in 1998 with different objective functions. The goal programming method they proposed solves the problem with the most important objective. Then they add the previous solution as a constraint to the model and solve it with the next objective.

In the study of Erel and Gökçen (1999) a shortest-route formulation of the mixed-model assembly line balancing problem is presented. Common tasks across models are assumed to exist and these tasks are performed in the same stations. The formulation is based on an algorithm which solves the single-model version of the problem. The mixed-model problem is transformed into a single-model problem by using combined precedence diagram. They use TST associated with each model as a performance measure.

Ayral (1999) used combined precedence diagram method to solve the mixed-model assembly line balancing problem of Arçelik Dishwasher Plant. She has developed a decision support system. The system provides alternative solutions to decision makers for single or mixed-model assembly line balancing problems. The program uses single-model balancing methods proposed by Wee and Magazine (1981a, 1989) to solve the problem.

Bukchin and Rabinowitch (2006) seek to minimize the sum of costs of the stations and the task duplication. They develop an optimal solution procedure based on a backtracking, dept-first B&B algorithm and evaluate its performance via a large set of experiments. They also propose a B&B based heuristic for solving large-scale problems.

Adjusted Task Times Method

The second method to transform the MiALBP into SALBP is the "adjusted task times" method. This method is only useful for the situation that all models have the same precedence diagram, but with different task times. The method calculates the average task times with the following formula:

$$t_i = \Sigma_k f_k t_i^k$$

where t_i is the average task time of task i, t_i^k is the task time of task i on model k and f_k is the frequency of model k. Frequency of a model is the persentage of the production of that model in the total production.

Fokkert and de Kok (1997) also summarized the advantages and the disadvantages of the "adjusted task times" method. Their study suggests that using the cycle time base, instead of the shift base, is the advantage of this method. A disadvantage of the method is that there is no procedure which determines the sequence of models in which they are produced. Another disadvantage is that this method is not appropriate, if models have different precedence diagrams, which is a more realistic situation.

2.2.3 Multi-Model ALBP

Multi-model assembly line balancing problem (MuALB) differs from MiALB in the magnitude of the lot sizes. The problem shifts to MuALBP when lot sizes get larger. So, changeover costs are important in MuABP. In the mixed-model assembly line balancing, because the lot sizes are very small, solution approaches try to balance the line such that tasks would be performed on the same station for different models. As it is mentioned before, these procedures may ignore the changeover costs. But in the multi-model assembly line balancing, although it is not a preferred situation because of the learning effect costs, it may be preferred to assign a certain task to different stations for different models. In other words, it may be more appropriate to make more model specific balancing. In the literature some studies ignore the learning curve effects and make completely separate balancing for different models as in the case of SALB.

Wild (1972) proposed to balance a multi-model line with the balancing methods of MiALBP, when the lot sizes are small and carrying out every repetition of a task at the same station is more beneficial. Moreover, he suggested to solve MuALBP with successive applications of the solution methods of SALBP for each model, when the lot sizes are large. He proposed a heuristic method that starts with balancing the line for the model which has the biggest production rate and then assigns the tasks for the remaining models according to this model's balance. The algorithm computes the efficiency of the balance by using the slack times. Then it repeats the same procedure for the model which has the second biggest production rate and so on. At the end, the solution which has the best efficiency is chosen. The next step searches for the best sequence of the models to be produced by formulating the problem as an assignment problem so as to minimize the set up cost. The last step is finding the batch sizes.

Buxey, Slack and Wild (1993) stated that the objective of MuALBP as the minimization of the production costs which also include the changeover costs. They suggested that the number of stations and the location of parts and equipment should be static and common tasks should be allocated to the same worker and by the manipulation of the cycle time, the balance delay could be minimized.

Chakravarty and Shtub (1985) presented a method to solve MuALBP that considers labor, set-up and inventory costs. They assume that the models are produced in batches which are transported to the next station as a whole batch. By placing buffers between two adjacent workstations, they allow the batch sizes to vary between workstations. They use the combined precedence diagram approach to transform their problem into SALBP.

Berger, Bourjolly and Laporte (1992) described a Branch & Bound algorithm to solve MuALBP which uses the combined precedence diagram and the depth-first search.

Altekin (1999) developed a method to balance multi-model assembly lines. The method tries to minimize the number of used stations. The proposed method includes upper and lower bounds and branch-and bound procedures. She first constructs the ‘base model’ which is obtained by choosing the common tasks for each model and balances the line for the base model as a single-model assembly line by using EUREKA method. Then she generates the individual balances for each model by using the balance of the base model. While generating the individual balances the algorithm she proposes satisfies the feasibility.

2.2.4 Meta-Heuristic Approaches

The most popular meta-heuristic algorithm is the ***Genetic Algorithm***. These algorithms simulate the genetic processes of biological organisms. The algorithms use the 'survival of the fittest' principle of the nature. It was first proposed by Holland (1975). Genetic algorithms run with a solution set called generation. Each solution is called a chromosome and each solution component is called a gene. Generation is a set of chromosomes. The algorithm also simulates the crossover and mutation processes of the biological organisms to find the solutions and by using these operators, produces the next generation according to the fitness values of the solutions. The first operator of Genetic Algorithms is crossover operator. This is an operator that constructs a chromosome, called offspring, by using two parent chromosomes. Many problem specific crossover operators may be defined. But two-crossover operators are more popular. The first one is one-point crossover. There is only one crossover point at this operator and this point can be selected randomly or with any other strategy. The offspring is constructed by taking the first part of the first parent and the second part of the second parent according to this crossover point. The second operator is two-point crossover. With this strategy, there are two crossover points and offspring is constructed by taking middle part from one parent and outside parts from the other parent. The second operator of the Genetic Algorithm is the mutation operator. This operator generally makes point changes on a chromosome. Changing the number of stations of a task, corresponding to the gene that the mutation operator effects, or changing the places of two genes on the chromosome are some examples of mutation operator. Many problem specific mutation operators may be defined. The algorithm constructs a new generation from the current one and converges after some iteration. According to a parent selection strategy, two parents are chosen, and with the crossover probability, they are exposed to crossover operator. After crossover operator, with the mutation probability, offsprings are exposed to mutation operator. Then according to regeneration strategy, the next generation is generated from the offsprings and parents. Parent selection and regeneration strategies are user_specified. Hence, lots of strategies can be developed. One of the widespread strategies is Roulette Wheel Strategy. According to this strategy, chromosomes are ranked according to their fitness values. Then selection probabilities are computed by using fitness values. The algorithm generates a random number, let it be P, from the uniform distribution between 0 and 1. The chromosome whose P value is between its selection probabilities is chosen as one of the parents or passes to the next generation. One of the other parent selection or regeneration strategies is selecting two chromosomes randomly and comparing their fitness function values and taking the better chromosome as one of the parents or passing the better one to the next generation.

Adapting the general Genetic Algorithms approach to the ALBP involves some difficulties. The first one is representing a solution appropriately. There are two most general representations: standard encoding and order encoding.

Standard encoding: The chromosome is defined as a vector containing the labels of the stations to which the tasks 1,...,*n* are assigned (Scholl and Becker, 2004).

Order encoding: The chromosomes are defined as precedence feasible sequences of tasks (Scholl and Becker, 2004).

The other difficulty faced, while constructing Genetic Algorithm to solve ALBP, is feasibility. There are many relations between genes of a chromosome. For example, a chromosome has to satisfy: precedence restrictions, cycle time or number of stations limitations, assignment of all tasks, representation of each task only once in a chromosome, etc. All of these relations may cause infeasibilities after crossover or mutation operators. After these operators, offspring may have a task that is repeated two times or a task may not be represented or cycle time or precedence relations may be violated. To overcome these difficulties, a repair algorithm has to be developed or infeasible solutions have to be penalized.

The best solution is updated and stored while the algorithm is running and when the algorithm stops, the best solution is obtained.

There are many studies that use GA approaches to solve various assembly line balancing problems. Some of them are: Anderson and Ferris, 1994; Rubinovitz and Levitin, 1995; Kim, Kim and Kim, 2000; Sabuncuoğlu, Erel and Tanyer, 2000; Goncalves and Almeida, 2002; Ponnambalam, Aravindan and Subba Rao, 2003.

Another meta-heuristic approache is ***Tabu Search***, which tries to improve a given feasible solution by iteratively *transforming* it into other feasible solutions. Such transformations are referred to as *moves*. Solutions which may be obtained from a given solution S by means of a single move are called *neighborhood* of S (School and Becker, 2004). The main logic of Tabu Search is preventing the moves that give the recently searched solutions for a certain amount of time and thus, searching for new solutions without cycling. There are some other strategies of Tabu Search approach like *intensification* and *diversification* which are mentioned below.

There are two types of moves for SALBP: *shift* and *swap.* They are explained using the following notations:

LP_j : latest station to which a predecessor of task *j* is currently assigned.
ES_j : earliest station to which a successor of task *j* is currently assigned.

- A *shift* (j,k_1,k_2) describes the movement of a task *j* from station k_1 to station k_2 with $k_1 \neq k_2$. This move is feasible if $k_2 \in [LP_j, ES_j]$.
- A *swap* (j_1,k_1,j_2,k_2) exchanges tasks j_1 and j_2, which are not related to precedence, between different stations k_1 and k_2. This move is feasible if the two corresponding shifts (j_1,k_1,k_2) and (j_2,k_2,k_1) are feasible (Scholl and Becker, 2004).

The Tabu Search approach forbids the attributes of the moves most recently performed and makes them *tabu* for a number of iterations TD (tabu duration) and stores them in a tabu list TL (recency based memory). When a swap (j_1,k_1,j_2,k_2) is performed, the attributes (j_1,k_1) and (j_2,k_2) are added to TL such that removing j_1 to k_1 and j_2 to k_2 is temporarily forbidden for TD iterations (Scholl and Becker, 2004).

Tabu Search algorithm runs by making local search. Sometimes, all neighborhood of S is searched and the best move or the first improving move made or any randomly selected move is chosen as the new current solution, if it is not tabu. Sometimes, the algorithm needs to overwrite a tabu. The criteria that determine this need are called *tabu aspiration criteria.* For any current solution S, all of its neighborhood solutions may be tabu. In this situation, in order to continue searching the algorithm, the oldest tabu is abolished or the best move in the neighborhood is selected. Occasionally, the algorithm can find a solution that is the best solution found so far, but one of the tabu attributes may prevent this move. At this situation the algorithm can abolish that tabu.

The algorithm starts with an initial solution which is created by any constructive procedure like COMSOAL or RPWT, and stops when the *stopping criteria* are satisfied. The stopping criteria may be the number of iterations or a computational time limit or any convergence measure.

In order to intensify the search in certain regions or to direct the search into yet unvisited parts of the solution space, a frequency based memory is used. In this memory, the relative number of iterations and task-station assignments are stored (denoted as z_{jk}). Several phases of the search are either used for collecting frequency information, fixing tasks j in a station k where they have a high z_{jk} value (*intensification*) or avoiding those tasks j reenter a station k where they have a high z_{jk} value (*diversification*) (Scholl and Becker, 2004).

Some of the studies use TS to solve various assembly line balancing problems are: Chiang, 1998; Pastor, Andres, Duran and Perez, 2002; Lapierre, Ruiz and Soriano, 2006.

Another well-known and efficient meta-heuristic approach is ***Simulated Annealing***. This approach simulates the annealing processes of materials on the decision problems. The main idea of the algorithm is to escape from the local optima by giving an acceptance chance to inferior solutions as the next current solution.

Simulated Annealing algorithm starts with an initial solution which is initiated by any constructive algorithm and makes moves with swaps or shifts.

The probability of accepting inferior solutions decreases, if the negative (bad) difference between the current solution and worse candidate solution increases or the value of the *control parameter t* decreases. Where *F* is a function to evaluate a solution, the function that gives an acceptance probability of bad solution is:

Exp(-(F[candidate solution]-F[current solution])/t).

At the beginning of the algorithm, the value of *t* is higher and it decreases during the iterations. This is called *cooling* and this cooling provides intensification during the procedure. Algorithm initially searches the space roughly, and as time passes, it focuses on some good solution regions. Generally, the final value of the control parameter *t* is used as a termination criterion.

Some of the studies that use SA to solve line balancing problems are: Suresh and Sahu, 1994; Bolat, 1997; McMullen and Frazier, 1998; Xiaobo and Zhou, 1999; Alp, Cercioglu, Tokaylı and Dengiz, 2001; Mendes, Ramos, Simaria, Vilarinho, (2005).

Another meta-heuristic approach is ***Ant Colony Optimization***. This approach is one of the most recent approaches and there are fewer studies on this method than the previously mentioned approaches. This approach simulates the process that ants search and find the shortest path that goes to food. Bautista and Pereria (2002) presented an ant colony algorithm to solve SALBP-1. McMullen and Tarasewich (2003) proposed an ant colony algorithm for a generalization of SALBP with respect to parallel stations, stochastic task times, multiple objectives and mixed-model production.

CHAPTER 3

THE CASE STUDY

3.1 The Company in the Study

Today's global competitive market forces the companies to diversify their products and develop new models. Companies try to enlarge their market share, or at least, to save it by producing various models that have different specifications according to their costumer needs. The consumer durables plant studied is one of the companies that continue their production with different models. The firm develops new models and produces different models. It also modifies its standard models according to customer specifications. But the ratio of these modifications is very small. Recently, the firm produces four main models with high production amounts; Model1, Model2, Model3 and Model4. (See Appendix A for sketch of the layout of the assembly line of the firm).

Model1, Model2, Model3 and Model4 comprise approximately 99-100 % of total production. According to the information obtained from the production planning department: roughly, Model1, Model2, Model3 and Model4 each has 70%, 15%, 10% and 5% share in total production respectively. The production amount is 500 units per shift.

3.2 Current Balancing Method and Development of the Proposed Method

There is no precedence relationships diagram in the firm. Assignments of tasks to stations are made manually according to personal experiences by trial and error method. Daily production is adjusted according to the production plans of a number of months. Then, the line is balanced such that it satisfies this production rate. Batch sizes of the different models, similarities and common tasks among models and consequently, assembly sequence of the models are neglected. This situation is similar to balancing the multi-model line by using combined precedence relationships diagram and obtaining a unique assignment, as if it is a mixed-model line. The firm even does not have the combined precedence relationships diagram, but the assignments are made by taking into account the list of all tasks and omitting the specifications of the models. Sometimes, with some more trial studies on this unique balance, small changes related to the models are made.

Production becomes significantly inconsistent at the week that balancing is made; because of the trial and error method many assignments violate the precedence relationships and it stops the production. Trials and adjustments continue till a feasible solution is achieved. This is a major disadvantage of the current balancing procedure. Rarely, a small amount of a different model passes throughout the line among other models. But, generally system works with large batch sizes as a multi-model assembly line. Balancing the multi-model assembly line as if it is a mixed-model assembly line is another disadvantage of the current line balancing procedure. Because of the lack of the objectives which will be mentioned in Chapter 4, the quality of the solution thus obtained is not known. Furthermore, even it is a great success to find any feasible solution to such a large problem based on individual experiences and trial methods. Due to the lack of evaluating functions and difficulty of the current method, better solutions may not be searched for. This is another disadvantage of the procedure.

Our study started as a case study. The main intention was obtaining a good line balance for the assembly line. The firm wanted us to develop such a program that uses the daily production information and computes the cycle time and balances the line. The firm was not interested in the objectives explained in Chapter 4 and related costs. The main interest of the firm was obtaining any feasible solution that fulfills the daily production. The batch sizes of the different models in the total daily production and differences among the models as to the processing requirements were not important for the firm. Namely, the firm wanted us to develop a software that makes the balancing job that is currently being made manually.

Every assembly line balancing procedure needs a list of the tasks, task times, precedence relationships and zoning restrictions. The lists of the tasks and task times have been obtained from the firm. Then we have determined the precedence relationships and sub-task lists of the models with our observations and contributions of the workers.

Initially, because the firm wanted us to develop such a program that produces a unique balance for all models, we have tried to develop integer programming-based method and find the optimum solution. At the beginning of the modeling effort, the size of the problem was absolutely large. Although we have achieved to decrease the problem size significantly with some manipulations, the running time was still too long.

During the time of construction of the precedence relationships diagram, we have observed that the production was more suitable for the multi-model production rather than the mixed-model production. Hence, balancing the line according to the mixed-model line balancing method was insufficient. Then we have determined the individual task lists of the models. We have realized that some other objectives and the sequencing problem should be also taken into account. Solving the problem with integer programming for all models and all possible sequences would require extremely long computation times. In addition, considering different batch sizes, cycle times and cost component combinations, it is almost impossible to solve the whole problem with integer programming-based methods.

As it is mentioned in the following paragraphs, we have already made some assumptions and gave up with the overall optimal solution. Because of these reasons, we have decided to develop a heuristic approach that can find good solutions in acceptable computational times, few hours, and can be adapted to different scenarios with different model mix, batch sizes, objective weights, etc.. The proposed approach and the relevant code are explained in the following chapter. The problem is explained in the following parts of this chapter.

3.3 Determining the Problem

3.3.1 Tasks

The first step is to determine the tasks and to construct the list of tasks. Any task consists of some sub-operations. For example, in order to perform a task, we may take a part from a specific location, do some operations on that part and then assemble it into the main part. Sometimes, it may be very difficult to determine the bounds of the task. If tasks are defined such that they consist of many operations, this may cause a task to be defined as aggregation of tasks. As a result, this situation dictates any solution to assign this group of tasks to the same station. It shrinks the solution space and may exclude the optimum solution. On the other hand, defining a task such that it includes very few operations may cause infeasibility. For instance, some sub-parts of a given task may be defined as separate tasks. Hence, sub-parts of a task may be assigned to different stations which results in infeasible solutions. In conclusion, tasks have to be defined such that they are not groups of tasks or sub-parts of a specific task.

In our study, tasks were already defined in the firm. We have got these definitions, but it was difficult to observe production and identify these tasks. While we try to construct precedence relationships diagram according to this task list, we have realized that there were some mistakes in this list. There were some tasks in the list which were already abolished. In contrast, there were some tasks that we have observed on the line but missing in the list. Sometimes, a task was performed more than once on the line, but coded and named once in the list. In order to balance any line, all tasks that have to be done on that line must be known. If any task is repeated more than once, every repetition may have the same name, but each of them must have different codes. By discussing these situations with workers, we have adjusted the task list. There were some other undefined tasks which were being performed automatically by robots. Because we have needed them in the precedence relationships diagram, we have defined and coded them. Then we have distinguished the task list for each model. Task lists are given in Appendix B.

There is a task “Oil the reel of hinge” in the list which is repeated two times on the line. It is adjusted by defining two separate tasks “Oil the right reel of hinge” and “Oil the left reel of hinge” (task 7 and task 27). There are some automatically made tasks which are defined as “Erect the main part”, “Functional test” and “Fill water to the salt box” (Tasks 72, 289 and 310). Many others are similarly added or removed to/from the list by discussing with the workers and the list is updated.

3.3.2 Task Times

Next step is determining the task times. Actually, it requires a lot of observations, measures, some statistical and analytical computations and goodness of fit tests, etc.. However, task times were obtained from the firm. Since no other task can be assigned to the stations of newly defined and automatically performed tasks, the task times of these tasks are taken as cycle time. Task times are given in Appendix B.

There were some zoning restrictions due to which it was impossible to assign any other task to the same station with these tasks. To prevent infeasible assignments, task times of these special tasks were taken as being equal to C. These tasks are task 72, task 195, task 259, task 289, task 310 and task 317.

3.3.3 Precedence Relationships Diagram

The most difficult step of the case study was to build the precedence relationships diagram. There were lots of alternative diagrams. It was a demanding work to represent the real situation on the paper. Occasionally, we were to make some assumptions and decisions. On the other hand, we were trying to represent the real situation as much as possible with minimal essential assumptions.

While we were trying to construct the diagram, we have realized that it was not obligatory to perform all of the listed tasks on the line. There were a lot of tasks which could be performed off the line. This relaxation gives rise to thousands of alternative precedence relationships diagrams. It messed up our studies up to that point. We faced with a lot of questions and decisions like;

➔ Which tasks were to be made on the line?

➔ Which tasks could be performed off the line?

➔ If we had determined all of these tasks and extracted them from the list, what would have happened?

➔ Since extracting all of these tasks from the line messes up the real situation, which subsets of these tasks should be extracted?

➔ What were the advantages and disadvantages of the decision about extracting tasks from the line?

When we consider all of the subsets of these tasks, there are thousands of alternative precedence diagrams and consequently, thousands of alternative solutions. Since we were trying to solve this real life problem and find the best solution, each of these alternatives was an alternative applicable solution.

Finally, since the advantages and disadvantages of the alternative solutions are not known, we have decided to consider only the current situation of the line; we have decided to assume that all tasks being performed on the line currently have to be performed on the line.

The other important and difficult decision was about the tasks that require opening and closing the lid of the machine (product). There are two tasks as, "Open the lid" and "Close the lid". There is a code for "Open the lid" and another one for "Close the lid". But on the line, each of them is repeated more than once. In order to balance the line, we have to know exactly how many tasks we assign to the stations, the relationships between them, the task times and the zoning restrictions. But at almost every step of our observations, we have faced with very flexible situations. There are some tasks which have to be performed inside the machine. Let us consider two of them. It is possible to assign one of them to a station and the other one to another station, or it may be possible to assign them to the same station according to the precedence relationships. If these two tasks are assigned to different stations, there would be two alternative situations. In the first case, a pair of "Open the lid", "Close the lid" tasks would be also assigned to each of the stations and those two tasks would be performed on the machine. This situation requires two "Open the lid" and two "Close the lid" tasks. In the second case, the lid is opened at the first station, the first task is performed, the machine moves to the second station with the open lid, the second task is performed and then the lid is closed. This situation requires one "Open the lid" and one "Close the lid" tasks. But this time if we allow moving the machine with the open lid between stations, the "Open the lid" task may be assigned to a previous station of the first station and the “Close the lid” task may be assigned to a successor station of the second station. At this point some other questions may arise; “Is it feasible to move the machine with the open lid between stations?”, “If it is infeasible for some stations, what will happen?”, “Sometimes the open lid forces the worker to go away from the machine and gets the work harder, how will the moves with the open lid affect the production?”, etc. If these two tasks are assigned to the same station, it is needed to assign one “Open the lid” task and one “Close the lid” task to this station. In the real problem, there are 38 such tasks and it is possible to attain thousands of different alternative precedence diagrams.

Increasing the number of “Open the lid”-“Close the lid” pairs and decreasing the number of inside-tasks between each pair on the precedence relationships diagram enlarges the solution space and gives a chance to find better solutions. But at the same time, it increases the number of tasks, work content, number of stations and most importantly the size of the problem. Decreasing the number of “Open the lid”-“Close the lid” pairs and increasing the number of inside-tasks between each pair on the precedence relationships diagram decreases the work content and problem size, but it shrinks the solution space and may lead to worse solutions. It was impossible to construct all possible precedence relationships diagrams and solve the problem overall alternatives. We were to choose one of them. Thus, we decided to give up the overall optimum solution. Instead, we chose to find the best possible solution. There are some zoning restrictions and tasks that have to be assigned to the same station. One of the groups of these tasks (317 TASK GROUP 4) has a total task time of 43.3 seconds. By considering this situation, we have grouped the inside-machine tasks such that their total task time can not exceed 30-35 seconds. According to these groups we have added “Open the lid”-“Close the lid” pairs. The selection procedure is a heuristic approach, but we have tried to save the flexible structure and represent the current production line as realistic as possible. The final task list is given in Appendix B. Precedence relationships for individual models are given in Table C.1 and combined precedence diagram is given in Figure C.1 in Appendix C.

3.3.4 Zoning Restrictions

In addition to precedence relationships, zoning restrictions specify some special restrictions. Because of the requirement of some special equipment, a task can be performed at only some specific stations. Occasionally, it can be neccessary to perform some specific tasks together at the same station or separately at different stations. Such limitations are called zoning restrictions. We have determined many zoning restrictions at the assembly of consumer durables in the firm. Sometimes we have represented them in the precedence diagram or we have manipulated the task times so as to satisfy these zoning restrictions or we have used them in the file which consists of the station numbers at which a task may be performed (assignable station numbers).

There is a robot and special equipment at station 11. Tasks 12, 15, 16, 18 and 20 are to be performed at this station because of this special equipment. Because of the precedence relationships, tasks 13, 14 and 17 are to be assigned to station 11. Since the worker at station 11 can handle many tasks, it is feasible to assign other tasks to station 11. Furthermore, since the worker does tasks 13, 14 and 17, while the robot turns the pallet, the task times of task 12 and task 20 are defined as zero. Assignable station numbers are fixed to 11 for tasks 12, 13, 14, 15, 16, 17, 18 and 20.

There is another robot at station 17 which changes the position of the machine. It holds and lifts the machine. Then, it turns the machine and puts it again on the pallet. There is no worker at this station. Hence, it is impossible to assign some other tasks to station 17. The robot can only perform task 72. The task time of task 72 is taken as cycle time and the assignable station number is fixed as 17 for task 72.

Task 310 is performed by a robot automatically at station 22. Task time of task 310 is taken as the cycle time and the assignable station number is fixed as 22 for this task. Similarly, task 195 is performed by a robot automatically at station 43. Task time of task 195 is taken as the cycle time and the assignable station number is fixed as 43 for this task.

Tasks 207, 210, 211, 212 and 216 are to be done at station 44, because of another robot. Likewise, because of the precedence relationships, tasks 208 and 209 are assigned to station 44. There is a worker at the station and it is possible to assign some other tasks to this station. Since the worker performs tasks 208 and 209 while the robot works, their task times are defined as zero on the line. Assignable station numbers are fixed as 44 for these tasks.

There is a parallel station (station 29) to the line and tasks 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309 and 311 are to be performed at this station because of a specific equipment: fixture.

Tasks 173 and 178 are to be done at the same station. This situation first is represented by taking each of them as a predecessor and the other as a successor. But after developing the proposed meta-heuristic algorithm, since this situation is preventing the running of the algorithm, tasks 173 and 178 are taken as one combined task (323 TASK GROUP 10).

Tasks 275 and 280 are to be performed at the same station. Because of the precedence relationships, tasks 272, 273, 274, 279 are also to be assigned to the same station. This restriction is satisfied by adding the arc (280,275) to the precedence relationships diagram.

There is a special section on the line. This section includes stations 45, 46, 47 and 48. There is much space to put the product (machine). There are workers at these stations who set the machine and test it. A machine works as a finished item. If there is a problem, the machine is sent to the repair department. This section is dedicated to test operations only. In order to represent this situation in the precedence diagram, we have defined a task (functional test) and give a code (289). Then we have taken its task time as the cycle time and fixed the assignable station number as 45. The task "289 test" is always assigned to station 45, but it shows that test is made at one of the stations 45, 46, 47, 48. For other tasks, these stations are removed from the assignable station numbers in order to prevent assigning any other task to these stations.

There is a parallel sub-assembly line to the assembly of the inner lid. A conveyor moves an inner lid and a worker takes this inner lid and assembles it to the main part. The task 86 is to be assigned to station 23. By using assignable station numbers and fixing it as 23 for task 86, this zoning restriction is integrated into the algorithm.

Similarly, task 259 is to be performed by a robot automatically at station 54. Task time of task 259 is taken as the cycle time and assignable station number is fixed as 54 for this task.

Since it is not allowed to move a machine between stations with the open lid, a pair of "Open the lid"-"Close the lid" tasks has to be assigned to the same station. If this is the case, the tasks which are in between this pair in the precedence relationships diagram have to be assigned to the same station. According to this result, tasks 106, 199, 200, 201, 202, 203 and 189 have to be assigned to the same station. Tasks 190, 252, 253, 255, 261, 262, 263, 264, 256, 254, 257, 258, 265 and 194 have to be assigned to the same station. Similarly, tasks 312, 281, 282, 283 and 313; tasks 160, 284, 290, 285, 286, 288, 296, 161, 287, 291 and 292; tasks 217, 218, 219, 220, 222, 223, 224, 225, 226, 227 and 228 have to be assigned to the same stations. Because an equipment performs task 219 while the worker is doing some other tasks, task times of tasks 220 and 223 are defined as zero on the line.

3.4 Integer Programming Studies

At the beginning of the studies with integer programming, the problem size is found to be absolutely large. There are 313 tasks at the combined precedence diagram and 68 stations on the line which is equivalent to (68)(313)=21284 binary decision variables in the mathematical model. The main models of the product (Model 1, 2, 3 and 4) consist of 270, 271, 282 and 297 tasks, respectively. Hence, there are approximately 18360 to 20196 (=(68)(270) to (68)(297)) binary decision variables in the individual mathematical models of the individual product models. We have used the precedence relationships and zoning restrictions, and made the following manipulations to reduce the problem size:

➔ There are 6 tasks which have task times equal to the cycle time (tasks 72, 195, 259, 289, 310 and 317). Since the assignment of any other task to the same stations with these tasks is impossible, we have discarded assignment variables of other tasks to these stations. We have also discarded assignment variables of all tasks to stations 46, 47, 48 because of task “289 functional test”. These operations decrease the number of binary variables approximately by 2700 (=(6+3)(300)) for roughly 300 tasks.

➔ Since tasks 72, 195, 259, 289, 310 and 317 are to be assigned to the specific stations, it is possible to remove the assignment variables of these tasks to other stations. This process reduces the number of binary variables by 402 (=(68-1)(6)).

➔ Some tasks between a pair of "Open the lid"-"Close the lid" are to be assigned to the same station with that pair. So, it is possible to group these tasks and assume them as one task.

- Tasks 106, 199, 200, 201, 202, 203 and 189 are combined and called as "315 TASK GROUP 2". This reduces the number of variables by 408 (=(7-1)(68)).
- Tasks 12, 13, 14, 15, 16, 17, 18 and 20 are combined and called as "314 TASK GROUP 1". It reduces the number of variables by 476 (=(8-1)(68)).
- Tasks 207, 208, 209, 210, 211, 212 and 216 are combined and called as "316 TASK GROUP 3". It reduces the number of variables by 408 (=(7-1)(68)).
- Tasks 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309 and 311 are combined and called as "317 TASK GROUP 4". It reduces the number of variables by 816 (=(13-1)(68)).
- Tasks 275, 272, 273, 274, 279 and 280 are combined and called as "318 TASK GROUP 5". It reduces the number of variables by 340 (=(6-1)(68)).
- Tasks 190, 252, 253, 255, 261, 262, 263, 264, 256, 254, 257, 258, 265 and 194 are combined and called as "319 TASK GROUP 6". It reduces the number of variables by 884 (=(14-1)(68)).
- Tasks 312, 281, 282, 283 and 313 are combined and called as "320 TASK GROUP 7". It reduces the number of variables by 272 (=(5-1)(68)).
- Tasks 160, 284, 290, 285, 286, 288, 296, 161, 287, 291 and 292 are combined and called as "321 TASK GROUP 8". It reduces the number of variables by 680 (=(11-1)(68)).
- Tasks 217, 218, 219, 220, 222, 223, 224, 225, 226, 227 and 228 are combined and called as "322 TASK GROUP 9". It reduces the number of variables by 680 (=(11-1)(68)).

- Tasks 173 and 178 are combined and called as “323 TASK GROUP 10”. It reduces the number of variables by 68 (=(2-1)(68)).

➔ After these preliminary studies, the number of binary variables is reduced by approximately 50% (by 8000 to10000 variables). But the number of variables is still high to try to solve the problem optimally. It is possible to use precedence relationships and zoning restrictions to reduce this number further. For example, task 72 is to be assigned to station 11. If that is the case, no one of the preceding tasks of task 72 at precedence relationships diagram can be assigned to the successor stations of station 11. By using precedence relationships, task times, a pre-determined cycle time and zoning restrictions, we have found the upper and lower bounds of stations that a given task may be assigned to for each of the tasks. Then we have removed the unnecessary assignment variables.

The number of assignment variables is reduced to approximately 2000. Then we have constructed the mathematical model IP formulation of which is given in Chapter 2 for each machine type for a given cycle time and searched the minimum number of stations. We have used LINGO 8.0 and CPLEX 8.1 programs, but still the running times were very high; more than a day for one product model. We have stopped the runs without achieving any solution. For four product models, there are 24 possible sequences. To evaluate a sequence, a model has to be constructed and solved for each of the four product models. To evaluate all sequences for a specific cycle time, it is necessary to construct and solve 96 mathematical programming models. Considering different cycle times, different cost components and different batch sizes, it is concluded that mathematical models can not be used to solve this problem.

In general, in today’s production environment, companies produce more than one type of a product. The companies that benefit from the assembly lines use the same line to produce different product models. According to our limited observations, these lines do not consist of a few number of tasks. Furthermore, almost everything is flexible and consists of many decision criteria in the real life production processes. Hence, it is very important to be able to evaluate different situations according to different objective function combinations and find good solutions in acceptable times, even if it is possible to find the optimum solution. In this study, a heuristic solution algorithm is developed to find good solutions in reasonable times for especially multi/mixed-model. Our algorithm is used to solve such a real life problem which can be defined as a large-size assembly line balancing problem, consisting of flexible and multi-criteria real life environment. The proposed algorithm is explained in detail in the following chapter.

CHAPTER 4

THE PROPOSED APPROACH

4.1 Simulated Annealing (SA)

Simulated Annealing is a well-known and efficient meta-heuristic approach. This approach simulates the annealing processes of materials on the decision problems. The main idea of the algorithm is to give a chance to the inferior solutions to be accepted as the next current solution in order to escape from the local optimums.

Simulated Annealing algorithm starts with an initial solution which is constructed with any constructive algorithm. At any iteration, the algorithm generates a neighboring solution by making a randomly chosen small variation on the current solution. Generating a neighboring solution by making small perturbations on the current solution provides a way to make detailed search on the special regions of the solution space. If the candidate solution is generated by making many changes on the current solution, the algorithm jumps from the current solution to any other solution residing in a very different region of the solution space. Thus, using a near neighboring solution as a candidate solution improves the algorithm performance.

At any iteration, if the candidate solution is better than the current one, a move to the candidate solution is made. However, if the candidate does not improve the current solution, the algorithm may adopt the candidate solution as the next current solution with some acceptance probability or reject it. If the transition from the current solution to the candidate solution is rejected, another solution in the neighborhood of the current solution is generated and evaluated.

The probability of accepting a poor solution decreases if the negative (bad) difference between the current solution and worse candidate solution increases or the value of the *control parameter t*, which denotes the temperature, decreases. The function that gives an acceptance probability of a bad solution is,

Exp (-(F [candidate solution]-F [current solution])/t)

where *F* is a function to evaluate a solution.

At the beginning of the algorithm, the value of *t* is higher and it decreases during the search according to a function known as the cooling schedule. This cooling provides intensification during the time. Because of the higher value of *t*, initially the algorithm searches the space roughly and as time passes, because of the cooling effect, it focuses on some good solution regions.

If the initial value of the parameter *t* is chosen very small, the algorithm cannot escape from the local proximity of the initial solution and approximates to a local optimal solution in this region. On the other hand, choosing a very high initial value of *t* causes a long extended search before starting to intensify on good regions. Figure 4.1 and Figure 4.2 show examples for the convergence of the simulated annealing algorithm with a very small and a very high initial temperature, respectively.

The algorithm stops when the termination criterion is satisfied. Number of the iterations, the running time or the final value of the control parameter *t* can be used as the termination criterion.

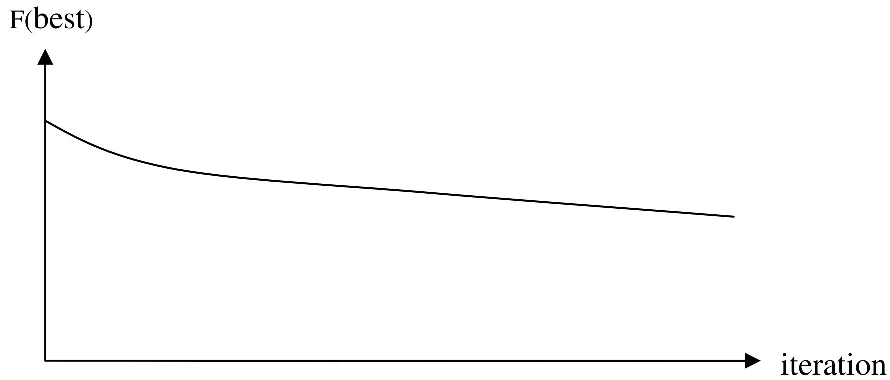


Figure 4.1 An example of the convergence of a SA algorithm with very small initial

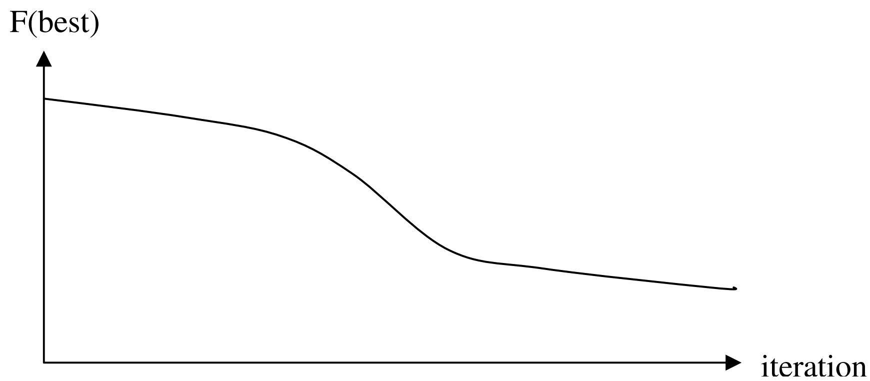


Figure 4.2 An example of the convergence of a SA algorithm with very high initial

4.2 Adaptive Simulated Annealing (ASA)

In 1984, a proof was established that, by carefully controlling the rates of cooling of temperatures, SA could statistically find the best minimum. This was good news for researchers trying to solve hard problems which could not be solved by other algorithms. The bad news was that finding the optimum is only guaranteed if they were willing to run SA forever. In 1987, a method of fast annealing (FA) was developed, which permitted lowering the temperature exponentially faster, thereby statistically guaranteeing that the minimum could be found in some finite time. However, that time still could be quite long.

Shortly thereafter, in 1987, L. Ingber developed Very Fast Simulated Re-annealing (VFSR) which is exponentially faster than FA. The main idea of the method was generating the new solution and balancing the temperature by using the information obtained during the search. The original method was especially useful for D-dimensional, continuous solution space problems where one component of the solution is independent from the other components. The method was affecting the direction of search and the step sizes in each dimension by evaluating the changes on the objective function values of the old and the new solutions. Then the temperature was being changed by using the best solution found so far and the last accepted solution. The original method was not applicable to all kinds of problems with the original structure. But the idea of adjusting the algorithm according to the search history pioneered to the development of ASA. Then the ASA approach was applied to many different problems (Ingber, 1998; Chen, Istepanian and Luk, 2001).

The temperature change mechanism is an important part of the transition probability equation. In conventional simulated annealing, the search begins with a high temperature allowing a higher chance of transition to an inferior solution. By doing so, the search is able to move out of local minima. However, as the search continues, the temperature continuously decreases resulting in a reduced chance of uphill transition. Such an approach could be useful if the local minima are near the starting point, but may not lead to a near optimal solution if some local minima are encountered at a relatively low temperature toward the end of the search. Instead of this monotonically non-increasing cooling schedule, ASA approach allows adjustment of the temperature dynamically based on the profile of the search path. Such adjustments could be in any direction including the possibility of reheating. Because of these adjustments, the algorithm is not completely dependent on the initial solution and the initial temperature; the algorithm balances the parameter itself. Nevertheless, it could be affected from the initial values. Figure 4.3 shows an example of the convergence of an ASA. Figure 4.4 and Figure 4.5

show examples of the conventional cooling schedule. Figure 4.6 shows an example of an ASA cooling schedule (Azizi and Zolfaghari, 2004)

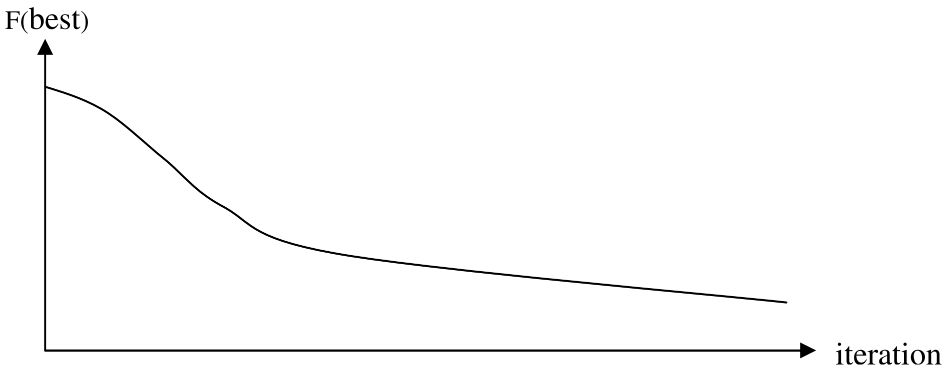


Figure 4.3 An example of the convergence of an ASA

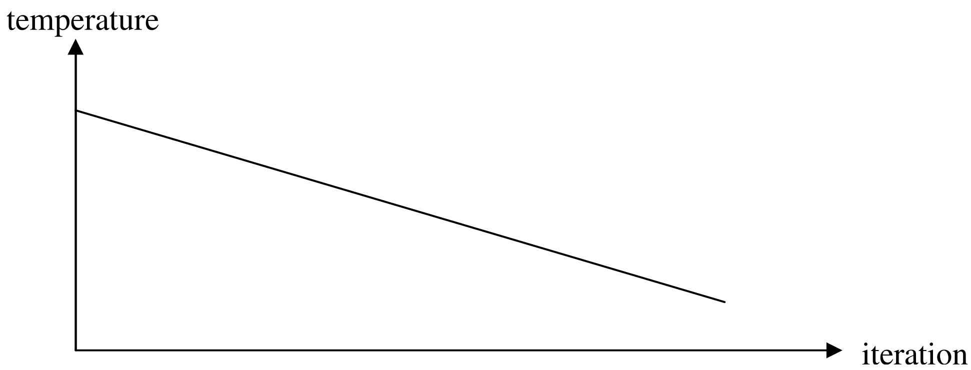


Figure 4.4 An example of the conventional cooling schedule of a SA algorithm (Example 1)

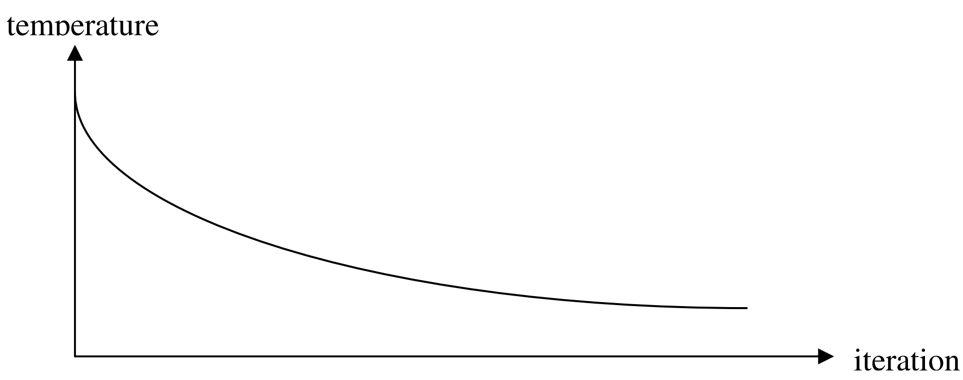


Figure 4.5 An example of the conventional cooling schedule of a SA algorithm (Example 2)

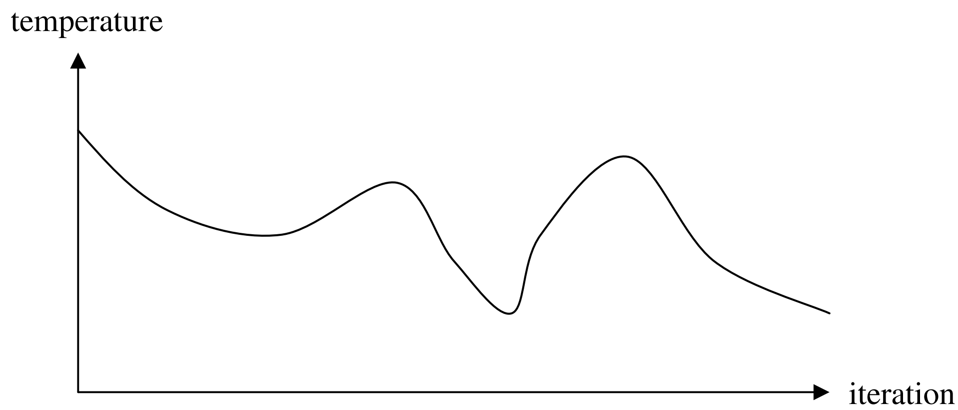


Figure 4.6 An example of the cooling schedule of an ASA algorithm

4.3 Construction of the Solutions

The majority of the constructive procedures are based on priority rules, others are restricted to enumerative procedures (Scholl and Becker, 2004).

Restricted enumerative procedures are generally based on the exact enumeration techniques, which are modified by restricting the search space in a heuristic manner. Each B&B (or DP) procedure can be applied as a heuristic by adding heuristic fathoming rules or imposing a time limit. All these procedures together with the Heuristic of Hoffmann (1963) and its modifications can be examples of the restricted enumerative procedures.

There are two *construction schemes* relevant to the priority rule based approaches. They differ with respect to the manner in which the tasks to be assigned are selected out of the set of available tasks.

- *Station-oriented procedures.* They start with the first station ($k=1$). The following stations are considered successively. In each iteration, a task with highest priority which is assignable to the current station k is selected and assigned. When station k is loaded maximally, it is closed, and the next station *k+1* is opened (Scholl and Becker, 2004).

- *Task (Operation)-oriented procedures.* Among all available tasks, one with the highest priority is chosen and assigned to the earliest station to which it is assignable (Scholl and Becker, 2004).

The priority rule based approaches use any one of the construction scheme and work, generally, uni-directionally in forward direction and construct a single feasible solution. But there are many techniques that work in backward direction, or flexible bi-direction.

4.4 Representation of the Solutions

There are two most general representations: standard encoding and order encoding.

Standard encoding: The solution is defined as a vector containing the labels of the stations to which the tasks 1,...,*n* are assigned

Order encoding: The solutions are defined as precedence feasible sequences of tasks (Scholl and Becker, 2004). Numbers of stations that tasks are assigned to and the station times are computed by adding task times until the station time of current station exceeds the cycle time. If the station time exceeds the cycle time by adding the current task to the current station, the next station is opened and that task is assigned to the next station. An illustrative example is given below.

Example:

Let us consider the operations shown in Figure 4.7 and let the operation times be 3, 1, 2, 4, 4, 5, 3, 6, 2 seconds respectively and cycle time (C) be 8 seconds.

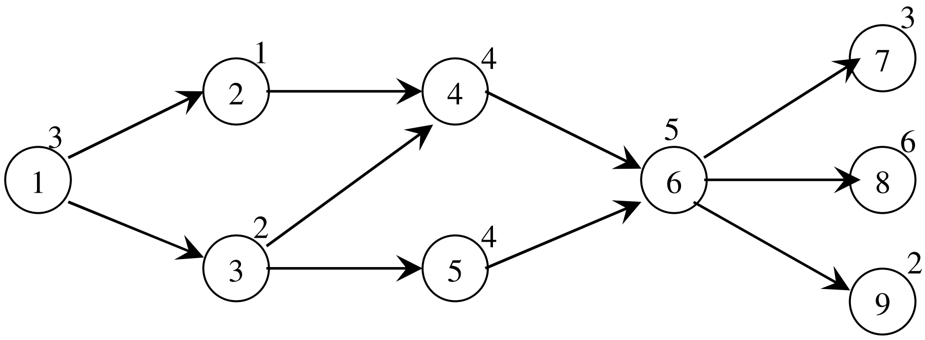


Figure 4.7 Precedence Diagram of the Example

X = (1,3,5,2,4,6,8,9,7) is an example of order encoding. Then we can determine the station numbers that the operations are assigned as follows:

Table 4.1 Computations of station numbers and station times for the example

Station (i)	Operations assigned to station i	Station time of station i
1	1	3
1	1,3	3+2=5
2	5	4
2	5,2	4+1=5
3	4	4
4	6	5
5	8	6
5	8,9	6+2=8
6	7	3

The solution found above can be represented by standard encoding like; X = (1,2,1,3,2,4,6,5,5).

4.5 Types of Moves

There are two types of moves for SALBP: *shift* and *swap*. They are explained using the following notation:

LP_j : latest station to which a predecessor of task j is currently assigned.

ES_j : earliest station to which a successor of task j is currently assigned.

- A *shift* (j,k_1,k_2) describes the movement of a task j from station k_1 to station k_2 with $k_1 \neq k_2$. This move is feasible if $k_2 \in [LP_j, ES_j]$ (Scholl and Becker, 2004).
- A *swap* (j_1,k_1,j_2,k_2) exchanges tasks j_1 and j_2, which are not related to precedence, between different stations k_1 and k_2. This move is feasible if the two corresponding shifts (j_1,k_1,k_2) and (j_2,k_2,k_1) are feasible (Scholl and Becker, 2004).

4.6 Objectives of ALBP and Evaluation of Solutions

4.6.1 Minimization of the Number of Stations

It is the best known and the most studied objective of the assembly line balancing problem. Assembly line type production and assembly line balancing problems are transformed from the simple types (single-model, deterministic etc.) to the complicated types (multi/mixed-model, stochastic, parallel, U type, S type etc.) in the course of time. At the single-model assembly lines, achieving a pre-determined amount of production with the minimum number of stations, saves the system from all the costs related to the unused stations permanently. Consequently, at the single-model assembly lines, minimizing the number of stations may be the first objective without any other challenging objectives. On the other hand, assembly lines with the multi/mixed models, having an unused station at any model’s production, does not save the system from all the costs related to that station permanently, it saves the system from these costs at only that model’s production period. In this situation, there may be any other challenging objective and using that station with a high station slack time may be preferred to getting that station unused at that model’s production period.

Because the system avoids the costs of unused stations while that model is produced, minimizing the number of stations must be more important for the models that have large batch sizes. The component used to evaluate the solutions according to their number of stations is:

*F1[x]=(m1)(Batch Size)(Cycle Time)(**Number of Stations**)*

where *x* is a solution (line balance) for the model.

The time that is equal to the multiplication of cycle time and the number of stations is the assembly time and it is equal to the maximum time allowed to complete a unit product. ((Batch Size)(Cycle Time)(Number of Stations)) is equal to the total assembly time to complete the batch size units of products of a model. Here, *m1* is the cost of using a station for a unit time. The batch size and cycle time are constant. This component represents the total assembly cost of a model. So, if a move decreases the number of stations by one, it improves the solution by the total cost of using that station in the production of that model.

4.6.2 Minimization of Cycle Time

This is the second best known objective for assembly line balancing. If it is certain that the production is to be made with any number of stations, it is desired to achieve the most frequent production with these stations. It increases the daily production. Because of the production plan, even it is not wanted to increase the daily production, minimizing the cycle time decreases the total production time and the production cost. Furthermore, it provides opportunity to tolerate some simple problems that may arise during production. Producing any product with smaller cycle times makes the system more flexible for the production of other products, if it is necessary to increase the cycle time. Due to these reasons, if it becomes certain that production is to be made with any number of stations, minimizing cycle time arises as a second objective. The component used to evaluate the solutions according to their cycle times is:

*F2[x]=(m1)(Batch Size)(**Cycle Time**)(Number of Stations)*

Here, *m1* is again the cost of using a station for a unit time and the batch size is constant as well as the number of stations. Because this component shows the total assembly cost of a model, if any solution decreases the cycle time by one unit, it saves all stations from this cost for the whole batch size.

4.6.3 Maximization of Irregularity between Station Times

In general, meta-heuristic approaches search the space by passing from a current solution to a candidate solution which is generated from the current solution by making small changes. Simulated Annealing algorithm moves to the candidate solution if it has a better objective function value. Otherwise, it passes to the given candidate solution according to the acceptance probability. Hence, correct evaluation of solutions is very important. If the objective function uses only the number of stations while evaluating the solutions, all candidate solutions that have the same number of stations with the current solution have the same objective function value; however, the objective function value must decrease by the moves which try to get any station empty. Because the aim is minimization of the number of stations, the objective function must encourage these moves by reducing its value. An illustrative example is given below:

Example:

Let there be an assembly line that has 10 tasks; a, b, c, d, e, f, g, h, i, k. There is no precedence restriction, all task times are 5 seconds and cycle time is 25 seconds. Let us consider the current solution and two candidate solutions as follows:

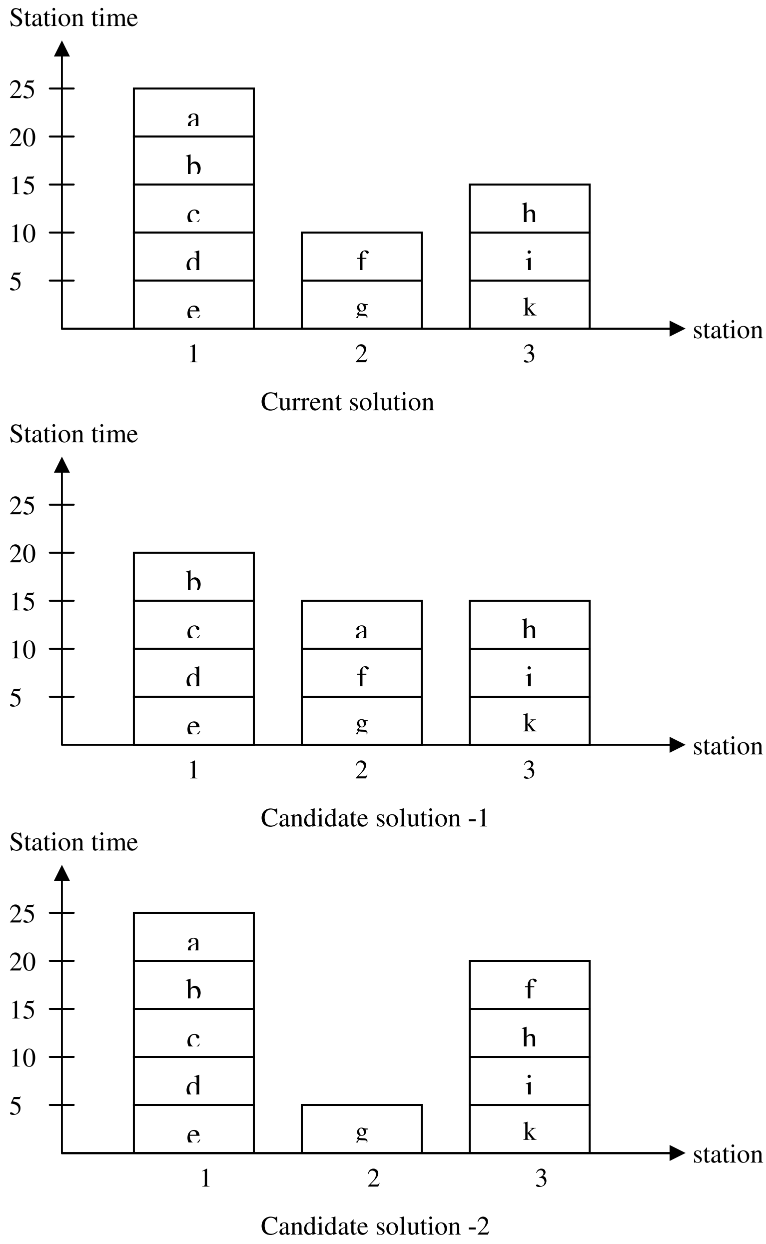


Figure 4.8 Current and candidate solutions for the example

If the objective function uses only the number of stations while evaluating the solutions, candidate solutions and the current solution have the same objective function value. So, if the algorithm generates the candidate solution-1, it directly passes to this solution or if it generates the candidate solution-2, it again directly passes to this solution. The candidate solution-1 makes decreasing the number of stations harder. On the other hand, the candidate solution-2 makes decreasing the number of stations easier. In this case, the algorithm should understand that the candidate solution-1 is worse than the current one and penalize this move by increasing its objective function value. It should also realize that the candidate solution-2 is better than the current one and encourage this move by decreasing its objective function value. To achieve this, the following cost component of the objective function is developed:

$$F3[x] = (m2)\sum_{\forall i \in K}\sqrt{C\text{-}WC_i}$$

where K is the set of used station and $m2$ is a penalty

Since the SA algorithms search the solution space by passing from a solution to its neighboring solution, using only the number of stations as an objective function is not enough to evaluate the solutions to minimize the number of stations. Maximization of variance (irregularity) in station times is a sub-objective to achieve the minimization of the number of stations.

4.6.4 Maximization of Smoothness between Station Times

If the stations that are to be used in the production are determined, it is required to minimize the deviations between the workloads of these stations. In other words, it is desired to maximize the smoothness between these stations' workloads. If the deviations among stations' workloads are high, some stations are highly loaded, while some of them work at low levels. In this situation, some of the employees work continuously and some of them have a lot of idle time. This may cause some satisfaction problems, that is bottleneck station. On the other hand, the stations that have high workload become more critical. Any problem occurring in these stations may affect the whole line. Therefore, when the stations that are to be used are known, total workload is required to be shared equally by these stations as much as possible.

At the previous parts, the cycle time minimization objective is explained. For the meta-heuristic approaches, as it is a sub-objective to maximize irregularity to achieve minimization of the number of stations, maximization of smoothness is a sub-objective to achieve minimization of cycle time. Determination of the stations that will be used in production means having a line balance that the production quantities can be met. After having such a balance, it is required to minimize the cycle time and maximize smoothness to improve this balance. In order to minimize the cycle time, if the objective function only uses cycle time, it could not be enough to evaluate the solutions truly. There should be such an objective function component that encourages the moves which transfer a task from a station that has high station work content to a station that has low station work content and punish the reverse moves. The component developed to achieve this is given below:

$$F4[x] = (m3)\sum_{\forall i \in K}(C\text{-}WC_i)^2$$

where K is the set of used stations and $m3$ is a penalty.

4.6.5 Maximization of Common Tasks that Assigned to the Same Stations between Consecutive Models

There are common tasks among models or individual tasks in multi/mixed-model assembly lines. After balancing the line for a model, while passing to another model, some tasks are deleted from the line while some others are added to the line. Because of the precedence relations and the zoning restrictions, the balance is changed. Because of this transition, common tasks between two consecutive models may be assigned to different stations in each balance.

While passing from one model to another, because of added, extracted or common tasks that are assigned to different stations, it may be needed to add or remove some equipment, workers, sub-items and materials to/from the line or it may be needed to change location of some of them. There may exist a setup cost related to these changes. Furthermore, until the system arrives at a steady state at the production of the new model, it bears to learning curve effect. The following component is used to evaluate common tasks:

F5[x]= (m4)(Number of common tasks between two consecutive models assigned to different stations)

Here, *m4* is the cost of changing the assignment of a common task from one station to another.

4.7 Sequencing Problem

Especially for the multi-model assembly lines, sequencing of models arises as another problem besides balancing problem. Because the common tasks between consecutive models differ with respect to the models, it becomes important to determine the best sequence. From a sequence of models to another one; remaining times, cycle times and correspondingly number of stations, assignments and values of all components of the objective functions and consequently the best balances are changed. If so, besides balancing the line for each model, determining the true sequence of the models turns out to be another critical problem.

4.8 The Proposed Methodology

In this study, a methodology is developed to solve multi-criteria multi/mixed or single-model assembly line balancing problems heuristically. The method contains an algorithm that uses COMSOAL and two ASA in a sequential manner. For different cost components and batch sizes, the algorithm yields different final solutions which can be appropriate for different assembly lines (multi-model assembly lines with large batch sizes, mixed-model assembly lines with small batch sizes, mixture of these two types, single assembly lines). If the assembly line is multi-model, the algorithm uses the explained method below to find the task assignments for each model and the production sequence of the models. If the line is mixed-model, then the algorithm uses the combined precedence relationships diagram and finds a single balance for all models. If the line is single-model, or if the user wants to balance the line as a single-model for each model, the algorithm gives a balance for only that model. If the line consists of some models with large batch sizes and some others with small batch sizes, it is possible to adjust the cost parameters according to this situation and the algorithm can find a good solution.

4.8.1 Representation of the Solutions

There are 63 workstations on the assembly line and there are many zoning restrictions about tasks. Some of the tasks have to be assigned to some specific stations. The number of used stations (m) does not mean that first m stations are used. Some stations between any other busy stations could be idle. This situation makes the usage of standard encoding more appropriate for this problem. Besides, standard encoding is more appropriate for making a small change on the current solution, generating near neighboring solutions and making more detailed search on special regions. These situations may be understood more clearly with the following example.

Example:

Let us consider an assembly that consists of 9 tasks. Furthermore, let there be a zoning restriction that task 4 has to be assigned to station 3.

Cycle time is 8 seconds. Task times for the tasks 1 thru 9 are 4, 3, 4, 3, 3, 5, 4, 7, 2 seconds respectively and precedence diagram is as follows:

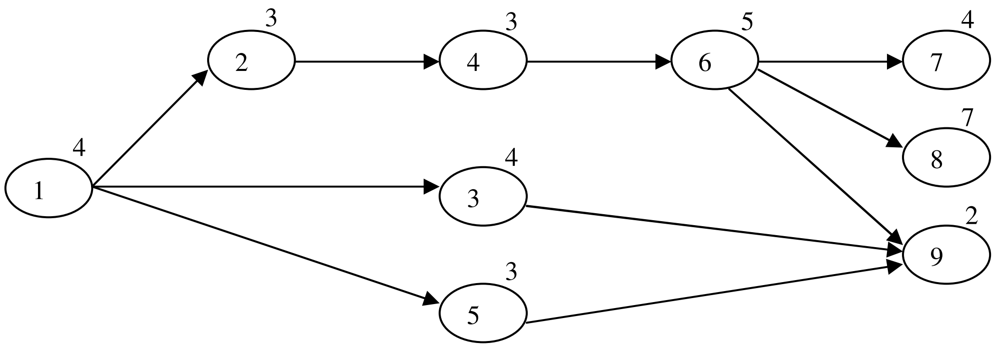


Figure 4.9 Precedence Diagram of the Example

Let us consider that we have the following solution as a current solution and we transfer task 3 from station 1 to station 5 and obtain a neighboring solution:

Table 4.2 Representations of the current and candidate solution in the example with standard and order encoding

	Current solution	Candidate solution
Standard encoding	(1,3,**1**,3,4,4,5,6,7)	(1,3,**5**,3,4,4,5,6,7)
Order encoding	(1,**3**,2,4,5,6,7,8,9)	(1,2,4,5,6,**3**,7,8,9)

The order encoding solutions show the order of tasks for the same solutions at the standard encoding. From the standard encoding we can see that station 2 is empty, task 4 is assigned to station 3. Zoning restriction is satisfied. By making a small change, we obtain a neighboring solution. But on the other hand, at order encoding it seems like only a small change is made; only the order of the task 3 is changed. Hence, it can be considered that these two solutions are very similar. But from the order encoding if we try to determine the assignments to the stations and station times, we face with the following situation:

Table 4.3 Differences between current and candidate solution of the example according to standard and order encoding

	Current solution			Candidate solution		
Standard encoding	(1,3,**1**,3,4,4,5,6,7)			(1,3,**5**,3,4,4,5,6,7)		
	Station	Tasks assigned	Station time (sec)	station	Tasks assigned	Station time (sec)
	1	1,**3**	**8**	1	1	**4**
	2	-	-	2	-	-
	3	2,4	6	3	2,4	6
	4	5,6	8	4	5,6	8
	5	7	**4**	5	**3**,7	**8**
	6	8	7	6	8	7
	7	9	2	7	9	2
Order encoding	(1,**3**,2,4,5,6,7,8,9)			(1,2,4,5,6,**3**,7,8,9)		
	Station	Tasks assigned	Station time (sec)	station	Tasks assigned	Station time (sec)
	1	1,**3**	**8**	1	1,**2**	**7**
	2	**2**,4	6	2	4,**5**	6
	3	**5**,6	**8**	3	6	**5**
	4	7	**4**	4	**3**,7	**8**
	5	8	7	5	8	7
	6	9	2	6	9	2
	7	-	-	7	-	-

The order encoding solutions show the order of the corresponding solutions at the standard encoding. However, when we try to determine the station numbers that tasks are assigned to and the station times, we face with some difficulties. The first one is about the station numbers. We can not understand the assignments from the order of tasks easily. If we try to compute these numbers as explained in the paragraph of order encoding, we can obtain any solution that does not represent the real situation as shown in the table. If we try to fix the number of station as 3 that task 4 is assigned to, we can not be sure that whether the task 2 is assigned to station 2 or station 3. The other difficulty is about generating the neighboring solutions. It seems that only the order of task 3 is changed. But if we try to determine the assignments and the station times and calculate the objective value of this candidate solution (a function of number of stations, cycle time, common tasks, batch sizes, etc.), wee see that this new solution is very far from the current solution (The changes about the solutions are bold-typed in Table 4.3). In conclusion, order encoding may have an adverse effect on detailed search in a region. Because of these disadvantages of order encoding, standard encoding is used in the constructed algorithm.

4.8.2 The Move Procedure

Shift is used as the move procedure. A swap makes two shifts simultaneously. Because swap mechanism is more restrictive than shift and shift mechanism is more appropriate for making smaller changes on the current solution, it is adopted as the move procedure.

Each of the two ASA algorithms designed in the study chooses a task *k* randomly. Then the algorithm determines the set of stations that task *k* may be assigned to by considering precedence relationships, cycle time, station times and zoning restrictions. Then the task *k* is moved to a station which is chosen randomly from this set.

4.8.3 The Adaptive Cooling Schedule

The Simulated Annealing approach can not escape from a local optima if acceptance probability is very small. As it is mentioned in the previous sections, the main idea of Adaptive Simulated Annealing is adjusting the algorithm according to the past search. In order to escape from local optimums, logic of the approach allows reheating. If so, the main job is to develop such a method that the algorithm perceives that it is in a local optimal region and it is difficult to escape from there. There are two dimensions about the subject. The first one is being in a local optimal region and the second one is being unable to escape from there. The SA algorithm generates a neighboring solution and if it is a better solution, the algorithm passes to that solution; if it is an inferior solution, the algorithm passes to that solution according to the acceptance probability. If the number of inferior solutions in the recently generated neighboring solutions increases, it may be a sign to being in a local optimal region. If the number of inferior solutions in the recently generated neighboring solutions is very high, it may be a sign to being in a local optimal region and not passing to inferior solutions. If the algorithm generates and passes to an inferior solution, then the probability to generate a better solution increases and the number of inferior solutions decreases. On the other hand, the algorithm may be in a local optimal region, but if the acceptance probability is sufficiently high, it may escape from that region. But if the ratio of accepted inferior solutions in the whole inferior solutions in the recently generated solutions is very low, it may be a sign to understand that the temperature is not high enough to escape from that region.

The cooling schedule used in the algorithm is given below:

$Tem[i]=K/j$

where $Tem[i]$ is the temperature at iteration i, j is a counter that controls the temperature and K is a positive integer.

The values of *j* and *i* are equal to 1 at the first iteration; the initial temperature is *K*. Then the algorithm increases *i* and *j* by one, and performs the next iteration and so on. At each 100 iterations, the developed approach checks the number of inferior solutions in the recently generated 100 solutions. If this number (*NUMINF*) exceeds 90, the algorithm checks the temperature: whether it is high enough to escape from that region or not. Then it controls the number of accepted inferior solutions in the *NUMINF* inferior solutions. If this number (*NUMACC*) is less than 9, then the algorithm adjusts the temperature by adjusting j as follows:

$$j = (K)(NUMACC)/NUMINF \qquad \{if\ NUMACC = 0\ then\ j = 1)$$

Increasing *NUMINF* or decreasing *NUMACC* increases the probability of being in a local optimal region. By adjusting *j* according to the above formula, if *NUMACC* decreases or *NUMINF* increases the value of *j* decreases. Correspondingly, at that iteration (*i*) temperature (*Tem[i]*) increases and the acceptance probability and chance to escape from that region increases. An example of the cooling schedule of the developed ASA algorithms is given in Figure-4.10.

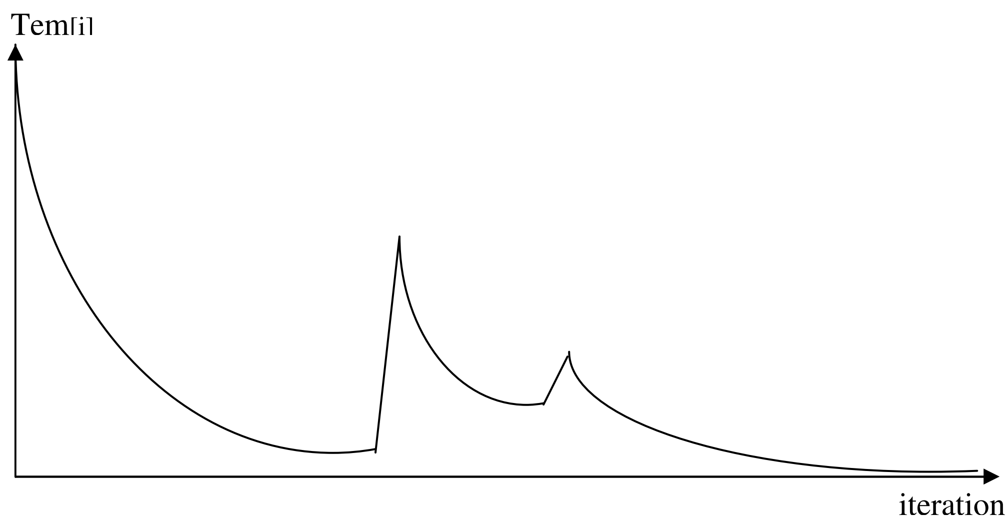


Figure 4.10 An example of cooling schedule of the developed ASAs

4.8.4 Construction of the Initial Solution

In real life, assembly lines generally include some zoning restrictions. Because of the zoning restrictions, while constructing a solution, we have to consider the list of stations that any task may be assigned to. As a result, at any iteration in the construction algorithm, we can not use only available tasks; we have to use the assignable tasks to the current station. Therefore, we have constructed a station-oriented and modified COMSOAL algorithm to generate a feasible starting solution. The algorithm first determines the available tasks from the precedence diagram. Then it chooses the assignable tasks among the available tasks by checking the zoning restrictions, the cycle time and the station time. After that, the algorithm takes a task randomly among the assignable tasks and assigns it to the current station. Then it updates the available and assignable tasks by considering the last assignment. If there is no assignable task, it passes to the next station. Because of the zoning restrictions, occasionally, there may be no assignable task, although the station is opened recently and empty. The modification on COMSOAL is about the zoning restrictions.

4.8.5 Evaluating the Solutions

4.8.5.1 Evaluating the Line Balances

Upon completing the COMSOAL routines, the algorithm passes to the ASA phases to improve the solution. Because the problem may be multi/mixed or single-model assembly line balancing problem and it is multi-objective, it requires using two ASA parts sequentially.

As it is mentioned in Chapter 2, there are two main approaches to balance the multi-model assembly lines. The first one is balancing the line separately for each model as a single-model assembly line balancing, while the second one is balancing the line as if it is a mixed-model assembly line.

When the first approach is accepted, the system uses the minimum number of stations for each model and avoids the costs related to the unused station at the period of that model's production. But, in this situation, the number of the common tasks assigned to different stations and the changes on the set of tasks assigned to the same station increase. Consequently, the setup costs and negative learning curve effect increase. When the batch sizes are very large, the advantages of this method dominate its disadvantages and, in general, this approach is adopted.

When the second approach is accepted, the problem is considered as a mixed-model assembly line balancing, and generally, by using the combined precedence diagram, a single balance is found for all models. With this approach, all common tasks are assigned to the same stations. When the production changes over to a new model, some tasks are extracted from the line and some others are added to the line. Hence, there still exists additional setup cost and learning curve effect, but it is minimized. Nevertheless, this time, the number of stations and the station slack times increase for each model. Furthermore, opportunity to increase smoothness and to minimize cycle time and their advantages can not be utilized. When the batch sizes are very small, the second approach is adopted, since the advantages of this approach generally dominate its disadvantages.

The first method assumes that the setup costs and the learning curve effects are negligible compared to the gain from balancing separately. On the other hand, the second method assumes that its disadvantages are negligible compared to its advantages. If the batch sizes are medium and none of the costs is negligible, balancing the line gets harder. In this situation, there exists challenging objectives. One of them is minimizing the number of stations while trying to maximize the common tasks assigned to the same station. The other one is minimizing the cycle time, while trying to maximize the common tasks assigned to the same station. Although it is possible to decrease the number of stations or the cycle time and to increase smoothness, common tasks may prevent the method from making these moves.

As it is mentioned in the previous parts, in order to minimize the cycle time or maximize smoothness, the number of stations and a feasible solution must be pre-determined. In addition, maximization of irregularity and maximization of smoothness are exactly opposites. So, they should be used separately. For these reasons, the proposed algorithm first tries to minimize the number of stations and uses maximization of irregularity while considering the common tasks and batch sizes. Then, it uses this solution as an input to the next ASA part and tries to minimize the cycle time and the total slack time, while maximizing the smoothness. The algorithm, at this stage, also takes the common tasks and batch sizes into account.

The objective functions used to evaluate the solutions in the first ASA (*Ffirst[x]*) and in the second ASA (*Fsecond[x]*) are given below:

$$Ffirst[x] = F1[x] + F3[x] + F5[x]$$
$$Fsecond[x] = F2[x] + F4[x] + F5[x]$$

where x is a line balance and,

F1[x] is the objective function used to minimize number of stations,

F2[x] is the objective function used to minimize cycle time,

F3[x] is the objective function used to maximize irregularity,

F4[x] is the objective function used to maximize smoothness,

F5[x] is the objective function used to maximize common tasks assigned to same station.

Because of the structure of the SA algorithm, the solutions are evaluated separately at the sequential ASA algorithms. But the whole problem is balancing the line and determining the best sequence. For single-model lines because the number of product models is one the sequencing problem drops. Similar to the single-model lines, because of the combined precedence diagram for mixed-model lines, the sequencing problem again drops. The best solution found for a model *i* is evaluated with the objective function of balancing model *i* ($Fmodel_i[x]$) which is given below:

$$Fmodel_i[x]=F2[x]+F4[x]+F5[x]$$

Here, *F2[x]* evaluates the solution according to the cycle time, number of used stations and batch sizes; *F4[x]* evaluates the solution according to the smoothness; *F5[x]* evaluates it according to the common tasks between the current model (*i*) and the previous model. Because *F1[x]* is identical with *F2[x]* and maximization of irregularity (*F3[x]*) is not really a desired objective, these two components are not used to evaluate the final balance of model *i*.

4.8.5.2 Evaluating the Sequences

The other problem is the sequencing problem. In order to evaluate the whole solution which consists of both the individual model balances and the sequence of these models, it is needed to use a more widespread objective function: *F[x]* which is given below:

$$F[x] = \sum_{\forall i \in K} Fmodel_i[x]$$

where *K* is the set of models of which batch size is greather than zero

For a single-model *i* (or mixed-model) line balancing, *F[x]* transforms to $Fmodel_i[x]$ (or $Fmodel_{combined}[x]$).

4.8.6 The Overall Methodology

The explained methodology is used to balance any type of assembly line. This methodology, consisting of the modified COMSOAL and two ASA algorithms to solve the multi-objective assembly line balancing problems, used as a main block and as an inner part of the complete algorithm. The external part of the algorithm adjusts the usage of the inner part. The external part determines the type of the assembly line, batch sizes of the models and the period of the production. If the assembly line is a single-model assembly line or the user wants to balance the line for a single-model, the external part computes the cycle time and runs the main part for this single-model only. Because of the minimization of the cycle time in the second ASA, the algorithm saves some time and the external part computes this time and reports it along with the assignments.

If the line is mixed-model assembly line, the algorithm uses the combined precedence diagram and finds a single common solution for all models.

If the line is multi-model assembly line, the external part first gets the batch sizes and the production period. Then it determines the first sequence of the models and runs the inner part for the first model in the sequence. The external part then computes the remaining time, calculates the cycle time and runs the inner part again for the next model in the sequence. After completing all models, the external part determines the next sequence and runs the inner part for all models once more. At the end, the algorithm finds the best sequence and all individual assignments.

If the line consists of some models with large batch sizes and some others with small batch sizes, the user may easily set the cost parameters and find a good solution suitable for this situation. If the line includes only the models with large batch sizes or small batch sizes, the user may balance the line as a single-model assembly line for all models with large batch sizes or as a mixed-model assembly line or he/she may adjust the cost parameters and find solutions between these two extremes. Furthermore, the firm may select some of the models to produce and the algorithm finds the best sequence and the individual assignments for only those selected models. Figure 4.11 shows the flowchart of the methodology and the pseudocode of the whole algorithm is given in Appendix D.

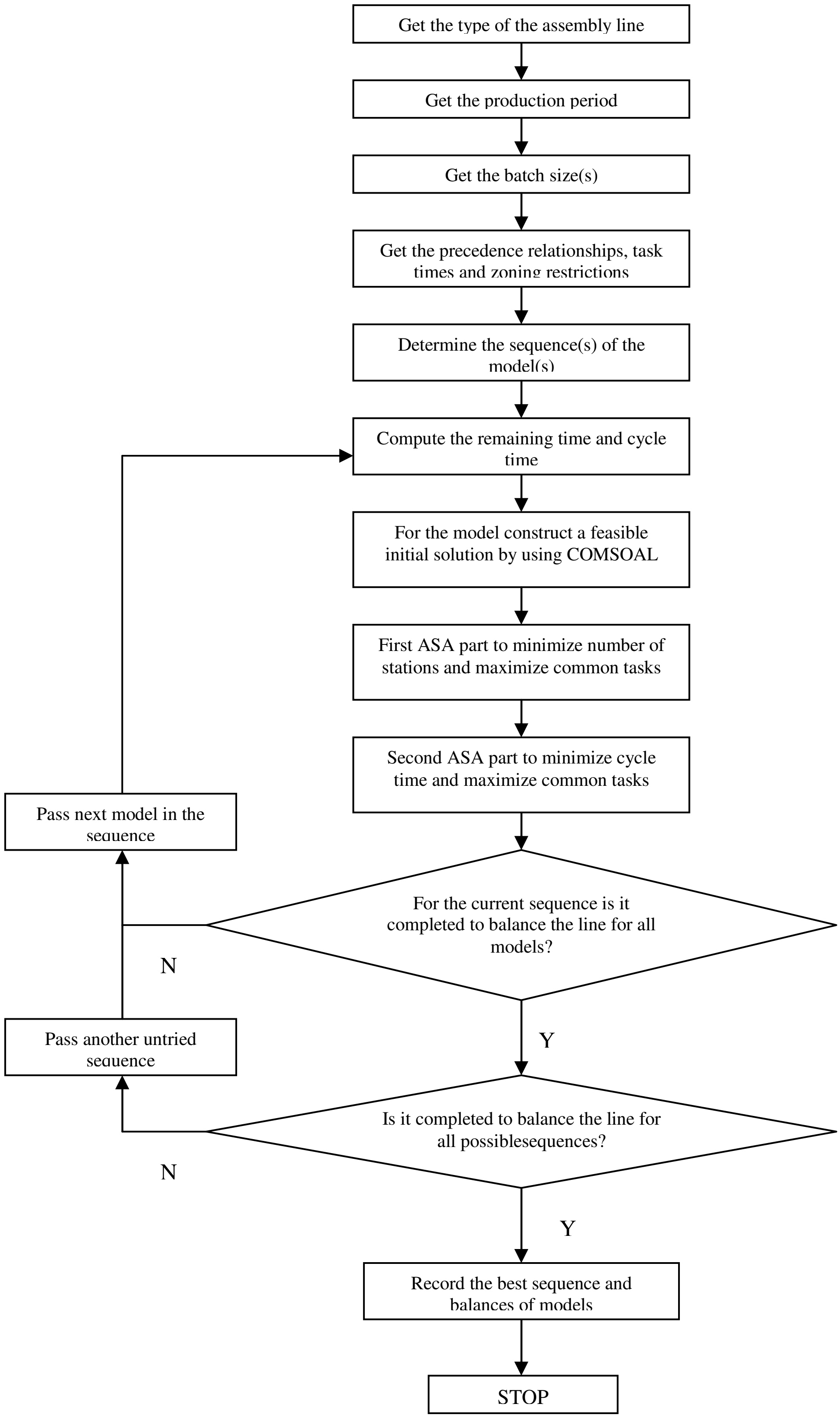


Figure 4.11 Flowchart of the algorithm

CHAPTER 5

EXPERIMENTAL ANALYSIS

5.1 Design of the Experiment

The proposed algorithm may be used to solve single, mixed or multi-model assembly line balancing problems. Furthermore, a problem may be solved by taking one or more objectives into account. Because the structure of the algorithm changes under different objective combination and assembly line type scenarios, the performance of the algorithm should be evaluated according to these scenarios.

There are five objective function components in the algorithm, but these objectives may be grouped in three classes. The first one is minimization of the number of used stations. Because the maximization of irregularity is sub objective to achieve minimization of the number of used stations and they are not conflicting objectives with each other, these two components may be considered as the first objective group. Similarly, the maximization of smoothness is sub objective to achieve minimization of cycle time and these two components may be considered as the second objective group. On the other hand, the maximization of common tasks which are assigned to the same station at the assembly of successive models is another objective class by itself. These three objectives are conflicting objectives with each other. One of the methods to deal with conflicting objectives is to take them into account successively. In this method, the problem is solved according to the first objective, then it is solved according to the next objective such that the previous solution is satisfied. Another method to deal with conflicting objectives is to give these objectives weights and to solve the problem according to these objectives simultaneously. The developed algorithm uses these two methods to overcome the difficulty of conflicting objectives. The first two objective groups are separated by using two ASA algorithms. The first ASA part tries to find the best solution according to the first and the third objective groups. On the other hand the second ASA part tries to find the best solution according to the second and the third objective groups such that the previous solution found in the first ASA part is satisfied.

The proposed algorithm solves the mixed-model assembly line balancing problems by using the combined precedence diagram method. This method transforms the problem to a single-model assembly line balancing problem. The third objective group is redundant when the problem is single-model or mixed-model assembly line balancing problem. Because the other two objective groups are used separately, for the single-model and mixed-model assembly line balancing problems, the performance of the first ASA part may be evaluated according to the minimization of the number of used stations and the performance of the second ASA part may be evaluated according to the minimization of cycle time. For this purpose, the test problems of SALBP-I from the literature are used to evaluate the performance of the first ASA part and those of SALBP-II are used to evaluate the performance of the second ASA part. Then the algorithm is tested on the case problem and it is run 10 times, and the results are analyzed. For the single and mixed-model assembly line balancing problems, the experimental analysis is explained in the following sections. The analysis about the multi-model assembly line balancing problems is explained in the following sections.

5.2 Single and Mixed-Model Assembly Line Balancing Problems

5.2.1 Test Problems

5.2.1.1 The First ASA Part

First the algorithm is tested on the SALBP-I problems in the literature. For this purpose the optimally solved problems from the sets of Talbot et. al. (1986), Hoffmann (1990, 1992) and Scholl (1993, 1995) are used. Table E.1 shows the test problems, optimum solutions and the best solutions found with the proposed algorithm.

Descriptive statistics are used to evaluate the performance of the algorithm on the test problems. Deviations are computed according to the following formula:

Deviation = (Solution Found-Optimum Solution)/Optimum Solution

Table E.2 shows that the algorithm is tested on 25 problem groups. Table E.1 shows the problems included in these groups. For example, Arcus1 is one of the problem groups and it consists of 16 problems with different cycle times. The columns of Table E.2 show the statistics of deviations of these 16 problems.

The algorithm is used to solve 265 test problems. The optimum solutions are found for 237 test problems (89.4%) by using the algorithm. 22 problems (8.3%) are solved with less than 5% deviations and the remaining 6 problems (2.3%) are solved with more than 5% deviations. The average of the deviations is 0.45%.

Table E.2 shows that the proposed algorithm has solved all of the problems optimally for the 18 groups. It solved at least one problem from each group optimally. The maximum deviation is 14%. For each one of the problem groups, the average of the deviations is less than 5%.

According to the results the performance of the heuristic method is considered to be satisfactory. The given statistics show that the proposed algorithm is very good for SALBP-I.

5.2.1.2 The Second ASA Part

The algorithm is tested on the SALBP-II problems in the literature. For this purpose the optimally solved problems from the sets of Data set 1 and Data set 2 (Scholl, 1993; 1999) are used. Table E.3 shows the test problems, optimum solutions and the best solutions found with the proposed algorithm.

Table E.4 shows that the algorithm is tested on 17 problem groups. Table E.3 gives detailed problems included in these groups.

Table E.3 shows that the algorithm is used to solve 286 test problems. The optimum solution is found for 213 test problems (74.4%) by the algorithm. All of the remaining problems (25.6%) are solved with less than 3% deviation. The average of the deviations is 0.16%.

Table E.4 shows that the proposed algorithm has solved all of the problems optimally for the 7 groups. It has solved at least one problem from each group optimally. The maximum value of deviations is 2.15%. For each one of the problem groups, the average of the deviations is less than 0.7%.

According to the given statistics, the proposed algorithm is considered to be satisfactory on SALBP-II.

The experiments on the test problems showed us that the performance of the first ASA part is very good at the minimization of the number of used stations and the performance of the second ASA part is very good at the minimization of cycle time, when the third objective group which is conflicting with the first two objective groups is neglected. The performance of the algorithm is very good at single-model assembly line balancing problems. Furthermore, because we transform the mixed-model problems to single-model problems by using combined precedence diagram method, the performance of the algorithm is also very good at mixed-model assembly line balancing problems at our case study. After these experiments the algorithm is tested on the case problem.

5.2.2 The Case Problem

Two factors are defined for these experiments: model and batch size. Levels of the model are Model1, Model2, Model3, Model4 and Mixed. Levels of the production amounts are 300, 500 and 600 units per shift; during the production period a single model, or more then one model with mixed-model type, is produced with batch size 300, 500 and 600 units. Then the response variables are used to analyze the effects of the factors on the performance of the algorithm. Response variables are the number of used stations (*m*), cycle time (*C*), total slack time (*TST*) and deviations from the theoretical optimums of the number of stations (*Dm*) and cycle time (*DC*) at the beginning of the run and at the end of the run. Table 5.1 shows the average and standard deviation values of the response variables for 10 runs.

Table 5.1 Average values and Standard Deviation values of response variables of 10 runs of SALB and MiALB

			Batch Size								
			300			500			600		
			initial	final	Impr.	initial	final	Impr.	initial	final	Impr.
Model1	*m*	Avg	25	21.4	0.144	34	31.1	0.0853	38.3	35.1	0.0836
		Std	0	0.5164		0	0.3162		0.6749	0.3162	
	C	Avg	84	77.78	0.074	50.4	49.62	0.0155	42	41.76	0.0057
		Std	0	3.0695		7E-15	0.5412		0	0.2836	
	TST	Avg	441	41.52	0.9059	256.2	90.47	0.6469	201.6	60.15	0.7016
		Std	0	20.149		6E-14	21.264		28.348	7.8589	
	Dm	Avg	5.25	0.5295	0.8991	5.0833	1.8206	0.6418	4.8	1.4408	0.6998
		Std	0	0.2429		9E-16	0.4168		0.6749	0.1936	
	DC	Avg	17.64	1.9444	0.8898	7.5353	2.9046	0.6145	5.2538	1.7124	0.6741
		Std	4E-15	0.9544		2E-15	0.6528		0.6275	0.2093	
Model2	*m*	Avg	25	22.6	0.096	35	32.1	0.0829	39.8	36.7	0.0779
		Std	0	0.6992		0	0.3162		0.4216	0.483	
	C	Avg	84	76.8	0.0857	50.4	49.41	0.0196	42	41.53	0.0112
		Std	0	2.2959		7E-15	0.3348		0	0.4668	
	TST	Avg	376.4	54.34	0.8556	242	70.01	0.7107	200	55.23	0.7239
		Std	6E-14	40.975		0	18.616		17.709	14.596	
	Dm	Avg	4.481	0.7069	0.8422	4.8016	1.4157	0.7052	4.7619	1.3299	0.7207
		Std	0	0.5358		9E-16	0.3717		0.4216	0.3483	
	DC	Avg	15.06	2.372	0.8425	6.9143	2.1767	0.6852	5.0213	1.5018	0.7009
		Std	2E-15	1.6993		2E-15	0.551		0.3977	0.3843	
Model3	*m*	Avg	25	21.3	0.148	34.9	31.2	0.106	38.1	35.3	0.0735
		Std	0	0.483		0.3162	0.4216		0.3162	0.483	
	C	Avg	84	79.87	0.0492	50.4	49.26	0.0226	42	41.81	0.0045
		Std	0	2.4909		7E-15	0.9395		0	0.3247	
	TST	Avg	416.4	41.55	0.9002	276.96	61.42	0.7782	168.6	45.36	0.731
		Std	0	24.282		15.938	8.7472		13.282	17.339	
	Dm	Avg	4.957	0.518	0.8955	5.4952	1.2456	0.7733	4.0143	1.0851	0.7297
		Std	9E-16	0.2968		0.3162	0.1646		0.3162	0.4143	
	DC	Avg	16.66	1.9445	0.8833	7.9326	1.9696	0.7517	4.4229	1.28	0.7106
		Std	4E-15	1.1259		0.3938	0.2883		0.3055	0.4697	
Model4	*m*	Avg	26	23.5	0.0962	37.5	34.2	0.088	42.1	39.6	0.0594
		Std	0	0.527		0.7071	0.4216		0.9944	0.5164	
	C	Avg	84	79.83	0.0496	50.4	49.82	0.0115	42	41.66	0.0081
		Std	0	2.4904		7E-15	0.7052		0	0.3893	
	TST	Avg	344	59.96	0.8257	251.6	68.72	0.7269	180.2	63.64	0.6468
		Std	0	19.137		35.638	14.286		41.766	14.63	
	Dm	Avg	4.095	0.7497	0.8169	4.9921	1.3785	0.7239	4.2905	1.5283	0.6438
		Std	0	0.2367		0.7071	0.283		0.9944	0.3523	
	DC	Avg	13.23	2.5503	0.8072	6.6956	2.0079	0.7001	4.2615	1.6038	0.6237
		Std	0	0.8055		0.81	0.4011		0.882	0.3526	
Mixed	*m*	Avg	27.6	24.4	0.1159	39.2	35.3	0.0995	43.4	41.2	0.0507
		Std	0.516	0.5164		0.4216	0.483		0.5164	0.4216	
	C	Avg	84	79.04	0.059	50.4	50.01	0.0077	42	41.64	0.0086
		Std	0	2.8175		7E-15	0.5724		0	0.3718	
	TST	Avg	406.8	45.52	0.8881	265.68	57.46	0.7837	163.2	58	0.6446
		Std	43.38	20.435		21.251	10.206		21.689	7.7554	
	Dm	Avg	4.843	0.5709	0.8821	5.2714	1.1503	0.7818	3.8857	1.3935	0.6414
		Std	0.516	0.2385		0.4216	0.2126		0.5164	0.1924	
	DC	Avg	14.72	1.8724	0.8728	6.7731	1.6252	0.7601	3.7555	1.4067	0.6254
		Std	1.306	0.8625		0.4622	0.2677		0.453	0.1775	
Gen. Avg	*m*	Avg	25.72	22.64	0.12	36.12	32.78	0.092	40.34	37.58	0.069
	C	Avg	84	78.664	0.0635	50.4	49.624	0.015	42	41.68	0.0076
	TST	Avg	396.92	48.578	0.875	258.49	69.616	0.729	182.72	56.476	0.689
	Dm	Avg	4.7252	0.615	0.867	5.1287	1.402	0.725	4.3505	1.3555	0.687
	DC	Avg	15.46	2.1367	0.859	7.17	2.135	0.702	4.543	1.5009	0.667

The cycle time is computed as the production period (7 hours=a shift) divided by the total production amount. If the batch size increases, the initial value of cycle time decreases. If batch size is 300, 500 or 600 units, the corresponding initial values of cycle time are 84, 50.4 or 42 seconds. Improvement values are computed for a response variable as follows:

Improvement = (initial value-final value)/initial value

For each model, but Model1, improvement in number of stations (*m*) decreases, when batch size increases or initial value of cycle time decreases. General averages show that the improvement in *m* decreases, when batch size increases. It means that the performance of the first ASA part increases, when the initial cycle time increases.

For each model, but Mixed, improvement in *C* decreases, when batch size increases. If the batch size increases, the initial cycle time decreases and the number of stations needed increases. The general average values of *m* are 22.64, 32.78 and 37.58. When the number of stations increases, it is expected that the final value of cycle time would be lower and the improvement in the cycle time would increase. But results show the opposite of it; the improvement in *C* decreases when the number of stations increases.

For Model3, Model4 and Mixed, the improvement in *TST* decreases when batch size increases. For Model1 and Model2, the improvement in *TST* fluctuates, but in general, it decreases when the initial cycle time decreases. Because the improvement in *m* and *C* decreases, the result about *TST* is expected.

The results summarized above show that improvement in *m*, *C* and *TST* decreases, when the initial cycle time decreases, or equivalently, when the amount of production per shift increases. Consequently, as the initial cycle time increases, the performance of the algorithm gets better.

Deviation from the lower bound of the number of stations (*Dm*) is computed as:

$Dm = (TST)/C$

The integer part of *Dm* shows the maximum number by which the number of stations may be decreased to reach the theoretical minimum at that cycle time. The interesting result is that the integer part of *Dm* value with 300 batch size is zero for each model. It shows that the algorithm finds the optimum solutions. This value increases to 1 with 500 and 600 batch sizes. It means that the solution found deviates from the lower bound by one station only. In general, the improvement in *Dm* decreases, when the batch size increases.

Deviation from the lower bound of cycle time (*DC*) is computed according to the following formula:

$DC = (TST)/m$

If cycle time may be decreased by *DC* units, the perfect balance is obtained. The results show that *DC* value fluctuates with the batch size for individual models, but in general averages it decreases, when the batch size increases. Improvement in *DC* decreases when the initial cycle time decreases. At the end of the runs deviations from the lower bound of cycle time do not exceed 2 seconds.

For each model but Mixed, at the end of the run, the standard deviation of *m* is the smallest at 500 units per shift. The biggest value of standard deviations of *m* is 0.699 stations. For each model but Model1, at the end of the run, the standard deviation of *C* decreases, when the batch size increases. The biggest value of standard deviations of *C* is 3.069 seconds. For 500 units of production, this value decreases to 0.9 seconds. Standard deviation of *TST* fluctuates with batch sizes and models. Also the standard deviation of *Dm* fluctuates with batch sizes and models. For each model, standard deviation of *DC* decreases, when the batch size increases.

The most important results are about *Dm* and *DC* values, because these values give an opinion about the quality of the solutions. The deviations from the lower bound do not exceed 3% for the number of stations and 4% for the cycle time. Standard deviations of *Dm* do not exceed 0.53 stations and standard deviations of *DC* do not exceed 1.699 seconds. According to the results the algorithm finds very good solutions for the case problem, because the deviations from the lower bounds are less than 5%. Since the current amount of production per shift is 500, the convergence graphics with 500 batch size are given in Appendix E.

5.3 Multi-Model Assembly Line Balancing Problems

When the problem is multi-model assembly line balancing problem, the third objective group is to be taken into account which conflicts with the first two objectives. If the weight of the third objective is negligible, the assignments of the common tasks to the different stations get free, transforming the problem to a SALBP for each model. The performance of the algorithm is examined in the previous sections. On the other hand, if the weight of the third objective group is very high, it forces the algorithm to assign all of the common tasks to the same stations. In this situation, the problem shifts to a MiALBP which makes assignments by using the combined precedence diagram and obtains a single balance for all models. The performance of the algorithm is also studied in the previous sections in this situation. For

MuALBP, the problem has to be solved as a MuALBP. The test problems for MuALBP which consist of conflicting objectives could not be obtained from the literature. The analysis is made on the case problem. The problem is solved with three different weights of the third objective. For each one of the weights, the algorithm is run 10 times and the results are evaluated. The percentages of the number of common tasks which are assigned to the same stations and the effects of the third objective to the other objectives are analyzed.

The weights of the third objective group are low, intermediate and high. The daily batch sizes of the Model1, Model2, Model3 and Model4 are 350, 75, 50 and 25 units, respectively. At low level of the weight of the third objective, the contribution of the third objective is similar to the contributions of the other objectives for Model4. At intermediate level of the weight of the third objective, the contribution of the third objective is similar to the contributions of the other objectives for Model2 and it is similar to the contributions of the other objectives for Model1 at the high level of the weight of the third objective.

Table E.5 shows the sequences of the models and number of common tasks between models. Tables E.6, E.7 and E.8 show the numbers of common tasks that are assigned to the same stations at the successive models and their percentages. The values are average of 10 runs for each level of the third objective. For low, intermediate and high level of the weight of the third objective, the overall averages of percentages are 47.88%, 88.54% and 94%, respectively. These results indicate that the algorithm is sensitive to the third objective. The results show that when the weight of the third objective is at intermediate or higher levels, the algorithm assigns approximately 90% of the common tasks to the same stations.

Total slack time, number of used stations and cycle time values are recorded throughout the runs. Table 5.2 shows the average values of number of used stations (*m*), cycle time (*C*), total slack time (*TST*) and deviations from the lower bound of number of stations (*Tm*) and cycle time (*TC*) at the beginning of the run and at the end of the run.

Table 5.2 Average values of response variables of 10 runs for MuALB

		Low	Intermediate	High
Beginning	*m*	34.41146	34.87604	34.26458
	C	53.49594	52.07615	53.84875
	TST	287.2238	279.0299	286.2759
	Dm	5.371893	5.350897	5.315542
	DC	8.401711	8.015751	8.40985
End	*m*	31.18333	32.45313	34.16458
	C	51.95479	51.30927	50.97438
	TST	75.47677	133.0051	212.2435
	Dm	1.474284	2.578629	4.133182
	DC	2.417654	4.110379	6.17753
	Common	0.4788	0.88541	0.94002
Impr. In m = (mb-me)/mb		0.094081	0.069104	0.00027
Impr. In C = (Cb-Ce)/Cb		0.028443	0.014781	0.049083
Imp. in TST = (TSTb-TSTe)/TSTb		0.730645	0.524464	0.264433

Note: mb, Cb and TSTb represent the beginning values of m, C and TST. me, Ce and TSTe represent the end values of *m*, *C* and *TST*.

According to the results shown in Table 5.2 the increment in the weight of the third objective has negative effects on the other objectives. Initial values of *m*, *C* and *TST* are approximately 34, 52 and 280, respectively. On the other hand, final values of m are 31, 32, 34 for low, intermediate and high levels. Because the final value of *m* increases, it is expected that the final value of *C* decreases; but according to the results there is no meaningful decrease in *C*. Final values of *TST* are 75, 133 and 212 seconds. It increases according to the increment in the weight of the third objective. Deviations from the lower bounds increase for both of *m* and *C*. Each of the improvement values decreases, when the weight increases. But success in the third objective increases from 48% to 89% and then to 94%.

Tables from E.9 to E.32 in the Appendix E show the detailed results about the first, second, third and the last model in a sequence; Model1, Model2, Model3 and Model4; *m*, *C* and *TST*. General results obtained from these detailed results are summarized in Table 5.2 above.

5.4 Current Line Balance and Suggested Line Balances

According to the current balance, for Model1, Model2 and Model3 the number of used stations is 36, while it is 37 for Model4. When the line passes to produce Model4, station numbers of nine tasks change. As it is mentioned in Chapter3, the system finds this solution in a week, but the suggested method uses computers and balances the line in some minutes for the mixed-model case and in a few hours for multi-model case. Daily productions of Model1, Model2, Model3 and Model4 are taken as 350, 75, 50 and 25 units, respectively. On the other hand, in this study, the balancing problem of the company is solved according to the multi-model case. According to the suggested solution, numbers of the used stations for Model1, Model2, Model3 and Model4 are 31, 30, 30 and 31, respectively. Daily production amounts are the same. Production sequence is Model1, Model3, Model2, Model4. Stations of 43, 22 and 18 tasks change, when the system passes from Model1 to Model3, from Model3 to Model2 and from Model2 to Model4, respectively. If the system prefers to balance the line as a mixed-model line, the proposed method finds a solution with the number of used stations as 35, and all of the common tasks being assigned to the same stations. The current assignments and the suggested assignments are given in Appendix F.

5.5 Run Times of the Experiments

The algorithm is coded in Turbo Pascal Windows and the runs are made in a computer specifications of which are Intel Pentium 4, CPU 3 GHz, 512 MB RAM.

The algorithm is run for 10 minutes for each of the test problems and the best solutions are recorded.

For the experimental runs about the case problem, the algorithm is run for a limited number of iterations; 10000 iterations for each ASA part. The computer completes a run for any model in about 1-1.5 minutes. i.e., the algorithm finishes the run in 1-1.5 minutes for single-model or mixed-model balancing cases. For the multi-model case, the algorithm solves an individual single-model balancing for all sequences and for each of the models in a sequence. Because the case consists of 4 models, the algorithm makes 96 (4*4!) individual balancing and the whole run is completed in approximately 96-144 minutes.

CHAPTER 6

CONCLUSION AND FURTHER RESEARCH ISSUES

In this study, we deal with a real-life assembly line balancing problem and propose an approach which solves each type of SALBP, MiALBP and MuALBP with zoning restrictions. The proposed algorithm solves multi-objective assembly line balancing problems as well. Because the proposed algorithm has a flexible structure, it may be used to solve each type of assembly line balancing problems, furthermore, it is also appropriate to solve harder problems, real-life problems because it considers different objectives and zoning restrictions.

When the problem includes more than one and conflicting objectives, it gets harder to solve the problem. Assembly line balancing problems, especially multi/mixed model assembly line balancing problems, are complex problems, and generally consist of more than one conflicting objectives. Number of used stations, cycle time, common tasks among models, setup cost of passing from production of a model to another one's, etc. are some of the factors that affect the solution of the assembly line balancing problems.

Especially for the multi model assembly lines, sequencing arises as another problem besides the line balancing problem. Because the common tasks between sequential models change with respect to the models, it becomes important to determine the best sequence. If so, without balancing the line for each model, determining the true sequence of the models becomes another problem.

Most of the real-life problems are complex ones and consist of zoning restrictions, multi-model or mixed-model situations, conflicting objectives etc. which make the problem even harder. Although the real-life problems consist of these complexities most of the studies in the literature are about SALBPs. In this study, we attempt to solve a real-life multi-objective multi-model assembly line balancing problem with many zoning restrictions for which there is as yet no optimum-seeking algorithm in the literature. Because of these complexities of the problem, we have constructed a flexible heuristic algorithm and used to solve it. The developed approach is proposed to solve such complex assembly line balancing problems.

The developed algorithm uses a modified COMSOAL algorithm to construct an initial solution and two sequential ASA algorithms to improve the solution. To solve MuALBPs, the algorithm uses five objective function components to evaluate the solutions, regarding the three conflicting objectives. The first ASA algorithm tries to minimize the number of stations while trying to maximize the number of common tasks which are assigned to the same stations. The second ASA algorithm tries to minimize the cycle time while trying to maximize the number of common tasks assigned to the same stations by considering the batch sizes as well as the first ASA algorithm's results. Then the algorithm passes to the next models and next sequences. At the end of the run, the algorithm finds individual balances for each model and the best sequence of the models. To solve MiALBPs, the algorithm uses the combined precedence diagram method. Because the algorithm finds a single balance for all models, the sequencing problem and therefore the objective of maximization of number of common tasks which are assigned to the same stations at the sequential models drop. Thus as well as the SALBPs for the MiALBPs the first ASA algorithm tries to minimize only the number of used stations and the second ASA algorithm tries to minimize only the cycle time.

In this study, we have tested the proposed algorithm on test problems from the literature and on the case problem as well. For each type of the assembly line balancing problem, the experimental results are analyzed separately. The results may be summarized as follows:

The algorithm is tested on 265 SALBP-I problems from the literature. The optimum solution is found in 237 of the 265 test problems (89.4%) by the algorithm. On the average, for any cycle time, the proposed algorithm solves the problem with 0.45% deviation from the optimum solution. The given statistics show that the proposed algorithm is very good on SALBP-I. The algorithm is also tested to solve 286 SALBP-II test problems. The optimum solution is found in 213 of the 286 test problems (74.4%) by the algorithm. The proposed algorithm is very good on SALBP-II as well.

The algorithm is tested on the case problem for single-model and mixed model cases. According to the results the algorithm finds very good solutions for the case problem. The deviations from the lower bound does not exceed 3% in the number of stations and 4% in the cycle time. The solution for the case problem may be the optimum solution, but theoretically the number of stations may be decreased by ‘1’, when the total amount of daily production increases. On the other hand, if the total amount of daily production increases, i.e. the initial cycle time decreases, the deviation from the theoretical minimum (lower bound) of the cycle time decreases. The deviation from the lower bound does not exceed 2 seconds (4%).

The algorithm is finally tested on the case problem for the multi-model case. As it is expected, the increase in the weight of the ‘common tasks’ objective affects the other objectives adversely; if the weight is increased, the deviations from the lower bounds increases up to 4 stations and 6.17 seconds. But the percentage of the common tasks that are assigned to the same stations increases to 94%.

At the end of this study, some worthwhile contributions to the company can be stated as follows:

Task list has been updated and corrected. The tasks which are performed on the line but are not defined yet are defined and coded. The tasks which were formerly performed more than once on the line, but coded and named once in the list, are defined and coded separately. Some automatically made tasks are defined and added to the list.

The assembly line and the models of the product are observed; precedence relationships diagram for each individual model and combined precedence relationships diagram are constructed. Zoning restrictions are determined.

A meta-heuristic approach is developed and computer program of the method is coded. Thus, the disadvantages of balancing the line manually are eradicated. It is possible to balance the line in some minutes for the mixed-model case or in some hours for the multi-model case for the assembly line under study.

According to the current balance in the plant, the number of stations is 36 for Model1, Model2 and Model3, and 37 for Model4. When the line passes to produce Model4, station numbers of 9 tasks change. Daily productions of Model1, Model2, Model3 and Model4 are 350, 75, 50 and 25 units, respectively. On the other hand, in this study, the balancing problem of the company is solved according to the multi-model case. According to our suggested solution, numbers of stations for Model1, Model2, Model3 and Model4 are 31, 30, 30 and 31, respectively. Daily production amounts are the same. Production sequence is Model1, Model3, Model2, Model4. Station numbers of 17, 32 and 16 tasks change when the system passes from Model1 to Model3, from Model3 to Model2 and from Model2 to Model4. If the system prefers to balance the line as a mixed-model line, the proposed method finds a solution with 35 stations.

The contributions of this study to the literature may be summarized as follows:

We offer to use an objective function that maximizes the irregularity among station times (workloads) in order to minimize the number of used stations. Similarly, we offer an objective function that maximizes the smoothness in order to minimize the cycle time.

We use an original cooling mechanism in the Adaptive Simulated Annealing algorithms.

Further research issues:

There are a few studies in the literature that solves multi-objective MiALBPs but unfortunately we have not found a study that solves multi-objective MuALBPs. In this study we solve any type of assembly line balancing problem by considering multiple objectives and solve the sequencing problem in the MuALBPs.

Although the proposed algorithm has a flexible structure and solves any type of assembly line balancing problem, there may be some further improvements in the algorithm. The most important drawback of the algorithm is that currently the algorithm can solve multi-model assembly line balancing problems, if the number of models is less than or equal to 4. With some more studies this limit may be eradicated. But on the other hand, for the multi-model cases the algorithm solves the sequencing problem by an enumerative manner and solves $n*n!$ individual balancing problems for n models. When the number of models increases, solution time may be very long. In order to prevent this disadvantage, a heuristic sequence determination method may be developed which may use the similarities among the models, common task numbers, and batch sizes etc..

The performance of the proposed methodology on the single and mixed-model assembly line balancing problems is evaluated with the experiments made on the case problem. Three different daily production levels are used in these experiments. It may be more appropriate to make further experiments with more than three different daily production levels to understand the changes of the performance of the algorithm according to the chances in the production amounts.

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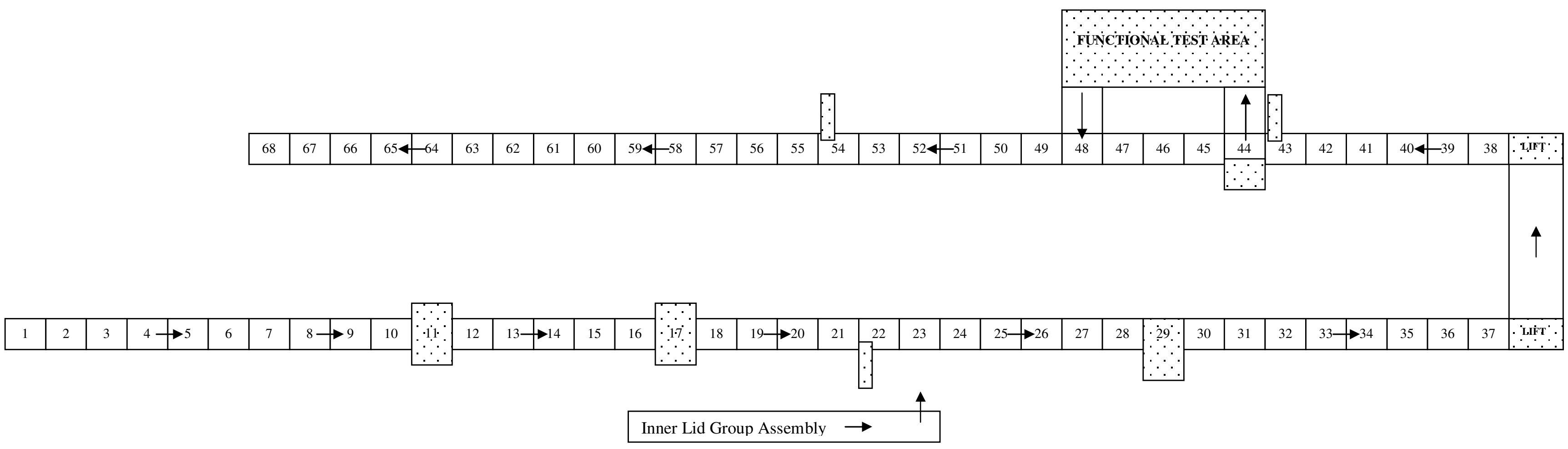
APPENDIX A

SKETCH OF THE ASSEMBLY LINE OF THE FIRM



1,...,68: workstations

Product flow direction

Special equipments

Figure A.1 Sketch of the Assembly Line of the Firm

APPENDIX B

TASK LIST

Table B.1 Task List

TASK CODE	TASK DEFINITION	TASK TIME (SEC)	MODEL1	MODEL2	MODEL3	MODEL4
1	Put the main part on to the pallet	13	1	1	1	1
2	Attach the plastic support part of back leg to the right frame	3.5	1	1	1	1
3	Attach the plastic support part of back leg to the left frame	3.5	1	1	1	1
4	fix the sheet iron of left leg to the frame with 3 screws	14.6	1	1	1	1
5	fix the sheet iron of right leg to the frame with 3 screws	14.6	1	1	1	1
6	fix the sheet iron of hanger of motor to the frame with 2 screws	12.5	1	1	1	1
7	oil the right reel of hinge	2.5	1	1	1	1
8	attach the right reel of hinge to its handle	3.1	1	1	1	1
9	nail the rondela to the right reel	4.1	1	1	1	1
10	put the fan group to the frame and fix it from the bottom with 2 screws	12	0	0	0	1
11	fix the fan group to the frame from the side with 2 screws	10	0	0	0	1
12	turn the pallet 90 degree	0	1	1	1	1
13	take the group of reservoir from the conveyor and assembly the gasket to the reservoir	6.4	1	1	1	1
14	oil the gasket and reservoir	3.5	1	1	1	1
15	put the reservoir into the fixture	2	1	1	1	1
16	put the group of reservoir to the main part by using piston	2.1	1	1	1	1
17	attach the support part of colander to the reservoir and control that it is set	4.5	1	1	1	1
18	fix the group of reservoir to the main part with 4 screws	14.5	1	1	1	1
19	put the U strafor to the right frame	3.5	0	1	1	1
20	turn the pallet 90 degree	0	1	1	1	1
21	set the circulation motor to the reservoir and tighten the clamp	8.9	1	1	1	1
22	attach the hose of heater-motor and tighten the clamp	6.5	1	1	1	1
23	fixate the circulation motor by using cover of motor	3.6	1	1	1	1
24	put the U strafor to the left frame	3.5	0	1	1	1
25	attach the long hose (having string) to the valve (3 outlets)	4	1	1	1	1
26	tighten the clamp which is attached to the hose (having string)	3.6	1	1	1	1

Table B.1 (Continued)

27	oil the left reel of hinge	2.5	1	1	1	1
28	attach the left reel of hinge to its handle	3.1	1	1	1	1
29	nail the rondela to the left reel	4.1	1	1	1	1
30	set the salt box to the main part	3	1	1	1	1
31	put the nut of salt box from inside of the main part manually	4.2	1	1	1	1
32	tighten the nut of salt box by using special equipment	8	1	1	1	1
33	Attach the 4. transparent hose to the salt box	4.5	1	1	0	0
34	tighten the clamp of 4. transparent hose	4.5	1	1	0	0
35	Attach the group of counter to the back frame	5.6	1	1	1	1
36	set the group of water pocket to the main part	3.5	1	1	1	1
37	set the nails of the water pocket to the frame	4	1	1	1	1
38	spread the soap to the outlets of the water pocket	3.5	1	1	1	1
39	Attach two parts of new water pocket and salt box to each other	9.5	0	0	1	1
40	put two O-RINGs to salt box if the water pocket is new model	7.2	0	0	1	1
41	Attach a clamp to the 4. transparent hose	3.5	1	1	0	0
42	link the 4. transparent hose to the reservoir	4.5	1	1	0	0
43	tighten the clamp of 4. transparent hose	4.5	1	1	0	0
44	bind a sponge to a side of salt box if the water pocket is new model	11	0	0	1	1
45	tie the thin and thick transparent hoses to the frame by using a plastic tie	6	1	1	1	1
46	fixate an adjustable foot to the part of right back leg	3.8	0	1	1	1
47	fixate an adjustable foot to the part of left back leg	3.8	0	1	1	1
48	fixate an adjustable foot to the sheet iron of right front foot	3.8	1	1	1	1
49	fixate an adjustable foot to the sheet iron of left front foot	3.8	1	1	1	1
50	set the nail of fan to the sheet iron and adjust the outlet of the fan	7	0	0	0	1
51	set the outlet of the fan onto the main part and fix the cover of fan to the main part by using a special equipment	11	0	0	0	1
52	attach a clamp to the hose which will be connected to the fan	2.5	0	0	0	1
53	connect the hose to the fan	3.5	0	0	0	1
54	tighten the clamp of the hose of fan	3.5	0	0	0	1
55	attach a hose to the pipe of fan	3	0	0	0	1
56	tie the hose which is attached to the pipe of fan to the front upper frame	4.5	0	0	0	1
57	oil the pin of right hinge	2	1	1	1	1
58	oil the pin of left hinge	2	1	1	1	1
59	put the arm of left hinge to the sheet iron	2.5	1	1	1	1
60	put the arm of right hinge to the sheet iron	2.5	1	1	1	1
61	fixate the water pocket to the main part by using cover of air pocket	10.7	1	1	1	1
62	set a string to the right reel of hinge	4.3	1	1	1	1
63	set a string to the left reel of hinge	4.3	1	1	1	1

Table B.1 (Continued)

64	attach the group of pipe of upper spray to the main part	5.9	1	0	0	0
65	attach the group of upper spray to the main part and fix it	4.9	0	1	1	1
66	set the sheet iron of left rail to the reels	2.9	1	1	1	1
67	set the sheet iron of right rail to the reels	2.9	1	1	1	1
68	attach the cover of right rail from the back	4	1	1	1	1
69	attach the cover of left rail from the back	4	1	1	1	1
70	attach the bottom propeller to the pump reservoir	2.7	1	1	1	1
71	peel the foil which is bind to the frame	5	1	1	1	1
72	erect the main part	C	1	1	1	1
73	set the handle of motor card to the main part	5.5	0	0	0	1
74	attach two screws to the handle of motor card	9.3	0	0	0	1
75	attach a screw to the group	4.2	1	1	1	0
76	attach the part of the lock	4.5	1	1	1	1
77	spread the soap to the sheet iron of gasket	3.9	1	1	1	1
78	attach two covers to the sheet iron of gasket	8	1	1	1	1
79	attach the gasket of the lid to its sheet iron manually	21	1	1	1	1
80	tighten the bottom part of sheet iron of gasket of the lid by using hammer	1.5	1	1	1	1
81	set the handle of spring to the right frame	2.5	1	1	1	1
82	attach the spring to the right spring handle	1.2	1	1	1	1
83	take the group of inner lid from the conveyor and put it onto the arms of hinge	6.1	1	1	1	1
84	fix the left arm of hinge to the inner lid with 2 screws	7.8	1	1	1	1
85	fix the right arm of hinge to the inner lid with 2 screws	7.8	1	1	1	1
86	close the inner lid which is screwed	2.5	1	1	1	1
87	stretch the right spring and connect it to the string	4.2	1	1	1	1
88	stretch the left spring and connect it to the string	4.2	1	1	1	1
89	set the handle of spring to the left frame	2.5	1	1	1	1
90	attach the spring to the left spring handle	1.8	1	1	1	1
91	put the support sheet iron onto the arms of hinge	2.3	1	1	1	1
92	fix the support sheet iron to the arms of hinge with a screw	3.7	1	1	1	1
93	fix the support sheet iron to the arms of hinge with a screw	3.7	1	1	1	1
94	fix the support sheet iron with a screw	3.7	1	1	1	1
95	fix the cable of earth to the support sheet iron with a screw	5.3	1	1	1	1
96	pass the hose of flusher from the hook of heater-reservoir hose	2	1	1	1	1
97	attach the other end of the hose of flusher to the buoy	7.4	1	1	1	1
98	tie the 2. hose of flusher to the buoy	5.5	1	1	1	1
99	attach the polisher switch to the detergent box	3.8	1	1	1	1
100	attach a cable to the detergent box	3.9	1	1	0	0
101	attach a isolater to the detergent box cable	3	1	1	0	0
102	attach a cable to the detergent box	3.9	1	1	1	0
103	set the support strafor to the support sheet iron	2.6	1	1	1	1
104	fix the strafor to the sheet iron by tighten the sheet iron	4.5	1	1	1	1

Table B.1 (Continued)

105	attach a cable tie to detergent box and tie the cable	8.5	1	0	1	0
106	open the lid	0.5	1	1	1	1
107	attach the sound gasket to the front upper support sheet iron	7.1	1	1	1	1
108	pass the group of cable from the upper side of "s" hose	5.5	1	1	1	1
109	turn the pallet	3	1	1	1	1
110	attach a cable to the switch of salt box	4.5	1	1	1	1
111	attach 2 cables to the buoy	8.5	1	1	1	1
112	attach a cable to the buoy	4.5	1	1	1	1
113	oil the NTC and attach it to the pump reservoir	3.5	1	1	1	1
114	attach a cable to the valve (3 outlets)	3.9	1	1	0	0
115	bind a felt to the main part from the left side	6.5	1	1	1	1
116	fixate the circulation motor and cover of motor with a screw	4.2	1	1	1	1
117	attach a socket to the counter card	4.5	0	1	0	1
118	attach an isolater to the cable which is attached to the circulation motor	3	1	1	1	1
119	attach 2 cables to the circulation motor	7.5	1	1	1	1
120	attach a cable to the circulation motor	3	0	0	0	1
121	bind a felt to the main part from the right side	6.5	1	1	1	1
122	bind the sponge of sound isolation to the main part from back under	6.5	1	1	1	1
123	attach an isolater to the cable which is attached to the regeneration valve	3	0	1	0	1
124	attach 2 cables to the regeneration valve	9	0	1	0	1
125	attach an isolater to the cable which is attached to the heater	3	1	1	1	1
126	attach an isolater to the cable which is attached to the heater	3	1	1	1	1
127	attach a cable to the heater	5.5	1	1	1	1
128	attach a cable to the switch of salt box	4.5	1	1	1	1
129	attach a cable to the valve (3 outlets)	3.9	1	0	1	0
130	attach 2 cables to the fan motor	7	0	0	0	1
131	put the sheet iron of concrete to the pallet	2.5	1	1	1	1
132	attach a wire tie to the sheet iron of concrete	2.5	1	1	1	1
133	attach an isolater to the cable which is connected to the parasite filter and one of the cable of main group of cables	3	1	1	1	1
134	attach an isolater to the cable which is connected to the parasite filter and one of the cable of main group of cables	3	1	1	1	1
135	connect the ends of the cables of main group of cables to the parasite filter (1 unit)	4	1	1	1	1
136	connect the ends of the cables of main group of cables to the parasite filter (1 unit)	4	1	1	1	1
137	connect the ends of the cables of main group of cables to the parasite filter (1 unit)	4	1	1	1	1

Table B.1 (Continued)

138	attach an isolater to the cable which is connected to the parasite filter and one of the cables of net cable	3	1	1	1	1
139	attach an isolater to the cable which is connected to the parasite filter and one of the cables of net cable	3	1	1	1	1
140	connect the ends of the cables of net cable to the parasite filter (1 unit)	4	1	1	1	1
141	connect the ends of the cables of net cable to the parasite filter (1 unit)	4	1	1	1	1
142	attach a cable to the valve (3 outlets)	3.9	1	1	1	0
143	put the net cable to the socket	3.5	1	1	1	1
144	attach a clamp to the frame (left)	2.5	1	1	1	1
145	tie a camel neck to the frame with a clamp	5.9	1	1	1	1
146	connect the ends of the cables of net cable to the parasite filter (1 unit)	4	1	1	1	1
147	put the concrete part to the sheet iron of concrete	3	1	1	1	1
148	adjust the concrete part and fix it by using piston	3.5	1	1	1	1
149	fix the sheet iron of concrete to the frame from right back side with a screw	4.9	1	1	1	1
150	fix the sheet iron of concrete to the frame from right back side with a screw	4.9	1	1	1	1
151	fix the flexible part of the sheet iron to the frame from the right side with a screw	4	1	1	1	1
152	fix the flexible part of the sheet iron to the frame from the left side with a screw	4	1	1	1	1
153	attach a clamp to the hose (string)	3.5	1	1	1	1
154	heat the end of the hose (string) and connect it to the water pocket	18	1	1	1	1
155	tighten the clamp of the hose (string)	6	1	1	1	1
156	attach the hose of aqua-stop to the pallet and tighten it	13	0	1	0	1
157	attach cable protections to the ends of cables of the aqua-stop	4.5	0	1	0	1
158	attach the green and green-white cables to the aqua-stop socket	5.2	0	1	0	1
159	tie the cables of aqua-stop to the hanger of hose with a plastic clamp	9.5	0	1	0	1
160	open the lid	0.5	1	1	1	1
161	close the lid	0.5	1	1	1	1
162	attach a cable to the heater	4.5	1	1	1	0
163	attach a cable to the heater	4.5	1	1	1	0
164	put the bottom part of the hose hanger to the fixture	2.9	1	1	1	1
165	connect the end of the emptying hose to the fixture	4.7	1	1	1	1
166	put the upper part of the hose hanger to the fixture and connect its nails to the bottom part	3.7	1	1	1	1
167	move the emptying hose	0.3	1	1	1	1
168	connect the aqua-stop hose to the hanger	6.5	0	1	0	1

Table B.1 (Continued)

169	put the group of hanger to the sheet iron of concrete	5.2	0	1	0	1
170	attach a camel neck to the emptying hose	4.2	1	1	1	1
171	tie the emptying hose to the frame with a clamp	6.5	1	1	1	1
172	adjust the emptying hose and attach its free end to the pallet	5.4	1	1	1	1
173	attach a clamp to the emptying hose	2.5	1	1	1	1
174	connect the emptying hose to the motor and adjust it	4.5	1	1	1	1
175	tighten the clamp of emptying hose	5.5	1	1	1	1
176	oil the emptying hose	2.5	1	1	1	1
177	connect the emptying hose to the reservoir and set its nails	4.2	1	1	1	1
178	set the cables of heater to the part on the reservoir	2.4	1	1	1	1
179	attach an isolater to the cable which is connected to the emptying motor	3	1	1	1	1
180	attach 2 cables to the emptying motor	8.4	1	1	1	1
181	adjust the machine (product)	2.5	1	1	1	1
182	set the front bottom support sheet iron between the frames	3.8	1	1	1	1
183	set the flusher between the bottom support sheet iron and main part	3.5	1	1	1	1
184	set the 2. flusher to the front bottom sheet iron	4.5	1	1	1	1
185	adjust the cable protection	2.2	1	1	1	1
186	fix the front bottom support sheet iron to the frame with a screw	6.3	1	1	1	1
187	fix the front bottom support sheet iron to the frame with a screw	5.8	1	1	1	1
188	fix the front support sheet iron of hinge from the right side with 2 screws	9.5	1	1	1	1
189	close the lid	0.5	1	1	1	1
190	open the lid	0.5	1	1	1	1
191	put the group of upper basket into the machine	5.9	1	1	1	1
192	attach the cover of right rail from the front	2.8	1	1	1	1
193	attach the cover of left rail from the front	2.8	1	1	1	1
194	close the lid	0.5	1	1	1	1
195	set the "start the program" button to test position	C	1	1	1	1
196	close the cover of salt box	4.3	1	1	1	1
197	fix the front support sheet iron of hinge from the left side with 2 screws	9.5	1	1	1	1
198	put the group of outer lid onto the inner lid and board	7.5	1	1	1	1
199	fix the inner-outer lid from the bottom side with a screw	3.2	1	1	1	1
200	fix the inner-outer lid from the bottom side with a screw	3.2	1	1	1	1
201	fix the inner-outer lid from the upper side with a screw	3.2	1	1	1	1
202	fix the inner-outer lid from the upper side with a screw	3.2	1	1	1	1
203	tighten the 2 screws which are half tightened on the board	3	0	1	0	1
204	pass the motor card cable (1. type) among the hoses	6.5	0	0	0	1
205	pass the motor card cable (2. type) among the hoses	4.3	0	0	0	1

Table B.1 (Continued)

206	connect the motor card cable (1. type) and adjust it	6.5	0	0	0	1
207	operate the bottom plane robot	5.5	1	1	1	1
208	attach the part which fixates the upper plane	0	1	1	1	1
209	attach 2 L strafors to the frame	0	1	1	1	1
210	connect the buoy and bottom plane	2.1	1	1	1	1
211	fixate the bottom plane with 2 screws to the frame	10.6	1	1	1	1
212	check the cables and hoses of buoy after attaching the bottom plane	2.1	1	1	1	1
213	attach the mistake trace paper to the lid with a magnet	2.1	1	1	1	1
214	control the 1. electrical test	1	1	1	1	1
215	connect the motor card cable (2. type) and adjust it	6.4	0	0	0	1
216	send the pallet	5.5	1	1	1	1
217	open the lid	0.5	1	1	1	1
218	open the cover of salt box	3	1	1	1	1
219	evacuate the water in the salt box with the vacuum machine	10.2	1	1	1	1
220	move the micro filter and reservoir	0	1	1	1	1
221	connect the cable of circulation motor card to the card	5.6	0	0	0	1
222	evacuate the water in the reservoir with the vacuum machine	6.8	1	1	1	1
223	close the cover of salt box	0	1	1	1	1
224	put the colander into the reservoir	2.1	1	1	1	1
225	put the micro filter to the colander and tighten it	2.1	1	1	1	1
226	bind a sticker to the cover of salt box	5.8	1	1	1	1
227	adjust the tuning screw in the water pocket by using screwdriver	3.5	1	1	1	1
228	close the lid	0.5	1	1	1	1
229	put a felt on to the main body	3.5	1	1	1	1
230	ravel the water entry hose from the pallet	6.8	1	1	1	1
231	ravel the emptying hose from the pallet	0.8	1	1	1	1
232	tie the water entry and emptying hoses according to the figure	5.1	1	1	1	1
233	tie the water entry and emptying hoses with a clamp	3.9	1	1	1	1
234	put a felt on to the machine	4.1	0	0	0	1
235	attach a clamp to the right frame	2.5	1	1	1	1
236	set a long starafor to the right back frame	4.7	1	1	1	1
237	set a long starafor to the left back frame	4.7	1	1	1	1
238	attach the sound gasket to the left side by using the equipment	7.8	0	0	1	1
239	attach a strafor to the left back side of main body	2.9	1	1	1	1
240	attach the left side plane and fix it with 2 screws	15	1	1	1	1
241	put 2 white stopper to the left side plane	4.1	1	1	1	1
242	attach the centralize part of inner lid (left and right)	8	1	1	1	1
243	attach the sound gasket to the right side by using the equipment	7.8	0	0	1	1
244	attach a strafor to the right back side of main body	2.9	1	1	1	1
245	attach the right side plane and fix it with 2 screws	15	1	1	1	1
246	put 2 white stopper to the right side plane	4.1	1	1	1	1

Table B.1 (Continued)

247	put the left side support starafor between the felts	2.3	1	1	1	1
248	attach a strafor to the back side of the upper basket	3.5	1	1	1	1
249	attach the lid of motor card cable	5.7	0	0	0	1
250	fix the right side plane to the frame from the upper side with 2 screws	7.8	1	1	1	1
251	fix the left side plane to the frame from the upper side with 2 screws	7.8	1	1	1	1
252	put the bottom basket into the machine	4.3	1	1	1	1
253	control the working of the group of bottom basket and the lid	0.8	1	1	1	1
254	transfer the bottom basket	0.5	1	1	1	1
255	put a pocket of detergent into the bottom basket	2.1	1	1	1	1
256	transfer the pocket of detergent	0.5	1	1	1	1
257	attach the shelf group to the bottom basket	4.5	1	1	1	1
258	after attaching the shelf group set 2 strafors to the back side of the basket	4.9	1	1	1	1
259	set the "start the program" button to test position and push the start button	C	1	1	1	1
260	bind an attention sticker to the lid of motor card	5.5	0	0	0	1
261	tie a sponge to the bottom basket	3.5	1	1	1	1
262	put a salt funnel to the bottom basket	2.1	1	1	1	1
263	attach 2 strafors to the back side of the bottom basket	4.9	1	1	1	1
264	set the CKB basket into the bottom basket	2	1	1	1	1
265	transfer the material	1	1	1	1	1
266	set the kick felt to the frame	9	1	1	1	1
267	set the kick sheet iron to the frame	3.7	1	1	1	1
268	transfer the kick sheet iron	0.5	1	1	1	1
269	fix the kick sheet iron to the frame from the upper side with 2 screws	11.6	1	1	1	1
270	fix the kick sheet iron to the frame from the right bottom side with 2 screws	7.8	1	1	1	1
271	bind a sponge to the kick sheet iron	6.5	1	1	1	1
272	fix the right side plane to the frame from the back side with 2 screws	7.8	1	1	1	1
273	fix the left side plane to the frame from the back side with 2 screws	7.8	1	1	1	1
274	fix the bottom plane from the back side with 2 screws	7.8	1	1	1	1
275	turn the pallet	3	1	1	1	1
276	fix the kick sheet iron to the frame from the left bottom side with 2 screws	7.8	1	1	1	1
277	attach the plastic kick part to the kick sheet iron	2.7	1	1	1	1
278	transfer the plastic kick part	0.5	1	1	1	1
279	ravel the net cable from the pallet and set it between the hoses	2.7	1	1	1	1
280	turn the pallet	3	1	1	1	1

Table B.1 (Continued)

281	test the machine according to the 2. control paper	22	1	1	1	1
282	put the sample pochette into the upper basket	2.8	1	1	1	1
283	attach a plastic part to the bottom basket and fixate the CSK. funnel and user guide	9	1	1	1	1
284	match the user guide. type sticker and barcode number	5.5	1	1	1	1
285	save the barcode number	2.8	1	1	1	1
286	bind a sticker to the mistake trace paper	3.2	1	1	1	1
287	put a separator into the user guide	5.3	1	1	1	1
288	put the user guide into the machine	2.7	1	1	1	1
289	functional test	C	1	1	1	1
290	give a barcode number	1.5	1	1	1	1
291	Attach a strafor to the bottom basket	4.5	1	1	1	1
292	bind a program sticker to the inside of the lid	5.5	1	1	1	1
293	clean the outside surfaces	20	1	1	1	1
294	bind a type sticker to the front barcode paper	5.1	1	1	1	1
295	bind a type sticker to the back barcode paper	5.1	1	1	1	1
296	control the existence of the user guide in the machine	1	1	1	1	1
297	bind the sticker of the firm to the outside of the lid from the upper left side	5.5	1	1	1	1
298	put the concrete sheet iron onto the fixture	2.5	1	1	1	1
299	put the bracket parasite filter to the fixture	1	1	1	1	1
300	Attach the bracket parasite filter to the concrete sheet iron	2.8	1	1	1	1
301	fix the parasite filter to the concrete sheet iron with 2 screws	7	1	1	1	1
302	turn the concrete sheet iron	2.8	0	0	0	1
303	attach a wire clamp to the concrete sheet iron	2.5	1	1	1	1
304	tie the net cable	2.8	1	1	1	1
305	put the net cable to the bottom part of its handle	3.1	1	1	1	1
306	connect the upper part of handle of the net cable to the bottom part	3.2	1	1	1	1
307	attach the handle of the net cable to the concrete sheet iron	3.6	1	1	1	1
308	pass the 3 cables of the net cable from the handle	4.5	1	1	1	1
309	collect the grouped parts	2	1	1	1	1
310	fill water to the salt box	C	1	1	1	1
311	attach the outlet part of fan to the concrete sheet iron	5.5	0	0	0	1
312	open the lid	0.5	1	1	1	1
313	close the lid	0.5	1	1	1	1
314	TASK GROUP 1	33	1	1	1	1
315	TASK GROUP 2	13.8	1	1	1	1
316	TASK GROUP 3	25.8	1	1	1	1
317	TASK GROUP 4	C	1	1	1	1
318	TASK GROUP 5	32.1	1	1	1	1
319	TASK GROUP 6	32.1	1	1	1	1
320	TASK GROUP 7	34.8	1	1	1	1

Table B.1 (Continued)

321	TASK GROUP 8	33	1	1	1	1
322	TASK GROUP 9	34.5	1	1	1	1
323	TASK GROUP 10	4.9	1	1	1	1

Note: The number 1 in model columns shows that corresponding model includes the corresponding task. and the number 0 in model columns shows that corresponding model does not include the corresponding task

APPENDIX C

PRECEDENCE RELATIONSHIPS

Table C.1 List of immediate predecessor-successor relationships for individual models

MODEL1		MODEL2		MODEL3		MODEL4	
Task	Immediate Successor	Task	Immediate Successor	Task	Immediate Successor	Task	Immediate Successor
1	7	1	24	1	24	1	24
1	57	1	7	1	7	1	7
1	237	1	57	1	57	1	57
1	36	1	237	1	237	1	73
1	33	1	36	1	36	1	237
1	12	1	33	1	40	1	36
1	6	1	12	1	33	1	40
1	2	1	6	1	12	1	12
1	3	1	2	1	6	1	6
1	4	1	3	1	2	1	10
1	5	1	4	1	3	1	2
1	58	1	5	1	4	1	3
1	27	1	58	1	5	1	4
1	122	1	27	1	58	1	5
1	236	1	122	1	27	1	58
2	72	1	19	1	122	1	27
3	72	1	236	1	19	1	122
4	49	2	46	1	236	1	19
5	48	3	47	2	46	1	236
6	21	4	49	3	47	2	46
7	8	5	48	4	49	3	47
8	9	6	21	5	48	4	49
9	62	7	8	6	21	5	48
12	13	8	9	7	8	6	21
13	14	9	62	8	9	7	8
14	15	12	13	9	62	8	9

Table C.1 (Continued)

15	16	13	14	12	13	9	62
16	17	14	15	13	14	10	11
17	18	15	16	14	15	11	21
17	75	16	17	15	16	12	13
18	20	17	18	16	17	13	14
20	21	17	75	17	18	14	15
20	25	18	20	17	75	15	16
21	22	19	245	18	20	16	17
22	23	20	21	19	245	17	18
23	72	20	25	20	21	18	20
25	26	21	22	20	25	19	245
26	72	22	23	21	22	20	21
27	28	23	72	22	23	20	25
28	29	24	240	23	72	21	22
29	63	25	26	24	240	22	23
30	31	26	72	25	26	23	72
31	32	27	28	26	72	24	240
32	41	28	29	27	28	25	26
33	34	29	63	28	29	26	72
34	30	30	31	29	63	27	28
35	30	31	32	30	31	28	29
36	37	32	41	31	32	29	63
37	35	33	34	32	45	30	31
37	38	34	30	32	44	31	32
37	61	35	30	35	39	32	45
38	30	36	37	36	37	32	44
41	42	37	35	37	35	35	39
42	43	37	38	37	38	36	37
43	45	37	61	37	61	37	35
45	72	38	30	38	39	37	38
48	72	41	42	39	30	37	61
49	72	42	43	40	30	38	39
57	60	43	45	44	72	39	30
58	59	45	72	45	72	40	30
59	63	46	72	46	72	44	72
59	83	47	72	47	72	45	72
60	62	48	72	48	72	46	72
60	83	49	72	49	72	47	72
61	86	57	60	57	60	48	72
62	87	58	59	58	59	49	72
63	88	59	63	59	63	50	51
64	86	59	83	59	83	51	52

Table C.1 (Continued)

66	69	60	62	60	62	51	55
67	68	60	83	60	83	52	53
68	86	61	86	61	86	53	54
69	86	62	87	62	87	54	207
70	86	63	88	63	88	55	56
71	86	65	86	65	86	56	234
72	310	66	69	66	69	57	60
72	107	67	68	67	68	58	59
72	67	68	86	68	86	59	63
72	66	69	86	69	86	59	83
72	64	70	86	70	86	60	62
72	89	71	86	71	86	60	83
72	70	72	310	72	310	61	86
72	59	72	107	72	107	62	87
72	235	72	67	72	67	63	88
72	77	72	66	72	66	65	86
72	76	72	65	72	65	66	69
72	71	72	89	72	89	67	68
72	81	72	70	72	70	68	86
72	60	72	59	72	59	69	86
72	144	72	235	72	235	70	86
72	121	72	77	72	77	71	86
72	115	72	76	72	76	72	310
75	72	72	71	72	71	72	107
76	86	72	81	72	81	72	50
77	78	72	60	72	60	72	67
78	79	72	144	72	144	72	66
79	80	72	121	72	121	72	65
80	83	72	115	72	115	72	89
81	82	75	72	75	72	72	70
82	87	76	86	76	86	72	59
83	84	77	78	77	78	72	235
83	85	78	79	78	79	72	77
84	86	79	80	79	80	72	76
85	86	80	83	80	83	72	71
86	88	81	82	81	82	72	81
86	105	82	87	82	87	72	60
86	101	83	84	83	84	72	144
86	100	83	85	83	85	72	121
86	99	84	86	84	86	72	115
86	91	85	86	85	86	73	74
86	191	86	88	86	88	74	72

Table C.1 (Continued)

86	108	86	101	86	105	74	249
86	96	86	100	86	102	76	86
86	87	86	99	86	99	77	78
87	109	86	91	86	91	78	79
88	109	86	191	86	191	79	80
89	90	86	108	86	108	80	83
90	86	86	96	86	96	81	82
91	92	86	87	86	87	82	87
91	93	87	109	87	109	83	84
91	94	88	109	88	109	83	85
91	95	89	90	89	90	84	86
92	103	90	86	90	86	85	86
93	103	91	92	91	92	86	88
94	103	91	93	91	93	86	99
95	198	91	94	91	94	86	91
96	97	91	95	91	95	86	191
97	98	92	103	92	103	86	108
98	109	93	103	93	103	86	96
99	198	94	103	94	103	86	87
100	198	95	198	95	198	87	109
101	102	96	97	96	97	88	109
102	198	97	98	97	98	89	90
103	104	98	109	98	109	90	86
104	198	99	198	99	198	91	92
105	198	100	198	102	198	91	93
106	199	101	102	103	104	91	94
106	200	102	198	104	198	91	95
106	201	103	104	105	198	92	103
106	202	104	198	106	199	93	103
107	161	106	199	106	200	94	103
108	109	106	200	106	201	95	198
108	182	106	201	106	202	96	97
109	110	106	202	107	161	97	98
109	126	106	203	108	109	98	109
109	128	107	161	108	182	99	198
109	129	108	109	109	110	103	104
109	114	108	182	109	126	104	198
109	116	109	110	109	128	106	199
109	113	109	126	109	129	106	200
109	112	109	128	109	116	106	201
109	111	109	117	109	113	106	202
109	118	109	114	109	112	106	203

Table C.1 (Continued)

109	125	109	116	109	111	107	161
109	142	109	113	109	118	108	109
110	131	109	112	109	125	108	182
111	131	109	111	109	142	109	205
112	131	109	118	110	131	109	204
113	131	109	123	111	131	109	120
114	131	109	125	112	131	109	130
115	239	109	142	113	131	109	110
115	247	110	131	115	238	109	126
115	244	111	131	115	239	109	128
116	131	112	131	115	247	109	117
118	119	113	131	115	243	109	116
119	131	114	131	115	244	109	113
121	239	115	239	116	131	109	112
121	247	115	244	118	119	109	111
121	244	115	247	119	131	109	118
122	207	116	131	121	238	109	123
125	127	117	131	121	239	109	125
126	131	118	119	121	247	110	131
127	131	119	131	121	243	111	131
128	131	121	239	121	244	112	131
129	131	121	244	122	207	113	131
131	132	121	247	125	127	115	234
131	133	122	207	126	131	116	131
131	134	123	124	127	131	117	131
131	135	124	131	128	131	118	119
131	138	125	127	129	131	119	131
131	139	126	131	131	132	120	221
131	146	127	131	131	133	121	234
132	171	128	131	131	134	122	207
133	136	131	132	131	135	123	124
134	137	131	133	131	138	124	131
135	147	131	134	131	139	125	127
136	147	131	135	131	146	126	131
137	147	131	138	132	171	127	131
138	140	131	139	133	136	128	131
139	141	131	146	134	137	130	131
140	147	132	171	135	147	131	132
141	147	133	136	136	147	131	133
142	131	134	137	137	147	131	134
143	195	135	147	138	140	131	135
144	145	136	147	139	141	131	138

Table C.1 (Continued)

145	170	137	147	140	147	131	139
146	147	138	140	141	147	131	146
147	148	139	141	142	131	132	171
148	149	140	147	143	195	133	136
148	150	141	147	144	145	134	137
148	151	142	131	145	170	135	147
148	152	143	195	146	147	136	147
149	164	144	145	147	148	137	147
149	143	145	170	148	149	138	140
149	153	146	147	148	150	139	141
150	164	147	148	148	151	140	147
150	143	148	149	148	152	141	147
150	153	148	150	149	164	143	195
151	240	148	151	149	143	144	145
152	245	148	152	149	153	145	170
153	154	149	164	150	164	146	147
154	155	149	143	150	143	147	148
155	163	149	156	150	153	148	149
155	162	150	164	151	240	148	150
160	284	150	143	152	245	148	151
160	286	150	156	153	154	148	152
160	287	151	240	154	155	149	164
160	291	152	245	155	162	149	143
160	292	153	154	155	163	149	156
161	293	154	155	160	284	150	164
161	294	155	157	160	286	150	143
161	295	156	153	160	287	150	156
161	297	157	158	160	291	151	240
162	178	158	159	160	292	152	245
163	178	159	162	161	293	153	154
164	165	159	163	161	294	154	155
165	166	160	284	161	295	155	157
166	167	160	286	161	297	156	153
167	170	160	287	162	178	157	158
170	171	160	291	163	178	158	159
171	172	160	292	164	165	159	178
172	173	161	293	165	166	160	284
173	174	161	294	166	167	160	286
173	178	161	295	167	170	160	287
174	175	161	297	170	171	160	291
175	176	162	178	171	172	160	292
176	177	163	178	172	173	161	293

Table C.1 (Continued)

177	179	164	165	173	174	161	294
178	173	164	168	173	178	161	295
178	181	165	166	174	175	161	297
179	180	166	167	175	176	164	165
180	181	167	169	176	177	164	168
181	207	168	166	177	179	165	166
182	183	169	170	178	173	166	167
182	184	170	171	178	181	167	169
183	185	171	172	179	180	168	166
184	185	172	173	180	181	169	170
185	186	173	174	181	207	170	171
185	187	173	178	182	183	171	172
186	188	174	175	182	184	172	173
186	197	175	176	183	185	173	174
187	188	176	177	184	185	173	178
187	197	177	179	185	186	174	175
188	198	178	173	185	187	175	176
189	207	178	181	186	188	176	177
189	213	179	180	186	197	177	179
190	252	180	181	187	188	178	173
191	192	181	207	187	197	178	181
191	193	182	183	188	198	179	180
192	312	182	184	189	207	180	181
192	160	183	185	189	213	181	207
192	248	184	185	190	252	182	183
193	160	185	186	191	192	182	184
193	312	185	187	191	193	183	185
194	312	186	188	192	312	184	185
194	160	186	197	192	160	185	186
195	214	187	188	192	248	185	187
196	289	187	197	193	160	186	188
197	198	188	198	193	312	186	197
198	106	189	207	194	312	187	188
198	266	189	213	194	160	187	197
199	189	190	252	195	214	188	198
200	189	191	192	196	289	189	207
201	189	191	193	197	198	189	213
202	189	192	312	198	106	190	252
206	131	192	160	198	266	191	192
207	208	192	248	199	189	191	193
207	209	193	312	200	189	192	312
208	210	193	160	201	189	192	160

Table C.1 (Continued)

209	210	194	312	202	189	192	248
210	211	194	160	207	208	193	160
211	212	195	214	207	209	193	312
212	216	196	289	208	210	194	312
213	214	197	198	209	210	194	160
214	216	198	106	210	211	195	214
216	289	198	266	211	212	196	289
216	239	199	189	212	216	197	198
216	247	200	189	213	214	198	106
216	244	201	189	214	216	198	266
217	218	202	189	216	289	199	189
217	220	203	189	216	238	200	189
217	227	207	208	216	239	201	189
218	219	207	209	216	247	202	189
218	226	208	210	216	243	203	189
219	223	209	210	216	244	204	206
220	222	210	211	217	218	205	215
222	224	211	212	217	220	206	131
223	228	212	216	217	227	207	208
224	225	213	214	218	219	207	209
225	228	214	216	218	226	208	210
226	228	216	289	219	223	209	210
227	228	216	239	220	222	210	211
228	229	216	244	222	224	211	212
228	190	216	247	223	228	212	216
229	230	217	218	224	225	213	214
229	231	217	220	225	228	214	216
230	232	217	227	226	228	215	131
230	233	218	219	227	228	216	289
231	232	218	226	228	229	216	234
231	233	219	223	228	190	217	218
232	279	220	222	229	230	217	220
233	279	222	224	229	231	217	227
235	232	223	228	230	232	218	219
235	233	224	225	230	233	218	226
236	245	225	228	231	232	219	223
237	240	226	228	231	233	220	222
239	240	227	228	232	279	221	131
240	241	228	229	233	279	222	224
241	242	228	190	235	232	223	228
241	251	229	230	235	233	224	225
242	275	229	231	236	245	225	228

Table C.1 (Continued)

244	245	230	232	237	240	226	228
245	246	230	233	239	240	227	228
246	242	231	232	240	241	228	229
246	250	231	233	241	242	228	190
247	240	232	279	241	251	229	230
248	313	233	279	242	275	229	231
250	275	235	232	243	245	230	232
251	275	235	233	244	245	230	233
252	253	236	245	245	246	231	232
252	255	237	240	246	242	231	233
252	261	239	240	246	250	232	279
252	262	240	241	247	240	233	279
252	263	241	242	248	313	234	238
252	264	241	251	250	275	234	239
253	254	242	275	251	275	234	247
254	257	244	245	252	253	234	243
255	256	245	246	252	255	234	244
256	254	246	242	252	261	235	232
257	258	246	250	252	262	235	233
258	265	247	240	252	263	236	245
259	161	248	313	252	264	237	240
261	265	250	275	253	254	238	240
262	265	251	275	254	257	239	240
263	265	252	253	255	256	240	241
264	265	252	255	256	254	241	242
265	194	252	261	257	258	241	251
266	268	252	262	258	265	242	275
267	269	252	263	259	161	243	245
267	270	252	264	261	265	244	245
267	276	253	254	262	265	245	246
268	267	254	257	263	265	246	242
269	271	255	256	264	265	246	250
270	271	256	254	265	194	247	240
271	278	257	258	266	268	248	313
272	280	258	265	267	269	249	260
273	280	259	161	267	270	250	275
274	280	261	265	267	276	251	275
275	272	262	265	268	267	252	253
275	273	263	265	269	271	252	255
275	274	264	265	270	271	252	261
275	279	265	194	271	278	252	262
276	271	266	268	272	280	252	263

Table C.1 (Continued)

277	312	267	269	273	280	252	264
277	160	267	270	274	280	253	254
278	277	267	276	275	272	254	257
279	280	268	267	275	273	255	256
280	275	269	271	275	274	256	254
280	312	270	271	275	279	257	258
280	160	271	278	276	271	258	265
281	313	272	280	277	312	259	161
282	313	273	280	277	160	260	234
283	313	274	280	278	277	261	265
284	290	275	272	279	280	262	265
285	288	275	273	280	275	263	265
286	288	275	274	280	312	264	265
287	288	275	279	280	160	265	194
288	296	276	271	281	313	266	268
289	217	277	312	282	313	267	269
289	259	277	160	283	313	267	270
290	285	278	277	284	290	267	276
291	161	279	280	285	288	268	267
292	161	280	275	286	288	269	271
296	161	280	312	287	288	270	271
298	132	280	160	288	296	271	278
298	300	281	313	289	217	272	280
298	303	282	313	289	259	273	280
299	298	283	313	290	285	274	280
300	301	284	290	291	161	275	272
300	307	285	288	292	161	275	273
301	309	286	288	296	161	275	274
303	304	287	288	298	132	275	279
304	305	288	296	298	300	276	271
305	306	289	217	298	303	277	312
306	308	289	259	299	298	277	160
307	305	290	285	300	301	278	277
308	309	291	161	300	307	279	280
309	131	292	161	301	309	280	275
310	196	296	161	303	304	280	312
312	281	298	132	304	305	280	160
312	282	298	300	305	306	281	313
312	283	298	303	306	308	282	313
		299	298	307	305	283	313
		300	301	308	309	284	290
		300	307	309	131	285	288

Table C.1 (Continued)

		301	309	310	196	286	288
		303	304	312	281	287	288
		304	305	312	282	288	296
		305	306	312	283	289	217
		306	308			289	259
		307	305			290	285
		308	309			291	161
		309	131			292	161
		310	196			296	161
		312	281			298	132
		312	282			298	300
		312	283			298	303
						299	298
						300	301
						300	307
						301	302
						302	311
						303	304
						304	305
						305	306
						306	308
						307	305
						308	309
						309	131
						310	196
						311	309
						312	281
						312	282
						312	283

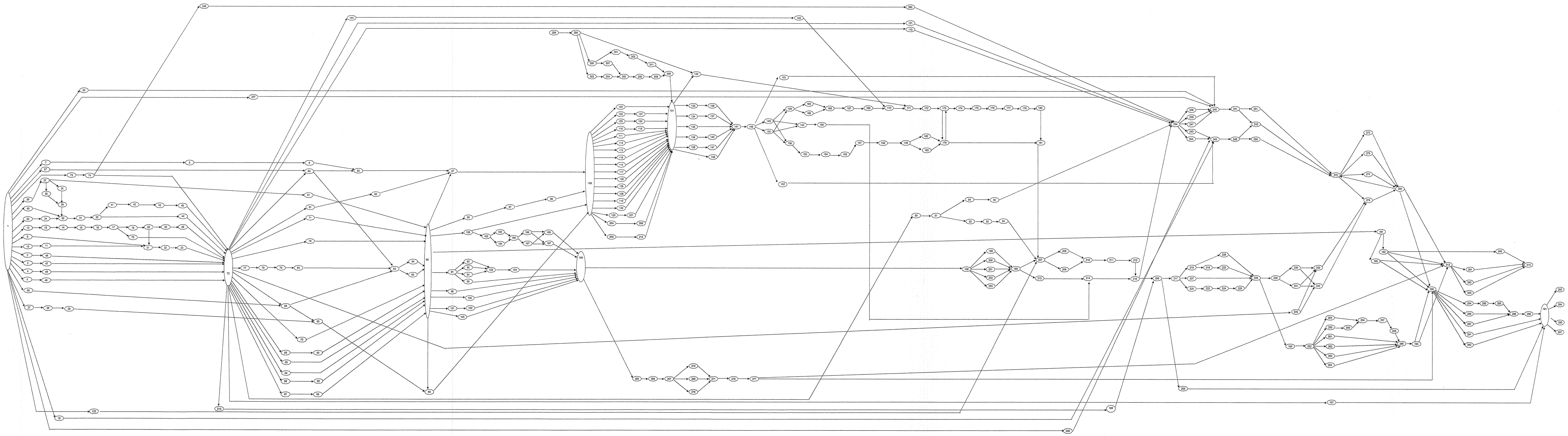


Figure C.1 Combined precedence diagram

APPENDIX D

PSEUDOCODE OF THE WHOLE ALGORITHM

STEP-0: Calculate the remaining time and beginning cycle time.

STEP-1: S1=Ø, i=1, assigned=0, WC(i)=0

STEP-2: Determine and extract the tasks that can be assigned to i^{th} station according to the precedence relationships and zoning restrictions among the non-assigned tasks and then put them into set S1.

STEP-3: Extract a task (k) from S1 randomly.

STEP-4: a) If C-WC(i)<t(k) then i=i+1

b) Assign task k to station i

STEP-5: assigned=assigned+1

STEP-6: If assigned<N then go to STEP-2

STEP-7: Calculate Ffirst(current);

Ffirst(current)=F1(current)+F3(current)+F5(current)

STEP-8: Best=current, Ffirst(Best)=Ffirst(current)

STEP-9: n1=0, n2=0, n3=1, worse=0, acc=0

STEP-10: temp=K1/n3

STEP-11: candidate=current

STEP-12: Choose a task (k) randomly

STEP-13: Determine the set (S2) of stations that task k can be assigned according to the precedence relationships, zoning restrictions, station times, cycle time and task time of task k, considering the candidate solution.

STEP-14: Transfer the task k to a new station which is chosen from S2 randomly.

STEP-15: Adjust the station times.

STEP-16: Calculate Ffirst(candidate)

STEP-17: If Ffirst(candidate)<=Ffirst(Best) then

Best=Candidate and Ffirst(Best)=Ffirst(candidate)

STEP-18: If Ffirst(candidate)<=Ffirst(current) then go to STEP-21

STEP-19: worse=worse+1

STEP-20: If Unif(0,1)>exp[(Ffirst(current)-Ffirst(candidate))/temp] then go to STEP-22 else acc=acc+1

STEP-21: current=candidate, Ffirst(current)=Ffirst(candidate)

STEP-22: n1=n1+1, n2=n2+1, n3=n3+1

STEP-23: If n2<100 then go to STEP-10

STEP-24: n2=0

STEP-25: If (worse>90) and (acc<9) then

a) n3=round(acc*K1/worse)

b) If n3=0 then n3=1

STEP-26: If n1<number of iterations then go to STEP-10

STEP-27: current=Best

STEP-28: Calculate Fsecond(current);

Fsecond(current)=F2(current)+F4(current)+F5(current)

STEP-29: Fsecon(Best)=Fsecond(current)

STEP-30: n1=0, n2=0, n3=1, worse=0, acc=0

STEP-31: temp=K2/n3

STEP-32: candidate=current

STEP-33: Choose a task (k) randomly

STEP-34: Determine the set (S2) of stations that task k can be assigned according to the precedence relationships, zoning restrictions, station times, cycle time and task time of task k, considering the candidate solution.

STEP-35: Transfer the task k to a new station which is chosen from S2 randomly.

STEP-36: Adjust the station times.

STEP-37: Calculate Fsecond(candidate)

STEP-38: If Fsecond(candidate)<=Fsecond(Best) then

Best=Candidate and Fsecond(Best)=Fsecond(candidate)

STEP-39: If Fsecond(candidate)<=Fsecond(current) then go to STEP-42

STEP-40: worse=worse+1

STEP-41: If Unif(0,1)>exp[(Fsecond(current)-Fsecond(candidate))/temp] then go to STEP-43 else acc=acc+1

STEP-42: current=candidate, Fsecond(current)=Fsecond(candidate)

STEP-43: n1=n1+1, n2=n2+1, n3=n3+1

STEP-44: If n2<100 then go to STEP-31

STEP-45: n2=0

STEP-46: If (worse>90) and (acc<9) then

a) n3=round(acc*K2/worse)

b) If n3=0 then n3=1

STEP-47: If n1<number of iterations then go to STEP-31

STEP-48: Repeat the all previous steps for each model and for each sequence and then STOP.

APPENDIX E

RESULTS OF THE EXPERIMENTAL RUNS

Table E.1 Test problems and deviations of the found solutions from the optimum solutions for SALBP-I

problem	# of tasks	# of pre. relations	C	# of stations (optimum)	# of stations (found)	(found-opt)/opt
arcus1	83	112	3786	21	21	0
arcus1	83	112	3985	20	20	0
arcus1	83	112	4206	19	19	0
arcus1	83	112	4454	18	18	0
arcus1	83	112	4732	17	17	0
arcus1	83	112	5048	16	16	0
arcus1	83	112	5408	15	15	0
arcus1	83	112	5824	14	14	0
arcus1	83	112	5853	14	14	0
arcus1	83	112	6309	13	13	0
arcus1	83	112	6842	12	12	0
arcus1	83	112	6883	12	12	0
arcus1	83	112	7571	11	11	0
arcus1	83	112	8412	10	10	0
arcus1	83	112	8898	9	9	0
arcus1	83	112	10816	8	8	0
arcus2	111	176	5755	27	27	0
arcus2	111	176	5785	27	27	0
arcus2	111	176	6016	26	26	0
arcus2	111	176	6267	25	25	0
arcus2	111	176	6540	24	24	0
arcus2	111	176	6837	23	23	0
arcus2	111	176	7162	22	22	0
arcus2	111	176	7916	20	20	0
arcus2	111	176	8356	19	19	0
arcus2	111	176	8847	18	18	0
arcus2	111	176	9400	17	17	0
arcus2	111	176	10027	16	16	0
arcus2	111	176	10743	15	15	0
arcus2	111	176	11378	14	14	0
arcus2	111	176	11570	13	14	0.076923
arcus2	111	176	17067	9	9	0
barthold	148	173	403	14	14	0
barthold	148	173	434	13	13	0
barthold	148	173	470	12	12	0

Table E.1 (Continued)

barthold	148	173	513	11	11	0
barthold	148	173	564	10	10	0
barthold	148	173	626	9	9	0
barthold	148	173	705	8	8	0
barthold	148	173	805	7	7	0
barthold2	148	173	84	51	51	0
barthold2	148	173	85	50	51	0.02
barthold2	148	173	87	49	49	0
barthold2	148	173	89	48	48	0
barthold2	148	173	91	47	47	0
barthold2	148	173	93	46	46	0
barthold2	148	173	95	45	45	0
barthold2	148	173	97	44	44	0
barthold2	148	173	99	43	43	0
barthold2	148	173	101	42	42	0
barthold2	148	173	104	41	41	0
barthold2	148	173	106	40	40	0
barthold2	148	173	109	39	39	0
barthold2	148	173	112	38	38	0
barthold2	148	173	115	37	37	0
barthold2	148	173	118	36	36	0
barthold2	148	173	121	35	35	0
barthold2	148	173	125	34	34	0
barthold2	148	173	129	33	33	0
barthold2	148	173	133	32	32	0
barthold2	148	173	137	31	31	0
barthold2	148	173	142	30	30	0
barthold2	148	173	146	29	29	0
barthold2	148	173	152	28	28	0
barthold2	148	173	157	27	27	0
barthold2	148	173	163	26	26	0
barthold2	148	173	170	25	25	0
bowman	8	8	20	5	5	0
buxey	29	36	27	13	13	0
buxey	29	36	30	12	12	0
buxey	29	36	33	11	11	0
buxey	29	36	36	10	10	0
buxey	29	36	41	8	8	0
buxey	29	36	47	7	8	0.142857
buxey	29	36	54	7	7	0
gunther	35	45	41	14	14	0
gunther	35	45	44	12	12	0
gunther	35	45	49	11	11	0
gunther	35	45	54	9	9	0
gunther	35	45	61	9	9	0
gunther	35	45	69	8	8	0
gunther	35	45	81	7	7	0
hahn	53	82	2004	8	8	0
hahn	53	82	2338	7	7	0
hahn	53	82	2806	6	6	0
hahn	53	82	3507	5	5	0

Table E.1 (Continued)

hahn	53	82	4676	4	4	0
heskiaof	28	39	138	8	8	0
heskiaof	28	39	205	5	5	0
heskiaof	28	39	216	5	5	0
heskiaof	28	39	256	4	4	0
heskiaof	28	39	324	4	4	0
heskiaof	28	39	342	3	3	0
jackson	11	13	7	8	8	0
jackson	11	13	9	6	6	0
jackson	11	13	10	5	5	0
jackson	11	13	13	4	4	0
jackson	11	13	14	4	4	0
jackson	11	13	21	3	3	0
jaeschke	9	11	6	8	8	0
jaeschke	9	11	7	7	7	0
jaeschke	9	11	8	6	6	0
jaeschke	9	11	10	4	4	0
jaeschke	9	11	18	3	3	0
kilbridge	45	62	56	10	10	0
kilbridge	45	62	57	10	10	0
kilbridge	45	62	62	9	9	0
kilbridge	45	62	69	8	8	0
kilbridge	45	62	79	7	7	0
kilbridge	45	62	92	6	6	0
kilbridge	45	62	110	6	6	0
kilbridge	45	62	111	5	5	0
kilbridge	45	62	138	4	4	0
kilbridge	45	62	184	3	3	0
lutz1	32	38	1414	11	11	0
lutz1	32	38	1572	10	10	0
lutz1	32	38	1768	9	9	0
lutz1	32	38	2020	8	8	0
lutz1	32	38	2357	7	7	0
lutz1	32	38	2828	6	6	0
lutz2	89	118	11	49	49	0
lutz2	89	118	12	44	44	0
lutz2	89	118	13	40	40	0
lutz2	89	118	14	37	37	0
lutz2	89	118	15	34	34	0
lutz2	89	118	16	31	31	0
lutz2	89	118	17	29	29	0
lutz2	89	118	18	28	28	0
lutz2	89	118	19	26	26	0
lutz2	89	118	20	25	25	0
lutz2	89	118	21	24	24	0
lutz3	89	118	75	23	23	0
lutz3	89	118	79	22	22	0
lutz3	89	118	83	21	21	0
lutz3	89	118	87	20	20	0
lutz3	89	118	92	19	19	0
lutz3	89	118	97	18	18	0

Table E.1 (Continued)

lutz3	89	118	103	17	17	0
lutz3	89	118	110	15	16	0.066667
lutz3	89	118	118	14	15	0.071429
lutz3	89	118	127	14	14	0
lutz3	89	118	137	13	13	0
lutz3	89	118	150	12	12	0
mansoor	11	11	48	4	4	0
mansoor	11	11	62	3	3	0
mansoor	11	11	94	2	2	0
mertens	7	6	6	6	6	0
mertens	7	6	7	5	5	0
mertens	7	6	8	5	5	0
mertens	7	6	10	3	3	0
mertens	7	6	15	2	2	0
mertens	7	6	18	2	2	0
mitchell	21	27	14	8	8	0
mitchell	21	27	15	8	8	0
mitchell	21	27	21	5	5	0
mitchell	21	27	26	5	5	0
mitchell	21	27	35	3	3	0
mitchell	21	27	39	3	3	0
mukherje	94	181	176	25	25	0
mukherje	94	181	183	24	24	0
mukherje	94	181	192	23	23	0
mukherje	94	181	201	22	22	0
mukherje	94	181	211	21	21	0
mukherje	94	181	222	20	20	0
mukherje	94	181	234	19	19	0
mukherje	94	181	248	18	18	0
mukherje	94	181	263	17	17	0
mukherje	94	181	281	16	16	0
mukherje	94	181	301	15	15	0
mukherje	94	181	324	14	14	0
mukherje	94	181	351	13	13	0
roszieg	25	32	14	10	10	0
roszieg	25	32	16	8	8	0
roszieg	25	32	18	8	8	0
roszieg	25	32	21	6	6	0
roszieg	25	32	25	6	6	0
roszieg	25	32	32	4	4	0
sawyer	30	32	25	14	14	0
sawyer	30	32	27	13	13	0
sawyer	30	32	30	12	12	0
sawyer	30	32	33	11	11	0
sawyer	30	32	36	10	10	0
sawyer	30	32	41	8	8	0
sawyer	30	32	47	7	8	0.142857
sawyer	30	32	54	7	7	0
sawyer	30	32	75	5	5	0
scholl	297	423	1394	50	51	0.02
scholl	297	423	1422	50	50	0

Table E.1 (Continued)

scholl	297	423	1452	48	49	0.020833
scholl	297	423	1515	46	47	0.021739
scholl	297	423	1548	46	46	0
scholl	297	423	1584	44	45	0.022727
scholl	297	423	1620	44	44	0
scholl	297	423	1659	42	43	0.02381
scholl	297	423	1742	40	41	0.025
scholl	297	423	1787	39	40	0.025641
scholl	297	423	1834	38	39	0.026316
scholl	297	423	1883	37	38	0.027027
scholl	297	423	1935	36	37	0.027778
scholl	297	423	1991	35	36	0.028571
scholl	297	423	2049	34	35	0.029412
scholl	297	423	2111	33	34	0.030303
scholl	297	423	2177	32	33	0.03125
scholl	297	423	2247	31	32	0.032258
scholl	297	423	2322	30	31	0.033333
scholl	297	423	2402	29	30	0.034483
scholl	297	423	2488	28	29	0.035714
scholl	297	423	2580	27	28	0.037037
scholl	297	423	2680	26	27	0.038462
scholl	297	423	2787	25	26	0.04
tonge	70	86	160	23	23	0
tonge	70	86	168	22	22	0
tonge	70	86	176	21	21	0
tonge	70	86	185	20	20	0
tonge	70	86	195	19	19	0
tonge	70	86	207	18	18	0
tonge	70	86	220	17	17	0
tonge	70	86	234	16	16	0
tonge	70	86	251	14	15	0.071429
tonge	70	86	270	14	14	0
tonge	70	86	293	13	13	0
tonge	70	86	320	11	11	0
tonge	70	86	364	10	10	0
tonge	70	86	410	9	9	0
tonge	70	86	468	8	8	0
tonge	70	86	527	7	7	0
warnecke	58	70	54	31	31	0
warnecke	58	70	56	29	29	0
warnecke	58	70	58	29	29	0
warnecke	58	70	60	27	27	0
warnecke	58	70	62	27	27	0
warnecke	58	70	65	25	25	0
warnecke	58	70	68	24	24	0
warnecke	58	70	71	23	23	0
warnecke	58	70	74	22	22	0
warnecke	58	70	78	21	21	0
warnecke	58	70	82	20	20	0
warnecke	58	70	86	19	19	0
warnecke	58	70	92	17	17	0

Table E.1 (Continued)

warnecke	58	70	97	17	17	0
warnecke	58	70	104	15	15	0
warnecke	58	70	111	14	14	0
wee-mag	75	87	28	63	63	0
wee-mag	75	87	29	63	63	0
wee-mag	75	87	30	62	62	0
wee-mag	75	87	31	62	62	0
wee-mag	75	87	32	61	61	0
wee-mag	75	87	33	61	61	0
wee-mag	75	87	34	61	61	0
wee-mag	75	87	35	60	60	0
wee-mag	75	87	36	60	60	0
wee-mag	75	87	37	60	60	0
wee-mag	75	87	38	60	60	0
wee-mag	75	87	39	60	60	0
wee-mag	75	87	40	60	60	0
wee-mag	75	87	41	59	59	0
wee-mag	75	87	42	55	55	0
wee-mag	75	87	43	50	50	0
wee-mag	75	87	45	38	38	0
wee-mag	75	87	46	34	34	0
wee-mag	75	87	49	32	32	0
wee-mag	75	87	50	32	32	0
wee-mag	75	87	52	31	31	0
wee-mag	75	87	54	31	31	0
wee-mag	75	87	56	30	30	0

Table E.2 Descriptive statistics of deviations for SALBP-I

problem	average of deviations	std.dev. of deviations	min. deviation	max. deviation
arcus1	0	0	0	0
arcus2	0.00480769	0.0192308	0	0.0769231
barthold	0	0	0	0
barthold2	0.00074074	0.003849	0	0.02
bowman	0	0	0	0
buxey	0.02040816	0.0539949	0	0.1428571
gunther	0	0	0	0
hahn	0	0	0	0
heskiaof	0	0	0	0
jackson	0	0	0	0
jaeschke	0	0	0	0
kilbridge	0	0	0	0
lutz1	0	0	0	0
lutz2	0	0	0	0
lutz3	0.01150794	0.0268959	0	0.0714286
mansoor	0	0	0	0
mertens	0	0	0	0
mitchell	0	0	0	0
mukherje	0	0	0	0
roszieg	0	0	0	0
sawyer	0.01587302	0.047619	0	0.1428571
scholl	0.02548726	0.0112679	0	0.04
tonge	0.00446429	0.0178571	0	0.0714286
warnecke	0	0	0	0
wee-mag	0	0	0	0

Table E.3 Test problems and deviations of the found solutions from the optimum solutions for SALBP-II

problem	# of tasks	# of pre. relations	m	Cycle time (unit) (optimum)	Cycle time (unit) (found)	(found-opt)/opt
arcus1	83	112	3	25236	25236	0
arcus1	83	112	4	18927	18928	5.28346E-05
arcus1	83	112	5	15142	15145	0.000198124
arcus1	83	112	6	12620	12620	0
arcus1	83	112	7	10826	10830	0.000369481
arcus1	83	112	8	9554	9557	0.000314005
arcus1	83	112	9	8499	8504	0.000588305
arcus1	83	112	10	7580	7594	0.001846966
arcus1	83	112	11	7084	7091	0.000988142
arcus1	83	112	12	6412	6422	0.001559576
arcus1	83	112	13	5864	5913	0.008356071
arcus1	83	112	14	5441	5441	0
arcus1	83	112	15	5104	5117	0.002547022
arcus1	83	112	16	4850	4889	0.008041237
arcus1	83	112	17	4516	4581	0.014393268
arcus1	83	112	18	4317	4362	0.010423905
arcus1	83	112	19	4068	4091	0.005653884
arcus1	83	112	20	3882	3904	0.005667182
arcus1	83	112	21	3691	3691	0
arcus1	83	112	22	3691	3691	0
arcus2	111	176	3	50133	50133	0
arcus2	111	176	4	37600	37600	0
arcus2	111	176	5	30080	30080	0
arcus2	111	176	6	25067	25067	0
arcus2	111	176	7	21486	21486	0
arcus2	111	176	8	18800	18801	5.31915E-05
arcus2	111	176	9	16711	16713	0.000119682
arcus2	111	176	10	15040	15043	0.000199468
arcus2	111	176	11	13673	13676	0.000219411
arcus2	111	176	12	12534	12537	0.000239349
arcus2	111	176	13	11570	11574	0.000345722
arcus2	111	176	14	10747	10751	0.000372197
arcus2	111	176	15	10035	10040	0.000498256
arcus2	111	176	16	9412	9424	0.001274968
arcus2	111	176	17	8855	8874	0.00214568
arcus2	111	176	27	5689	5694	0.000878889
barthold	148	173	3	1878	1878	0
barthold	148	173	4	1409	1409	0
barthold	148	173	5	1127	1127	0
barthold	148	173	6	939	939	0
barthold	148	173	7	805	805	0
barthold	148	173	8	705	705	0
barthold	148	173	9	626	626	0
barthold	148	173	10	564	564	0
barthold	148	173	11	513	513	0

Table E.3 (Continued)

barthold	148	173	12	470	470	0
barthold	148	173	13	434	434	0
barthold	148	173	14	403	403	0
barthold	148	173	15	383	383	0
barthold2	148	173	27	157	157	0
barthold2	148	173	28	152	152	0
barthold2	148	173	29	146	146	0
barthold2	148	173	30	142	142	0
barthold2	148	173	31	137	137	0
barthold2	148	173	32	133	133	0
barthold2	148	173	33	129	129	0
barthold2	148	173	34	125	125	0
barthold2	148	173	35	121	121	0
barthold2	148	173	36	118	118	0
barthold2	148	173	37	115	115	0
barthold2	148	173	38	112	112	0
barthold2	148	173	39	109	109	0
barthold2	148	173	40	106	106	0
barthold2	148	173	41	104	104	0
barthold2	148	173	42	101	101	0
barthold2	148	173	43	99	99	0
barthold2	148	173	44	97	97	0
barthold2	148	173	45	95	95	0
barthold2	148	173	46	93	93	0
barthold2	148	173	47	91	91	0
barthold2	148	173	48	89	89	0
barthold2	148	173	49	87	87	0
barthold2	148	173	50	85	86	0.011764706
barthold2	148	173	51	84	84	0
buxey	29	36	7	47	48	0.021276596
buxey	29	36	8	41	41	0
buxey	29	36	9	37	37	0
buxey	29	36	10	34	34	0
buxey	29	36	11	32	32	0
buxey	29	36	12	28	28	0
buxey	29	36	13	27	27	0
buxey	29	36	14	25	25	0
gunther	35	45	6	84	84	0
gunther	35	45	7	72	72	0
gunther	35	45	8	63	63	0
gunther	35	45	9	54	54	0
gunther	35	45	10	50	50	0
gunther	35	45	11	48	48	0
gunther	35	45	12	44	44	0
gunther	35	45	13	42	42	0
gunther	35	45	14	40	40	0
gunther	35	45	15	40	40	0
hahn	53	82	3	4787	4787	0
hahn	53	82	4	3677	3677	0
hahn	53	82	5	2823	2823	0
hahn	53	82	6	2400	2400	0

Table E.3 (Continued)

hahn	53	82	7	2336	2336	0
hahn	53	82	8	1907	1907	0
hahn	53	82	9	1827	1827	0
hahn	53	82	10	1775	1775	0
kilbridge	45	62	3	184	184	0
kilbridge	45	62	4	138	138	0
kilbridge	45	62	5	111	111	0
kilbridge	45	62	6	92	92	0
kilbridge	45	62	7	79	79	0
kilbridge	45	62	8	69	69	0
kilbridge	45	62	9	62	62	0
kilbridge	45	62	10	56	56	0
kilbridge	45	62	11	55	55	0
lutz1	32	38	8	1860	1860	0
lutz1	32	38	9	1638	1638	0
lutz1	32	38	10	1526	1526	0
lutz1	32	38	11	1400	1400	0
lutz1	32	38	12	1400	1400	0
lutz2	89	118	9	54	54	0
lutz2	89	118	10	49	49	0
lutz2	89	118	11	45	45	0
lutz2	89	118	12	41	41	0
lutz2	89	118	13	38	38	0
lutz2	89	118	14	35	35	0
lutz2	89	118	15	33	33	0
lutz2	89	118	16	31	31	0
lutz2	89	118	17	29	29	0
lutz2	89	118	18	28	28	0
lutz2	89	118	19	26	26	0
lutz2	89	118	20	25	25	0
lutz2	89	118	21	24	24	0
lutz2	89	118	22	23	23	0
lutz2	89	118	23	22	22	0
lutz2	89	118	24	21	21	0
lutz2	89	118	25	20	20	0
lutz2	89	118	26	19	19	0
lutz2	89	118	27	19	19	0
lutz2	89	118	28	18	18	0
Lutz3	89	118	3	548	548	0
Lutz3	89	118	4	411	411	0
Lutz3	89	118	5	329	329	0
Lutz3	89	118	6	275	275	0
Lutz3	89	118	7	236	236	0
Lutz3	89	118	8	207	207	0
Lutz3	89	118	9	184	185	0.005434783
Lutz3	89	118	10	165	166	0.006060606
Lutz3	89	118	11	151	151	0
Lutz3	89	118	12	138	138	0
Lutz3	89	118	13	128	128	0
Lutz3	89	118	14	118	119	0.008474576
Lutz3	89	118	15	110	111	0.009090909

Table E.3 (Continued)

Lutz3	89	118	16	105	105	0
Lutz3	89	118	17	98	98	0
Lutz3	89	118	18	93	93	0
Lutz3	89	118	19	89	89	0
Lutz3	89	118	20	85	85	0
Lutz3	89	118	21	80	80	0
Lutz3	89	118	22	76	77	0.013157895
Lutz3	89	118	23	74	74	0
mukherje	94	181	3	1403	1403	0
mukherje	94	181	4	1052	1052	0
mukherje	94	181	5	844	844	0
mukherje	94	181	6	704	704	0
mukherje	94	181	7	621	621	0
mukherje	94	181	8	532	532	0
mukherje	94	181	9	471	471	0
mukherje	94	181	10	424	424	0
mukherje	94	181	11	391	391	0
mukherje	94	181	12	358	358	0
mukherje	94	181	13	325	326	0.003076923
mukherje	94	181	14	311	311	0
mukherje	94	181	15	288	288	0
mukherje	94	181	16	268	270	0.007462687
mukherje	94	181	17	251	251	0
mukherje	94	181	18	239	239	0
mukherje	94	181	19	226	226	0
mukherje	94	181	20	220	221	0.004545455
mukherje	94	181	21	208	208	0
mukherje	94	181	22	200	200	0
mukherje	94	181	23	189	189	0
mukherje	94	181	24	179	179	0
mukherje	94	181	25	172	172	0
mukherje	94	181	26	171	171	0
sawyer	30	32	7	47	48	0.021276596
sawyer	30	32	8	41	41	0
sawyer	30	32	9	37	37	0
sawyer	30	32	10	34	34	0
sawyer	30	32	11	31	31	0
sawyer	30	32	12	28	28	0
sawyer	30	32	13	26	26	0
sawyer	30	32	14	25	25	0
scholl	297	423	25	2787	2796	0.003229279
scholl	297	423	26	2680	2687	0.00261194
scholl	297	423	27	2580	2587	0.002713178
scholl	297	423	28	2488	2496	0.003215434
scholl	297	423	29	2402	2408	0.002497918
scholl	297	423	30	2322	2330	0.003445306
scholl	297	423	31	2247	2257	0.004450378
scholl	297	423	32	2177	2195	0.008268259
scholl	297	423	33	2111	2127	0.007579346
scholl	297	423	34	2049	2068	0.009272816
scholl	297	423	35	1991	2007	0.008036163

Table E.3 (Continued)

scholl	297	423	36	1935	1952	0.00878553
scholl	297	423	37	1883	1901	0.009559214
scholl	297	423	38	1834	1849	0.008178844
scholl	297	423	39	1787	1798	0.006155568
scholl	297	423	40	1742	1757	0.008610792
scholl	297	423	42	1659	1671	0.007233273
scholl	297	423	43	1621	1634	0.008019741
scholl	297	423	44	1584	1592	0.005050505
scholl	297	423	45	1549	1558	0.0058102
scholl	297	423	46	1515	1532	0.011221122
scholl	297	423	47	1483	1506	0.015509103
scholl	297	423	48	1452	1474	0.015151515
scholl	297	423	50	1394	1419	0.017934003
scholl	297	423	51	1386	1395	0.006493506
scholl	297	423	52	1386	1386	0
tonge	70	86	3	1170	1170	0
tonge	70	86	4	878	878	0
tonge	70	86	5	702	702	0
tonge	70	86	6	585	585	0
tonge	70	86	7	502	502	0
tonge	70	86	8	439	439	0
tonge	70	86	9	391	391	0
tonge	70	86	10	352	352	0
tonge	70	86	11	320	320	0
tonge	70	86	12	294	294	0
tonge	70	86	13	271	271	0
tonge	70	86	14	251	252	0.003984064
tonge	70	86	15	235	235	0
tonge	70	86	16	221	221	0
tonge	70	86	17	208	209	0.004807692
tonge	70	86	18	196	197	0.005102041
tonge	70	86	19	186	190	0.021505376
tonge	70	86	20	177	178	0.005649718
tonge	70	86	21	170	172	0.011764706
tonge	70	86	22	162	162	0
tonge	70	86	23	156	157	0.006410256
tonge	70	86	24	156	156	0
tonge	70	86	25	156	156	0
warnecke	58	70	3	516	516	0
warnecke	58	70	4	387	388	0.002583979
warnecke	58	70	5	310	310	0
warnecke	58	70	6	258	258	0
warnecke	58	70	7	222	222	0
warnecke	58	70	8	194	194	0
warnecke	58	70	9	172	173	0.005813953
warnecke	58	70	10	155	156	0.006451613
warnecke	58	70	11	142	142	0
warnecke	58	70	12	130	130	0
warnecke	58	70	13	120	120	0
warnecke	58	70	14	111	111	0
warnecke	58	70	15	104	104	0

Table E.3 (Continued)

warnecke	58	70	16	98	98	0
warnecke	58	70	17	92	92	0
warnecke	58	70	18	87	87	0
warnecke	58	70	19	84	84	0
warnecke	58	70	20	79	79	0
warnecke	58	70	21	76	76	0
warnecke	58	70	22	73	73	0
warnecke	58	70	23	69	69	0
warnecke	58	70	24	66	66	0
warnecke	58	70	25	64	65	0.015625
warnecke	58	70	26	64	64	0
warnecke	58	70	27	60	60	0
warnecke	58	70	28	59	59	0
warnecke	58	70	29	56	56	0
wee-Mag	75	87	3	500	500	0
wee-Mag	75	87	4	375	375	0
wee-Mag	75	87	5	300	300	0
wee-Mag	75	87	6	250	250	0
wee-Mag	75	87	7	215	215	0
wee-Mag	75	87	8	188	188	0
wee-Mag	75	87	9	167	167	0
wee-Mag	75	87	10	150	150	0
wee-Mag	75	87	11	137	137	0
wee-Mag	75	87	12	125	125	0
wee-Mag	75	87	13	116	116	0
wee-Mag	75	87	14	108	108	0
wee-Mag	75	87	15	100	100	0
wee-Mag	75	87	16	94	94	0
wee-Mag	75	87	17	89	89	0
wee-Mag	75	87	20	77	77	0
wee-Mag	75	87	21	72	72	0
wee-Mag	75	87	22	69	69	0
wee-Mag	75	87	24	66	66	0
wee-Mag	75	87	25	66	66	0
wee-Mag	75	87	26	65	65	0
wee-Mag	75	87	29	63	63	0
wee-Mag	75	87	30	56	56	0

Table E.4 Descriptive statistics of deviations for SALBP-II

problem	average of deviations	std.dev. of deviations	Min. deviation	Max. deviation
arcus1	0.00305	0.004244	0	0.014393
arcus2	0.000397	0.000586	0	0.002146
barthold	0	0	0	0
barthold2	0.000471	0.002353	0	0.011765
Buxey	0.00266	0.007522	0	0.021277
gunther	0	0	0	0
hahn	0	0	0	0
kilbridge	0	0	0	0
lutz1	0	0	0	0
lutz2	0	0	0	0
lutz3	0.00201	0.003931	0	0.013158
mukherje	0.000629	0.001822	0	0.007463
sawyer	0.00266	0.007522	0	0.021277
scholl	0.00727	0.004281	0	0.017934
tonge	0.002575	0.005163	0	0.021505
warnecke	0.001129	0.00335	0	0.015625
wee-mag	0	0	0	0

Table E.5 Sequences and number of common tasks between successive models in a sequence

sequence	Model				# of common tasks between first and second model	# of common tasks between second and third model	# of common tasks between third and fourth model
1	1	2	3	4	267	264	264
2	1	2	4	3	267	269	264
3	1	3	2	4	261	264	269
4	1	3	4	2	261	264	269
5	1	4	2	3	254	269	264
6	1	4	3	2	254	264	264
7	2	1	3	4	267	261	264
8	2	1	4	3	267	254	264
9	2	3	1	4	264	261	254
10	2	3	4	1	264	264	254
11	2	4	1	3	269	254	261
12	2	4	3	1	269	264	261
13	3	1	2	4	261	267	269
14	3	1	4	2	261	254	269
15	3	2	1	4	264	267	254
16	3	2	4	1	264	269	254
17	3	4	1	2	264	254	267
18	3	4	2	1	264	269	267
19	4	1	2	3	254	267	264
20	4	1	3	2	254	261	264
21	4	2	1	3	269	267	261
22	4	2	3	1	269	264	261
23	4	3	1	2	264	261	267
24	4	3	2	1	264	264	267

Table E.6 Average values of common tasks that are assigned to the same stations with low level of the weight of the third objective

sequence	Average # of common tasks assigned to the same stations by the algorithm			Average % of common tasks assigned to the same stations by the algorithm			Average of the percentages
1	143.9	116.4	115.7	0.539	0.441	0.438	0.47271
2	132.1	141.3	122.2	0.495	0.525	0.463	0.4943
3	122.8	126.7	124.1	0.47	0.48	0.461	0.47059
4	118.3	122.3	135.1	0.453	0.463	0.502	0.47291
5	122	128.7	118.3	0.48	0.478	0.448	0.46895
6	128.3	118	113.3	0.505	0.447	0.429	0.46042
7	133.9	111.5	122.1	0.501	0.427	0.463	0.46373
8	135.7	128.6	123	0.508	0.506	0.466	0.49348
9	132.4	132	113.7	0.502	0.506	0.448	0.48497
10	124.4	117.4	124.4	0.471	0.445	0.49	0.46856
11	125.4	121.3	115.7	0.466	0.478	0.443	0.46234
12	140.2	121.2	118.3	0.521	0.459	0.453	0.47785
13	138.2	133.6	134.3	0.53	0.5	0.499	0.50971
14	129.9	119.7	141.2	0.498	0.471	0.525	0.49796
15	126.6	137.1	108.9	0.48	0.513	0.429	0.47392
16	130	142.2	132.3	0.492	0.529	0.521	0.51397
17	110.9	122	119.3	0.42	0.48	0.447	0.44907
18	117.6	130.6	137.9	0.445	0.486	0.516	0.48248
19	123.4	138.3	120.5	0.486	0.518	0.456	0.48675
20	128.5	119.8	114.1	0.506	0.459	0.432	0.4657
21	133	138.8	108.2	0.494	0.52	0.415	0.47628
22	130.1	131.4	136.1	0.484	0.498	0.521	0.50094
23	119.3	126.5	123.5	0.452	0.485	0.463	0.46637
24	115.5	132.4	131.6	0.438	0.502	0.493	0.4773
Average of percentages				0.485	0.484	0.468	**0.4788**

Table E.7 Average values of common tasks that are assigned to the same stations with intermediate level of the weight of the third objective

sequence	Average # of common tasks assigned to the same stations by the algorithm			Average % of common tasks assigned to the same stations by the algorithm			Average of the percentages
1	243.2	238.4	230	0.911	0.903	0.871	0.89503
2	240.4	229.2	240.4	0.9	0.852	0.911	0.88768
3	230	236.8	236.4	0.881	0.897	0.879	0.88567
4	233.8	235	242.7	0.896	0.89	0.902	0.89606
5	218	242.8	241.8	0.858	0.903	0.916	0.89226
6	206	235.4	242	0.811	0.892	0.917	0.87312
7	252.2	234.2	230	0.945	0.897	0.871	0.90437
8	249.4	218.8	242.4	0.934	0.861	0.918	0.90456
9	237	241.6	209.2	0.898	0.926	0.824	0.88234
10	237.8	230.4	227.2	0.901	0.873	0.894	0.88932
11	230.1	226.6	231.6	0.855	0.892	0.887	0.87829
12	230.4	236.8	238.2	0.857	0.897	0.913	0.88871
13	233.4	244	238.6	0.894	0.914	0.887	0.89837
14	237.2	216.8	243	0.909	0.854	0.903	0.88857
15	229	248	224.4	0.867	0.929	0.883	0.89324
16	228.6	223.4	224	0.866	0.83	0.882	0.85943
17	216.6	221.6	249.6	0.82	0.872	0.935	0.87591
18	215.4	239.1	253	0.816	0.889	0.948	0.88411
19	205.2	249.2	242.2	0.808	0.933	0.917	0.88621
20	205.2	235.8	240.8	0.808	0.903	0.912	0.87448
21	218.3	251.6	236	0.812	0.942	0.904	0.88602
22	218.1	241.6	242.6	0.811	0.915	0.93	0.88514
23	213.4	234	244.2	0.808	0.897	0.915	0.87316
24	217	222	251.2	0.822	0.841	0.941	0.8679
Average of percentages				0.862	0.892	0.902	**0.88541**

Table E.8 Average values of common tasks that are assigned to the same stations with high level of the weight of the third objective

sequence	Average # of common tasks assigned to the same stations by the algorithm			Average % of common tasks assigned to the same stations by the algorithm			Average of the percentages
1	255.1	259	254.2	0.955	0.981	0.963	0.96646
2	251.1	242.7	253.8	0.94	0.902	0.961	0.93468
3	251.7	254.5	260.8	0.964	0.964	0.97	0.96597
4	243.1	233	263.8	0.931	0.883	0.981	0.93155
5	233.2	262.2	250.9	0.918	0.975	0.95	0.94774
6	224.3	255.5	251.5	0.883	0.968	0.953	0.93451
7	253.9	251.8	250.4	0.951	0.965	0.948	0.95472
8	257.2	239.7	258.2	0.963	0.944	0.978	0.96168
9	244.3	246.5	244	0.925	0.944	0.961	0.94348
10	240.9	227.4	248	0.913	0.861	0.976	0.91675
11	234.1	244.3	258.3	0.87	0.962	0.99	0.94058
12	238.8	252.8	253.5	0.888	0.958	0.971	0.93886
13	231.2	245.4	256.6	0.886	0.919	0.954	0.91961
14	239	231.7	259.7	0.916	0.912	0.965	0.93111
15	222.2	254.9	245.9	0.842	0.955	0.968	0.92149
16	227.7	234.8	242.8	0.863	0.873	0.956	0.89709
17	217.3	237.8	261.9	0.823	0.936	0.981	0.91341
18	216.5	253.2	259.9	0.82	0.941	0.973	0.91158
19	244.8	260.4	255.7	0.964	0.975	0.969	0.96921
20	244.2	252.3	258.2	0.961	0.967	0.978	0.9687
21	251	258.8	253.6	0.933	0.969	0.972	0.95801
22	242.8	248	246.9	0.903	0.939	0.946	0.92932
23	255.5	247.2	262.2	0.968	0.947	0.982	0.96565
24	246.2	248.3	251.4	0.933	0.941	0.942	0.93823
Average of percentages				0.913	0.941	0.966	**0.94002**

Table E.9 Average values of TSTs at the beginning of the runs with low level of the weight of the third objective

Sequence	Average Values of TST	Average Values of TST	Average Values of TST	Average Values of TST
1	256.2	300.8	317.4	315.47
2	256.2	333.78	305.69	327.74
3	256.2	294.4	319.72	356.2
4	256.2	299.2	319.7	330.43
5	256.2	293.57	306.65	318.31
6	256.2	289.7	296.94	331.9
7	242	265.16	366.44	307.83
8	242	263.2	309.94	369.02
9	242	289.83	270.48	375.93
10	242	270.71	267.71	273
11	242	284.14	265.16	315.31
12	242	268.32	294.3	268.8
13	282	260.96	330.19	341.02
14	287.04	262.36	319.5	338.03
15	287.04	246.64	268.52	358.63
16	287.04	245.77	266.71	271.04
17	276.96	270.54	261.52	361.08
18	292.08	281.91	247.22	268.8
19	281.84	256.2	320.42	321.52
20	276.8	257.88	286.55	329.82
21	266.72	242.87	267.12	282.94
22	266.72	243.45	281.98	272.16
23	266.72	282.57	259.84	343.63
24	281.84	282.87	248.38	267.96
Avg. of the columns	264.25	274.4513	291.5867	318.6071
StdD. of the columns	17.3995	21.98391	30.27326	34.967
Avg. of the values of Model1 in the column	256.2	260.96	265.44	270.2933
StdD. of the values of Model1 in the column	0	3.36932	4.111331	2.062646
Avg. of the values of Model2 in the column	242	268.885	295.43	339.1483
StdD. of the values of Model2 in the column	0	38.94301	37.6472	11.98248
Avg. of the values of Model3 in the column	285.36	286.5967	307.2683	322.4733
StdD. of the values of Model3 in the column	5.20529	10.12599	31.45644	27.66503
Avg. of the values of Model4 in the column	273.44	281.3633	298.2083	342.5133
StdD. of the values of Model4 in the column	7.587948	10.13691	24.62165	26.45846

Table E.10 Average values of TSTs at the end of the runs with low level of the weight of the third objective

Sequence	Average Values of TST	Average Values of TST	Average Values of TST	Average Values of TST
1	97.62	77.07	48.35	68.46
2	79.45	66.22	66.81	46.6
3	81.05	69.83	64.57	66.61
4	84.13	53.69	57.44	62.06
5	97.66	67.3	77.09	50.8
6	74.26	55.69	67.66	86.67
7	83.81	87.77	66.47	66.37
8	85.3	86.26	71.27	61.31
9	81.68	69.05	96.79	52.13
10	90.78	69.32	81.43	84.71
11	81.75	73.81	93.74	58.35
12	87.17	80	71.44	88.14
13	69.54	83.18	60.18	61.89
14	64.75	96.09	60.95	71.87
15	75.45	81.83	95.94	63.44
16	67.43	84.46	77.42	85.31
17	58.48	84.78	93.5	63.96
18	70.98	86.14	91.54	82.02
19	85.49	89.22	94.22	56.77
20	81.22	88.56	65.21	67.6
21	81.94	61.68	71.66	73.15
22	73.95	86.34	72.64	86.91
23	80.14	72.67	96.5	79.71
24	67.66	67.54	88.68	89.24
Avg. of the columns	79.23708	76.60417	76.3125	69.75333
StdD. of the columns	9.702825	11.30089	14.42611	12.90015
Avg. of the values of Model1 in the column	85.695	88.51333	91.355	86.055
StdD. of the values of Model1 in the column	9.789294	4.289101	9.748997	2.602604
Avg. of the values of Model2 in the column	85.08167	76.26667	79.38	71.97833
StdD. of the values of Model2 in the column	3.497664	10.1381	14.4762	9.565273
Avg. of the values of Model3 in the column	67.77167	67.01667	65.295	57.83
StdD. of the values of Model3 in the column	5.795852	6.740753	8.784351	9.205874
Avg. of the values of Model4 in the column	78.4	74.62	69.22	63.15
StdD. of the values of Model4 in the column	6.464206	11.64014	9.311241	5.893186

Table E.11 Average values of numbers of stations at the beginning of the runs with low level of the weight of the third objective

Sequence	Average Values of m	Average Values of m	Average Values of m	Average Values of m
1	34	34.1	32.8	34.7
2	34	34.5	35.3	32.7
3	34	33.1	34	34.2
4	34	33.1	36	34
5	34	36.3	34.3	32.6
6	34	36	33.2	34.2
7	35	34	31.5	31.3
8	35	34	34.1	32
9	35	35	34	28.3
10	35	34.6	37.5	34
11	35	38	34	31.6
12	35	37.7	35.1	34
13	35	34	32.7	33
14	35.1	34	35.9	34
15	35.1	35	34	28.4
16	35.1	35	37.5	34
17	34.9	37.8	34	32.9
18	35.2	38	35	34
19	38.1	34	33.8	32.3
20	38	34	33.1	34.2
21	37.8	35	34	26.4
22	37.8	35	34.8	34
23	37.8	35	34	32.9
24	38.1	35	35	34
Avg. of the columns	35.5	35.09167	34.4	32.65417
StdD. of the columns	1.501014	1.475279	1.395334	2.144351
Avg. of the values of Model1 in the column	34	34	34	34
StdD. of the values of Model1 in the column	0	0	0	0
Avg. of the values of Model2 in the column	35	34.76667	34.13333	33.7
StdD. of the values of Model2 in the column	0	0.382971	0.861781	0.626099
Avg. of the values of Model3 in the column	35.06667	34.3	33.41667	31.26667
StdD. of the values of Model3 in the column	0.10328	0.942338	1.337784	2.417988
Avg. of the values of Model4 in the column	37.93333	37.3	36.05	31.65
StdD. of the values of Model4 in the column	0.150555	0.903327	1.311106	2.811939

Table E.12 Average values of numbers of stations at the end of the runs with low level of the weight of the third objective

Sequence	Average Values of m	Average Values of m	Average Values of m	Average Values of m
1	31.7	30.8	28.4	30.9
2	31.4	30.3	31.4	28.3
3	31.4	29.5	30.2	30.1
4	31.5	29.1	31.7	29.9
5	31.6	32.6	30.8	28.6
6	31.2	32	29.5	30.6
7	32.8	31.6	27.4	28.1
8	32.6	31.4	30.7	27.6
9	32.6	31.6	31.6	25.5
10	32.9	31.4	34.6	31.4
11	32.5	34.7	31.2	27.8
12	32.5	34.5	31.4	31.4
13	31.5	31.6	28.7	29.2
14	31.7	31.4	31.7	29.6
15	31.6	32.5	31.6	25.7
16	31.3	32.7	34.2	31.3
17	31.1	34.7	31.6	28.5
18	31.5	34.4	32.6	31.2
19	34.5	31.6	30.2	28.4
20	34.7	31.3	29.6	29.8
21	34.5	32.4	31.7	24.1
22	34.6	32.7	31.5	31.2
23	34.4	31.3	31.6	28.9
24	34.3	31.5	32.3	31.3
Avg. of the columns	32.51667	31.98333	31.09167	29.14167
StdD. of the columns	1.28153	1.478444	1.633858	2.012551
Avg. of the values of Model1 in the column	31.46667	31.48333	31.55	31.3
StdD. of the values of Model1 in the column	0.175119	0.132916	0.176068	0.089443
Avg. of the values of Model2 in the column	32.65	31.9	30.8	29.55
StdD. of the values of Model2 in the column	0.164317	1.063955	1.457395	0.750333
Avg. of the values of Model3 in the column	31.45	30.73333	29.63333	27.46667
StdD. of the values of Model3 in the column	0.216795	1.121903	1.620699	1.691942
Avg. of the values of Model4 in the column	34.5	33.81667	32.38333	28.25
StdD. of the values of Model4 in the column	0.141421	1.195687	1.609244	2.255438

Table E.13 Average values of the differences between the theoretical minimum numbers of used stations and the numbers of used stations found with the algorithm at the end of the runs with low level of the weight of the third objective

Sequence	Average Values of Dm	Average Values of Dm	Average Values of Dm	Average Values of Dm
1	2.002462	1.465766	0.879251	1.209113
2	1.634437	1.249198	1.205739	0.844662
3	1.665297	1.310623	1.212582	1.137272
4	1.73107	1.003551	1.058022	1.153746
5	1.995505	1.274139	1.470622	0.930914
6	1.522345	1.03938	1.273001	1.628217
7	1.723067	1.807455	1.137211	1.040282
8	1.738687	1.76473	1.245544	1.063856
9	1.669324	1.415249	1.979346	0.714893
10	1.862918	1.409516	1.642727	1.735505
11	1.664292	1.502035	1.891445	1.019748
12	1.767437	1.609982	1.450264	1.800613
13	1.419473	1.719305	1.062125	1.019269
14	1.336705	1.95067	1.121023	1.31054
15	1.538226	1.66592	1.963168	0.859854
16	1.367748	1.728966	1.544385	1.739955
17	1.185486	1.712381	1.917162	1.117986
18	1.4468	1.720048	1.856795	1.670468
19	1.713913	1.835425	1.730395	1.026397
20	1.644462	1.801831	1.235272	1.249307
21	1.646704	1.270443	1.501047	1.05161
22	1.499696	1.764922	1.478526	1.763238
23	1.606978	1.468081	1.973819	1.400141
24	1.363838	1.380621	1.782871	1.81419
Avg. of the columns	1.614453	1.53626	1.483848	1.262574
StdD. of the columns	0.200055	0.25847	0.341323	0.344074
Avg. of the values of Model1 in the column	1.758519	1.813236	1.870998	1.753995
StdD. of the values of Model1 in the column	0.198135	0.078383	0.18451	0.051764
Avg. of the values of Model2 in the column	1.737621	1.524203	1.519232	1.309989
StdD. of the values of Model2 in the column	0.073271	0.229519	0.326615	0.186738
Avg. of the values of Model3 in the column	1.382406	1.331274	1.242254	0.989531
StdD. of the values of Model3 in the column	0.119064	0.168614	0.220405	0.084939
Avg. of the values of Model4 in the column	1.579265	1.476328	1.302906	0.99678
StdD. of the values of Model4 in the column	0.126836	0.270351	0.236462	0.181896

Table E.14 Average values of cycle times at the beginning of the runs with low level of the weight of the third objective

Sequence	Average Values of C	Average Values of C	Average Values of C	Average Values of C
1	50.4	54.24	55.93	57.78
2	50.4	54.57	56.15	56.54
3	50.4	54.43	55.04	60.31
4	50.4	54.6	55.19	55.42
5	50.4	53.8	54	56.39
6	50.4	54.19	54.3	55.06
7	50.4	50.72	60.75	65.34
8	50.4	50.65	58.84	59.67
9	50.4	50.67	50.91	79.03
10	50.4	50.71	50.91	51
11	50.4	50.63	50.72	58.85
12	50.4	50.61	50.65	50.85
13	50.4	50.57	58.2	62.72
14	50.4	50.62	55.38	55.7
15	50.4	50.56	50.84	78.36
16	50.4	50.53	50.88	50.93
17	50.4	50.52	50.59	59.01
18	50.4	50.56	50.58	50.85
19	50.4	50.4	55.51	57.14
20	50.4	50.46	54.11	54.97
21	50.4	50.43	50.79	72.14
22	50.4	50.45	50.75	50.97
23	50.4	50.42	50.53	58.22
24	50.4	50.43	50.62	50.82
Avg. of the columns	50.4	51.49042	53.42375	58.66958
StdD. of the columns	1.49E-06	1.668145	3.1085	7.993274
Avg. of the values of Model1 in the column	50.4	50.57	50.73	50.90333
StdD. of the values of Model1 in the column	6.03E-07	0.120333	0.146833	0.073666
Avg. of the values of Model2 in the column	50.4	51.79667	53.99167	56.39667
StdD. of the values of Model2 in the column	6.03E-07	2.023677	2.970592	1.755866
Avg. of the values of Model3 in the column	50.4	51.87667	54.415	60.12167
StdD. of the values of Model3 in the column	6.03E-07	2.047825	3.745428	6.031674
Avg. of the values of Model4 in the column	50.4	51.71833	54.55833	67.25667
StdD. of the values of Model4 in the column	6.03E-07	1.768224	3.123481	9.211012

Table E.15 Average values of cycle times at the end of the runs with low level of the weight of the third objective

Sequence	Average Values of C	Average Values of C	Average Values of C	Average Values of C
1	48.75	52.58	54.99	56.62
2	48.61	53.01	55.41	55.17
3	48.67	53.28	53.25	58.57
4	48.6	53.5	54.29	53.79
5	48.94	52.82	52.42	54.57
6	48.78	53.58	53.15	53.23
7	48.64	48.56	58.45	63.8
8	49.06	48.88	57.22	57.63
9	48.93	48.79	48.9	72.92
10	48.73	49.18	49.57	48.81
11	49.12	49.14	49.56	57.22
12	49.32	49.69	49.26	48.95
13	48.99	48.38	56.66	60.72
14	48.44	49.26	54.37	54.84
15	49.05	49.12	48.87	73.78
16	49.3	48.85	50.13	49.03
17	49.33	49.51	48.77	57.21
18	49.06	50.08	49.3	49.1
19	49.88	48.61	54.45	55.31
20	49.39	49.15	52.79	54.11
21	49.76	48.55	47.74	69.56
22	49.31	48.92	49.13	49.29
23	49.87	49.5	48.89	56.93
24	49.61	48.92	49.74	49.19
Avg. of the columns	49.08917	50.0775	51.97125	56.68125
StdD. of the columns	0.412858	1.847502	3.181611	7.166972
Avg. of the values of Model1 in the column	48.725	48.80667	48.78833	49.06167
StdD. of the values of Model1 in the column	0.127867	0.34938	0.587245	0.171396
Avg. of the values of Model2 in the column	48.96667	50.17167	52.63667	55.01833
StdD. of the values of Model2 in the column	0.25343	2.044773	2.807936	1.674615
Avg. of the values of Model3 in the column	49.02833	50.52833	52.96167	58.24333
StdD. of the values of Model3 in the column	0.320588	2.230986	3.540759	5.675095
Avg. of the values of Model4 in the column	49.63667	50.80333	53.49833	64.40167
StdD. of the values of Model4 in the column	0.243776	1.896256	3.022227	7.334773

Table E.16 Average values of the differences between the theoretical minimum cycle times and the cycle times found with the algorithm at the end of the runs with low level of the weight of the third objective

Sequence	Average Values of DC	Average Values of DC	Average Values of DC	Average Values of DC
1	0.30795	0.250227	0.170246	0.221553
2	0.253025	0.218548	0.212771	0.164664
3	0.258121	0.236712	0.213808	0.221296
4	0.267079	0.184502	0.181199	0.207559
5	0.309051	0.206442	0.250292	0.177622
6	0.238013	0.174031	0.229356	0.283235
7	0.255518	0.277753	0.242591	0.236192
8	0.261656	0.274713	0.23215	0.222138
9	0.250552	0.218513	0.306297	0.204431
10	0.275927	0.220764	0.235347	0.269777
11	0.251538	0.212709	0.300449	0.209892
12	0.268215	0.231884	0.227516	0.280701
13	0.220762	0.263228	0.209686	0.211952
14	0.204259	0.306019	0.192271	0.242804
15	0.238766	0.251785	0.303608	0.246848
16	0.215431	0.258287	0.226374	0.272556
17	0.188039	0.244323	0.295886	0.224421
18	0.225333	0.250407	0.280798	0.262885
19	0.247797	0.282342	0.311987	0.199894
20	0.234063	0.282939	0.220304	0.226846
21	0.237507	0.19037	0.226057	0.303527
22	0.213728	0.264037	0.230603	0.278558
23	0.232965	0.232173	0.30538	0.275813
24	0.197259	0.214413	0.274551	0.285112
Avg. of the columns	0.243857	0.239463	0.24498	0.238762
StdD. of the columns	0.030318	0.03381	0.042327	0.036995
Avg. of the values of Model1 in the column	0.272206	0.281166	0.289613	0.274931
StdD. of the values of Model1 in the column	0.029654	0.014123	0.031365	0.008092
Avg. of the values of Model2 in the column	0.260568	0.238876	0.256854	0.243446
StdD. of the values of Model2 in the column	0.010029	0.028536	0.040117	0.030188
Avg. of the values of Model3 in the column	0.215432	0.217846	0.220103	0.212956
StdD. of the values of Model3 in the column	0.017585	0.018405	0.025465	0.049088
Avg. of the values of Model4 in the column	0.22722	0.219966	0.213352	0.223712
StdD. of the values of Model4 in the column	0.018378	0.028311	0.022295	0.015566

Table E.17 Average values of TSTs at the beginning of the runs with intermediate level of the weight of the third objective

Sequence	Average Values of TST	Average Values of TST	Average Values of TST	Average Values of TST
1	256.2	313.22	318.65	329.15
2	256.2	296.93	265.11	279.11
3	256.2	302.47	304.07	322.97
4	256.2	317.61	327.35	310.69
5	256.2	326.3	327.11	319.24
6	256.2	284.18	285.02	293.37
7	242	261.52	313.69	331.53
8	242	263.76	289.04	289.62
9	242	275.2	265.44	303.6
10	242	268.37	264.84	263.48
11	242	283.5	262.36	284.44
12	242	274.03	278.84	264.04
13	292.08	260.4	300.45	297.76
14	287.04	263.76	302.77	303.04
15	292.08	247.8	263.2	328.34
16	282	244.61	277.17	260.96
17	297.12	286	260.12	305.79
18	271.92	271.16	247.22	262.64
19	256.64	257.6	309.32	302.72
20	266.72	257.88	289.56	308.62
21	256.64	242.87	260.4	306.66
22	261.68	242.87	280.98	263.76
23	261.68	293.24	257.88	293.88
24	276.8	278.68	245.19	260.12
Avg. of the columns	262.15	275.5817	283.1575	295.2304
StdD. of the columns	17.53099	23.58185	24.88857	23.42245
Avg. of the values of Model1 in the column	256.2	260.82	261.5667	262.5
StdD. of the values of Model1 in the column	0	2.719029	2.658772	1.610913
Avg. of the values of Model2 in the column	242	264.7167	288.8933	302.565
StdD. of the values of Model2 in the column	0	31.73414	34.31705	7.392999
Avg. of the values of Model3 in the column	287.04	289.2617	294.4567	296.965
StdD. of the values of Model3 in the column	9.015826	18.65518	17.28449	15.18496
Avg. of the values of Model4 in the column	263.36	287.5283	287.7133	318.8917
StdD. of the values of Model4 in the column	7.587948	19.91554	24.26846	14.49998

Table E.18 Average values of TSTs at the end of the runs with intermediate level of the weight of the third objective

Sequence	Average Values of TST	Average Values of TST	Average Values of TST	Average Values of TST
1	71.72	137.75	152.95	148.88
2	97.89	125.67	111.5	177.57
3	73.21	154.64	136.95	138.93
4	83.16	150.95	141.95	182.42
5	75.17	134.93	207.53	178.09
6	84.43	119.93	173.22	182.83
7	87.06	136.35	144.09	142.12
8	86.49	152.21	114.85	212.59
9	78.16	123.41	145.63	142.47
10	82.86	130.83	110.58	182.19
11	89.17	113.35	167.16	159.8
12	78.36	102.71	158.54	159.34
13	64.27	118.59	150.3	144.15
14	60.55	131.55	124.19	184.86
15	67.15	122.02	161.65	153.06
16	80.91	114.62	103.47	163.64
17	64.2	113.76	161.1	163.53
18	65.82	100.68	148.25	195.97
19	75.43	174.9	188	198.48
20	76.48	167.43	173.34	166.18
21	88.4	143.18	177.4	210.61
22	88.11	133.2	146.55	171.51
23	73.23	159.02	162.72	166.13
24	79.23	167.14	119.99	160.95
Avg. of the columns	77.9775	134.5342	149.2463	170.2625
StdD. of the columns	9.413729	20.57389	26.10953	20.92796
Avg. of the values of Model1 in the column	80.93	146.8383	162.61	172.2667
StdD. of the values of Model1 in the column	9.823081	21.82675	10.30515	14.35603
Avg. of the values of Model2 in the column	83.68333	129.4067	158.5033	174.325
StdD. of the values of Model2 in the column	4.667028	10.59128	32.84484	9.988807
Avg. of the values of Model3 in the column	67.15	147.665	158.115	189.5233
StdD. of the values of Model3 in the column	7.094553	16.96688	12.78491	21.04291
Avg. of the values of Model4 in the column	80.14667	114.2267	117.7567	144.935
StdD. of the values of Model4 in the column	6.571212	12.47628	13.63754	5.14306

Table E.19 Average values of numbers of stations at the beginning of the runs with intermediate level of the weight of the third objective

Sequence	Average Values of m	Average Values of m	Average Values of m	Average Values of m
1	34	34	32.8	34.6
2	34	34.7	36.1	33.4
3	34	32.9	33.5	35.2
4	34	33.2	35.9	33.5
5	34	36	33.9	32.6
6	34	36.2	33.3	34
7	35	34	33.7	35.5
8	35	34	36.5	33.5
9	35	34.7	34	34.7
10	35	34.6	37.6	34
11	35	38	34	32.6
12	35	37.8	34.8	34
13	35.2	34	34.9	36.2
14	35.1	34	36.7	34.5
15	35.2	35	34	35.6
16	35	35	37.9	34
17	35.3	38.1	34	34.9
18	34.8	37.8	35	34
19	37.6	34	34.7	33.1
20	37.8	34	33.7	34.5
21	37.6	35	34	33.1
22	37.7	35	34.9	34
23	37.7	35.2	34	34.6
24	38	34.9	35	34
Avg. of the columns	35.45833	35.0875	34.7875	34.17083
StdD. of the columns	1.416031	1.497625	1.350785	0.916268
Avg. of the values of Model1 in the column	34	34	34	34
StdD. of the values of Model1 in the column	0	0	0	0
Avg. of the values of Model2 in the column	35	34.78333	34.5	34.33333
StdD. of the values of Model2 in the column	0	0.402078	0.641872	0.500666
Avg. of the values of Model3 in the column	35.1	34.25	33.86667	33.05
StdD. of the values of Model3 in the column	0.178885	0.956556	0.831064	0.383406
Avg. of the values of Model4 in the column	37.73333	37.31667	36.78333	35.3
StdD. of the values of Model4 in the column	0.150555	0.951665	0.806019	0.6

Table E.20 Average values of numbers of stations at the end of the runs with intermediate level of the weight of the third objective

Sequence	Average Values of m	Average Values of m	Average Values of m	Average Values of m
1	31.3	31.3	30.5	31.8
2	31.4	31.6	33.3	31.7
3	31.4	30.5	30.7	32.3
4	31.6	30.6	32.8	31.4
5	31.5	32.8	32	30.7
6	31.3	33.3	31.5	32.1
7	32.5	31.9	31.2	32.4
8	32.7	32.1	33.4	32.3
9	32.6	31.9	31.9	32.2
10	32.5	32	34.6	32.6
11	32.6	34.7	32.5	30.9
12	32.4	34.5	32.6	32.1
13	31.3	31.5	32.3	33.5
14	31.8	31.8	33.5	32.6
15	31.6	32.7	32.2	32.7
16	31.4	32.6	34.5	32.3
17	31.2	34.8	32.3	32.6
18	31.4	34.5	33.2	32.9
19	34.6	32.9	32.9	31.8
20	34.8	32.7	31.9	32.3
21	34.8	33.3	32.7	31.6
22	34.8	33.1	32.6	32.6
23	34.4	32.7	32.4	32.5
24	34.7	32.9	32.6	32.2
Avg. of the columns	32.525	32.6125	32.50417	32.17083
StdD. of the columns	1.36326	1.188464	0.994541	0.616779
Avg. of the values of Model1 in the column	31.41667	32.15	32.33333	32.45
StdD. of the values of Model1 in the column	0.116905	0.543139	0.273252	0.301662
Avg. of the values of Model2 in the column	32.55	32.43333	32.28333	32.25
StdD. of the values of Model2 in the column	0.104881	0.809115	0.884119	0.459347
Avg. of the values of Model3 in the column	31.45	31.76667	31.71667	31.5
StdD. of the values of Model3 in the column	0.216795	1.01915	0.823205	0.596657
Avg. of the values of Model4 in the column	34.68333	34.1	33.68333	32.48333
StdD. of the values of Model4 in the column	0.160208	0.83666	0.713909	0.577639

Table E.21 Average values of the differences between the theoretical minimum numbers of used stations and the numbers of used stations found with the algorithm at the end of the runs with intermediate level of the weight of the third objective

Sequence	Average Values of Dm	Average Values of Dm	Average Values of Dm	Average Values of Dm
1	1.478763	2.564699	2.811064	2.560275
2	1.984391	2.389163	2.100999	3.35798
3	1.513541	2.839515	2.490453	2.472944
4	1.718892	2.789688	2.571092	3.299928
5	1.557927	2.456399	3.776706	3.237411
6	1.723061	2.24546	3.260919	3.396433
7	1.765565	2.734657	2.739354	2.522542
8	1.767989	3.03873	2.165347	4.008863
9	1.601639	2.452991	2.899841	2.502547
10	1.685517	2.595833	2.18624	3.624229
11	1.81203	2.244554	3.3499	2.93696
12	1.593655	2.034667	3.151262	3.164019
13	1.307098	2.374174	2.885945	2.674893
14	1.259098	2.637858	2.336155	3.496501
15	1.378567	2.428259	3.216915	2.741046
16	1.630264	2.285088	2.048505	3.263662
17	1.300385	2.259833	3.219424	3.143599
18	1.34217	1.997223	2.947902	3.90223
19	1.52816	3.537621	3.592586	3.714072
20	1.558907	3.380376	3.315608	3.151527
21	1.786942	2.868189	3.55511	3.864404
22	1.78144	2.668269	2.93923	3.439142
23	1.475519	3.17152	3.258963	3.175875
24	1.606448	3.338127	2.382645	3.20426
Avg. of the columns	1.589915	2.638871	2.883423	3.202306
StdD. of the columns	0.187076	0.418258	0.505731	0.452205
Avg. of the values of Model1 in the column	1.662763	2.950569	3.250026	3.432924
StdD. of the values of Model1 in the column	0.188332	0.450283	0.213445	0.286402
Avg. of the values of Model2 in the column	1.704399	2.533945	3.012706	3.27731
StdD. of the values of Model2 in the column	0.092249	0.212023	0.567442	0.146107
Avg. of the values of Model3 in the column	1.369597	2.864612	3.036239	3.519948
StdD. of the values of Model3 in the column	0.13393	0.336549	0.240838	0.410197
Avg. of the values of Model4 in the column	1.622903	2.206356	2.234723	2.579041
StdD. of the values of Model4 in the column	0.13199	0.168276	0.191393	0.105911

Table E.22 Average values of cycle times at the beginning of the runs with intermediate level of the weight of the third objective

Sequence	Average Values of C	Average Values of C	Average Values of C	Average Values of C
1	50.4	54.82	55.97	59.05
2	50.4	52.89	53.2	53.28
3	50.4	55.15	55.5	56.93
4	50.4	55.11	55.64	55.74
5	50.4	55.41	55.5	56.38
6	50.4	53.67	53.72	54.12
7	50.4	50.59	54.01	56.83
8	50.4	50.67	53.32	53.49
9	50.4	50.69	50.73	57.9
10	50.4	50.63	50.66	50.66
11	50.4	50.61	50.62	55.65
12	50.4	50.63	50.64	50.68
13	50.4	50.55	52.61	54.12
14	50.4	50.67	53.43	53.49
15	50.4	50.6	50.65	56.33
16	50.4	50.49	50.57	50.57
17	50.4	50.53	50.54	52.79
18	50.4	50.54	50.58	50.63
19	50.4	50.45	53.31	54.78
20	50.4	50.46	53.1	53.67
21	50.4	50.43	50.55	55.1
22	50.4	50.43	50.54	50.67
23	50.4	50.44	50.46	53.03
24	50.4	50.46	50.51	50.54
Avg. of the columns	50.4	51.53833	52.34833	54.01792
StdD. of the columns	1.49E-06	1.81435	1.979527	2.535847
Avg. of the values of Model1 in the column	50.4	50.565	50.59167	50.625
StdD. of the values of Model1 in the column	6.03E-07	0.097108	0.094956	0.057533
Avg. of the values of Model2 in the column	50.4	51.61	53.00167	53.80667
StdD. of the values of Model2 in the column	6.03E-07	1.844007	2.227316	1.057519
Avg. of the values of Model3 in the column	50.4	52.08	52.99667	54.78
StdD. of the values of Model3 in the column	6.03E-07	2.364504	2.097166	1.211066
Avg. of the values of Model4 in the column	50.4	51.89833	52.80333	56.86
StdD. of the values of Model4 in the column	6.03E-07	2.119268	1.920694	1.653602

Table E.23 Average values of cycle times at the end of the runs with intermediate level of the weight of the third objective

Sequence	Average Values of C	Average Values of C	Average Values of C	Average Values of C
1	48.5	53.71	54.41	58.15
2	49.33	52.6	53.07	52.88
3	48.37	54.46	54.99	56.18
4	48.38	54.11	55.21	55.28
5	48.25	54.93	54.95	55.01
6	49	53.41	53.12	53.83
7	49.31	49.86	52.6	56.34
8	48.92	50.09	53.04	53.03
9	48.8	50.31	50.22	56.93
10	49.16	50.4	50.58	50.27
11	49.21	50.5	49.9	54.41
12	49.17	50.48	50.31	50.36
13	49.17	49.95	52.08	53.89
14	48.09	49.87	53.16	52.87
15	48.71	50.25	50.25	55.84
16	49.63	50.16	50.51	50.14
17	49.37	50.34	50.04	52.02
18	49.04	50.41	50.29	50.22
19	49.36	49.44	52.33	53.44
20	49.06	49.53	52.28	52.73
21	49.47	49.92	49.9	54.5
22	49.46	49.92	49.86	49.87
23	49.63	50.14	49.93	52.31
24	49.32	50.07	50.36	50.23
Avg. of the columns	49.02958	51.03583	51.80792	53.36375
StdD. of the columns	0.440568	1.734775	1.849945	2.401255
Avg. of the values of Model1 in the column	48.63833	49.79	50.04	50.18167
StdD. of the values of Model1 in the column	0.428458	0.251794	0.159875	0.168691
Avg. of the values of Model2 in the column	49.095	51.09333	52.5	53.17333
StdD. of the values of Model2 in the column	0.193365	1.640289	2.091488	1.202775
Avg. of the values of Model3 in the column	49.00167	51.58167	52.09667	53.87833
StdD. of the values of Model3 in the column	0.543412	2.100204	1.72514	0.87844
Avg. of the values of Model4 in the column	49.38333	51.67833	52.595	56.22167
StdD. of the values of Model4 in the column	0.191485	1.989788	1.788214	1.401305

Table E.24 Average values of the differences between the theoretical minimum cycle times and the cycle times found with the algorithm at the end of the runs with intermediate level of the weight of the third objective

Sequence	Average Values of DC	Average Values of DC	Average Values of DC	Average Values of DC
1	0.229137	0.440096	0.501475	0.468176
2	0.311752	0.39769	0.334835	0.560158
3	0.233153	0.507016	0.446091	0.430124
4	0.263165	0.493301	0.432774	0.580955
5	0.238635	0.411372	0.648531	0.580098
6	0.269744	0.36015	0.549905	0.569564
7	0.267877	0.427429	0.461827	0.438642
8	0.264495	0.474174	0.343862	0.658173
9	0.239755	0.386865	0.45652	0.442453
10	0.254954	0.408844	0.319595	0.558865
11	0.273528	0.326657	0.514338	0.517152
12	0.241852	0.29771	0.486319	0.496386
13	0.205335	0.376476	0.465325	0.430299
14	0.190409	0.413679	0.370716	0.567055
15	0.2125	0.37315	0.502019	0.468073
16	0.257675	0.351595	0.299913	0.506625
17	0.205769	0.326897	0.498762	0.501626
18	0.209618	0.291826	0.446536	0.595653
19	0.218006	0.531611	0.571429	0.624151
20	0.21977	0.512018	0.543386	0.514489
21	0.254023	0.42997	0.542508	0.666487
22	0.25319	0.402417	0.44954	0.526104
23	0.212878	0.4863	0.502222	0.511169
24	0.228329	0.508024	0.368067	0.499845
Avg. of the columns	0.239814	0.41397	0.460687	0.52968
StdD. of the columns	0.028303	0.069749	0.086577	0.067813
Avg. of the values of Model1 in the column	0.257598	0.455898	0.502728	0.53058
StdD. of the values of Model1 in the column	0.031236	0.060194	0.027817	0.039351
Avg. of the values of Model2 in the column	0.257077	0.399153	0.490997	0.54081
StdD. of the values of Model2 in the column	0.013991	0.033397	0.101045	0.03531
Avg. of the values of Model3 in the column	0.213551	0.465058	0.498742	0.601037
StdD. of the values of Model3 in the column	0.022922	0.053159	0.041367	0.058701
Avg. of the values of Model4 in the column	0.231032	0.335769	0.350283	0.446295
StdD. of the values of Model4 in the column	0.018182	0.044388	0.046864	0.017572

Table E.25 Average values of TSTs at the beginning of the runs with high level of the weight of the third objective

Sequence	Average Values of TST	Average Values of TST	Average Values of TST	Average Values of TST
1	256.2	308.33	336.28	325.2
2	256.2	334	307.17	323.53
3	256.2	328.46	364.82	346.1
4	256.2	304.62	335.9	303.62
5	256.2	313.61	348.2	301.57
6	256.2	296.98	313.63	338.53
7	242	269.64	317.45	374.09
8	242	266.84	311.12	348.64
9	242	257.73	271.32	338.4
10	242	260.58	268.4	276.64
11	242	274.7	264.04	332.64
12	242	256.49	267.05	274.12
13	292.08	263.2	312.39	341.16
14	276.96	264.04	294.41	296.28
15	297.12	246.64	263.2	333.17
16	292.08	246.64	269.89	263.76
17	292.08	274.34	263.48	329.08
18	276.96	258.84	249.25	264.04
19	256.64	257.32	306.24	320.11
20	271.76	257.6	298.18	317.64
21	286.88	242.87	262.08	314.17
22	256.64	243.74	275.22	269.08
23	271.76	288.49	261.24	345.11
24	281.84	273.64	247.51	266
Avg. of the columns	264.25	274.5558	292.0196	314.2783
StdD. of the columns	18.80841	26.52214	33.08313	31.5232
Avg. of the values of Model1 in the column	256.2	263.1067	264.2267	268.94
StdD. of the values of Model1 in the column	0	4.925666	3.61912	5.396814
Avg. of the values of Model2 in the column	242	270.37	304.735	321.71
StdD. of the values of Model2 in the column	0	40.20291	48.81304	19.3664
Avg. of the values of Model3 in the column	287.88	285.5867	301.3017	323.4433
StdD. of the values of Model3 in the column	8.680903	27.39661	26.4553	16.09352
Avg. of the values of Model4 in the column	270.92	279.16	297.815	343.02
StdD. of the values of Model4 in the column	12.51572	22.24549	25.96786	16.81791

Table E.26 Average values of TSTs at the end of the runs with high level of the weight of the third objective

Sequence	Average Values of TST	Average Values of TST	Average Values of TST	Average Values of TST
1	106.7	211.23	216	178.94
2	92.26	227.18	175.26	314.76
3	78.33	199.82	313.7	286.18
4	101.72	197.62	158.78	256.06
5	93.97	202.44	349.52	335.9
6	101.31	166.59	276.71	315.14
7	93.41	184.79	274.85	269.45
8	96.31	170.37	255.76	374.97
9	96.33	205.57	222	258.92
10	94.6	207.93	141.2	295.34
11	89.62	155.29	278.69	282.85
12	91.5	155.14	303.85	317.56
13	94.21	163.99	253.51	192.33
14	95.76	162.1	213.45	335.9
15	123.85	167.21	219.19	225.85
16	112.25	163.43	156.38	279.75
17	88.33	160.89	278.95	344.71
18	112.51	150.45	256.84	302.76
19	132.09	305.17	307.85	315.67
20	102.12	275.1	290.29	314.32
21	106.19	234.16	302.25	313.28
22	97.83	221.59	263.37	293.05
23	103.04	263.27	293.06	333.03
24	110.69	286.22	263.46	321.26
Avg. of the columns	100.6221	201.5646	252.705	294.0825
StdD. of the columns	11.70225	44.74557	54.54121	46.41638
Avg. of the values of Model1 in the column	95.715	210.2533	265.69	301.62
StdD. of the values of Model1 in the column	10.05241	63.10684	36.06007	15.699
Avg. of the values of Model2 in the column	93.62833	204.1333	290.8133	316.5267
StdD. of the values of Model2 in the column	2.686212	31.00949	38.87017	31.95308
Avg. of the values of Model3 in the column	104.485	226.7383	270.845	322.905
StdD. of the values of Model3 in the column	13.72869	38.07087	30.27119	30.6443
Avg. of the values of Model4 in the column	108.66	165.1333	183.4717	235.2783
StdD. of the values of Model4 in the column	12.25424	19.10117	43.17931	43.41675

Table E.27 Average values of numbers of stations at the beginning of the runs with high level of the weight of the third objective

Sequence	Average Values of m	Average Values of m	Average Values of m	Average Values of m
1	34	33.5	32.5	31.2
2	34	34	35.2	32.4
3	34	32.4	32.7	31.7
4	34	33.1	36	33.3
5	34	34.8	33.2	31.2
6	34	35.6	33	33.4
7	35	34	30.9	29.4
8	35	34	33	30.2
9	35	34.3	34	30.5
10	35	34.3	37.4	34
11	35	37.8	34	30
12	35	37.3	34.4	34
13	35.2	34	33.9	35.8
14	34.9	34	35	32.7
15	35.3	35	34	31.7
16	35.2	35	37.7	34
17	35.2	37.8	34	33.6
18	34.9	37.5	35	34
19	37.6	34	33.8	30.8
20	37.9	34	32.9	32.5
21	38.2	35	34	32.4
22	37.6	35	34.7	34
23	37.9	35.1	34	34
24	38.1	34.8	35	34
Avg. of the columns	35.5	34.84583	34.17917	32.53333
StdD. of the columns	1.480599	1.440102	1.489377	1.642285
Avg. of the values of Model1 in the column	34	34	34	34
StdD. of the values of Model1 in the column	0	0	0	0
Avg. of the values of Model2 in the column	35	34.58333	33.93333	33.25
StdD. of the values of Model2 in the column	0	0.66458	0.933095	0.561249
Avg. of the values of Model3 in the column	35.11667	34	33.06667	31.16667
StdD. of the values of Model3 in the column	0.17224	1.03923	1.377921	1.046263
Avg. of the values of Model4 in the column	37.88333	36.8	35.71667	31.71667
StdD. of the values of Model4 in the column	0.248328	1.279062	1.732532	2.181208

Table E.28 Average values of numbers of stations at the end of the runs with high level of the weight of the third objective

Sequence	Average Values of m	Average Values of m	Average Values of m	Average Values of m
1	32.2	32.5	32.6	33.1
2	31.9	32.4	33.4	33.4
3	32	32.4	32.8	33.9
4	31.9	32	33.1	33
5	32.4	33.6	33.6	33.8
6	32	33.6	33.6	33.6
7	33.5	33.5	33.6	34.4
8	33.3	33.4	34.3	34.2
9	33.3	33.9	33.9	34.8
10	33.6	34.1	35.2	34.9
11	32.7	35.7	35.4	36.1
12	33.5	35.7	35.6	35.4
13	32.5	32.7	33	33.9
14	32.6	33	34.8	34.6
15	32.6	33.7	33.8	34.7
16	32.4	33.6	35.6	35
17	32.2	35.8	35	35
18	32.7	35.5	35.3	35.2
19	35.8	35.9	35.9	36.1
20	35.2	35.3	35.6	35.8
21	35.2	35.3	35.3	35.7
22	35.2	35.2	35.2	35.3
23	35.2	35.2	35.3	35.4
24	35.5	35.6	35.8	35.8
Avg. of the columns	33.30833	34.15	34.4875	34.7125
StdD. of the columns	1.308473	1.292453	1.074735	0.931251
Avg. of the values of Model1 in the column	32.06667	33.96667	34.78333	35.26667
StdD. of the values of Model1 in the column	0.196638	1.310979	0.73598	0.320416
Avg. of the values of Model2 in the column	33.31667	33.78333	34.4	34.56667
StdD. of the values of Model2 in the column	0.325064	1.257643	1.426885	1.076414
Avg. of the values of Model3 in the column	32.5	33.86667	34.36667	34.88333
StdD. of the values of Model3 in the column	0.178885	1.447296	1.267544	1.222157
Avg. of the values of Model4 in the column	35.35	34.98333	34.4	34.13333
StdD. of the values of Model4 in the column	0.250998	1.075949	0.993982	0.63456

Table E.29 Average values of the differences between the theoretical minimum numbers of used stations and the numbers of used stations found with the algorithm at the end of the runs with high level of the weight of the third objective

Sequence	Average Values of Dm	Average Values of Dm	Average Values of Dm	Average Values of Dm
1	2.215992	3.910942	4.114286	3.199356
2	1.9153	4.147134	3.175	5.768004
3	1.649747	3.822843	5.489064	4.92141
4	2.096455	3.730791	2.875407	4.680314
5	1.984164	3.627957	6.142707	6.156525
6	2.096214	3.055576	5.24072	5.655779
7	1.955002	3.791342	5.214381	4.765653
8	1.997304	3.518587	4.533948	6.784331
9	1.997305	4.138716	4.495747	4.673646
10	1.985726	4.209109	2.791617	5.884439
11	1.827488	3.09281	5.715546	5.817565
12	1.918641	3.089823	6.06366	6.341054
13	1.959035	3.318964	4.648148	3.509031
14	1.995	3.317642	3.963052	6.175768
15	2.527551	3.339525	4.431662	4.143276
16	2.292688	3.261425	3.101547	5.650374
17	1.824623	3.203066	5.641052	6.39299
18	2.324587	2.985711	5.097043	6.064904
19	2.680942	6.248362	6.026821	6.350231
20	2.073082	5.633832	5.843196	6.100932
21	2.149595	4.719065	6.076598	6.230708
22	1.992059	4.489263	5.329219	5.928586
23	2.090485	5.328274	5.929988	6.304998
24	2.257137	5.779887	5.29355	6.484861
Avg. of the columns	2.075255	3.990027	4.884748	5.582697
StdD. of the columns	0.225117	0.935749	1.073015	0.962567
Avg. of the values of Model1 in the column	1.992979	4.304788	5.381765	6.059036
StdD. of the values of Model1 in the column	0.197494	1.293977	0.72797	0.308351
Avg. of the values of Model2 in the column	1.946911	3.977892	5.449555	5.88513
StdD. of the values of Model2 in the column	0.065897	0.594104	0.566765	0.64334
Avg. of the values of Model3 in the column	2.153914	4.501603	5.30091	6.184561
StdD. of the values of Model3 in the column	0.2682	0.84729	0.677621	0.373709
Avg. of the values of Model4 in the column	2.207217	3.175824	3.406762	4.202062
StdD. of the values of Model4 in the column	0.24825	0.232403	0.691031	0.713674

Table E.30 Average values of cycle times at the beginning of the runs with high level of the weight of the third objective

Sequence	Average Values of C	Average Values of C	Average Values of C	Average Values of C
1	50.4	55.64	57.3	66.87
2	50.4	55.6	56.43	57.06
3	50.4	57.2	59.71	67.29
4	50.4	54.78	55.73	55.86
5	50.4	57.49	57.83	59.24
6	50.4	55.23	55.37	57.08
7	50.4	50.88	60.76	76.88
8	50.4	50.78	61.81	64.55
9	50.4	50.79	50.94	72.65
10	50.4	50.89	51.1	51.13
11	50.4	50.65	50.68	64.04
12	50.4	50.88	50.94	51.04
13	50.4	50.65	55.03	56.46
14	50.4	50.68	57	58.04
15	50.4	50.56	50.65	67.35
16	50.4	50.56	50.66	50.67
17	50.4	50.64	50.66	56.23
18	50.4	50.63	50.65	50.68
19	50.4	50.44	54.99	60.9
20	50.4	50.45	55.02	58.58
21	50.4	50.43	50.61	56.71
22	50.4	50.46	50.69	50.86
23	50.4	50.45	50.58	56.01
24	50.4	50.46	50.59	50.75
Avg. of the columns	50.4	51.9675	53.98875	59.03875
StdD. of the columns	1.49E-06	2.431021	3.708968	7.256734
Avg. of the values of Model1 in the column	50.4	50.64667	50.68667	50.855
StdD. of the values of Model1 in the column	6.03E-07	0.175917	0.129254	0.192743
Avg. of the values of Model2 in the column	50.4	52.20833	54.8	56.96667
StdD. of the values of Model2 in the column	6.03E-07	2.643213	3.696609	1.135811
Avg. of the values of Model3 in the column	50.4	52.42833	55.01333	60.41667
StdD. of the values of Model3 in the column	6.03E-07	2.868375	3.838321	3.371579
Avg. of the values of Model4 in the column	50.4	52.58667	55.455	67.91667
StdD. of the values of Model4 in the column	6.03E-07	3.01036	4.141433	6.867464

Table E.31 Average values of cycle times at the end of the runs with high level of the weight of the third objective

Sequence	Average Values of C	Average Values of C	Average Values of C	Average Values of C
1	48.15	54.01	52.5	55.93
2	48.17	54.78	55.2	54.57
3	47.48	52.27	57.15	58.15
4	48.52	52.97	55.22	54.71
5	47.36	55.8	56.9	54.56
6	48.33	54.52	52.8	55.72
7	47.78	48.74	52.71	56.54
8	48.22	48.42	56.41	55.27
9	48.23	49.67	49.38	55.4
10	47.64	49.4	50.58	50.19
11	49.04	50.21	48.76	48.62
12	47.69	50.21	50.11	50.08
13	48.09	49.41	54.54	54.81
14	48	48.86	53.86	54.39
15	49	50.07	49.46	54.51
16	48.96	50.11	50.42	49.51
17	48.41	50.23	49.45	53.92
18	48.4	50.39	50.39	49.92
19	49.27	48.84	51.08	49.71
20	49.26	48.83	49.68	51.52
21	49.4	49.62	49.74	50.28
22	49.11	49.36	49.42	49.43
23	49.29	49.41	49.42	52.82
24	49.04	49.52	49.77	49.54
Avg. of the columns	48.45167	50.65208	51.87292	52.92083
StdD. of the columns	0.627893	2.158153	2.73561	2.831441
Avg. of the values of Model1 in the column	48.00167	48.85	49.36833	49.77833
StdD. of the values of Model1 in the column	0.471314	0.31975	0.324371	0.325786
Avg. of the values of Model2 in the column	48.1	51.325	53.305	53.84667
StdD. of the values of Model2 in the column	0.528583	2.406896	3.321968	1.484772
Avg. of the values of Model3 in the column	48.47667	50.54	51.20333	52.16833
StdD. of the values of Model3 in the column	0.422974	1.629208	1.624619	2.943069
Avg. of the values of Model4 in the column	49.22833	51.89333	53.615	55.89
StdD. of the values of Model4 in the column	0.130754	2.563409	2.544781	1.329857

Table E.32 Average values of the differences between the theoretical minimum cycle times and the cycle times found with the algorithm at the end of the runs with high level of the weight of the third objective

Sequence	Average Values of DC	Average Values of DC	Average Values of DC	Average Values of DC
1	0.331366	0.649938	0.662577	0.540604
2	0.289216	0.701173	0.524731	0.942395
3	0.244781	0.616728	0.956402	0.844189
4	0.318871	0.617563	0.479698	0.775939
5	0.290031	0.6025	1.040238	0.993787
6	0.316594	0.495804	0.823542	0.937917
7	0.278836	0.551612	0.818006	0.783285
8	0.289219	0.51009	0.745656	1.096404
9	0.289279	0.606401	0.654867	0.744023
10	0.281548	0.609765	0.401136	0.846246
11	0.274067	0.434986	0.78726	0.783518
12	0.273134	0.434566	0.853511	0.897062
13	0.289877	0.501498	0.768212	0.567345
14	0.293742	0.491212	0.613362	0.970809
15	0.379908	0.496172	0.648491	0.650865
16	0.346451	0.486399	0.43927	0.799286
17	0.274317	0.449413	0.797	0.984886
18	0.344067	0.423803	0.727592	0.860114
19	0.368966	0.850056	0.857521	0.874432
20	0.290114	0.77932	0.815421	0.877989
21	0.301676	0.663343	0.856232	0.877535
22	0.277926	0.629517	0.74821	0.83017
23	0.292727	0.747926	0.830198	0.940763
24	0.311803	0.803989	0.735922	0.897374
Avg. of the columns	0.302022	0.589741	0.732711	0.846539
StdD. of the columns	0.032315	0.123151	0.156921	0.130045
Avg. of the values of Model1 in the column	0.298477	0.613965	0.762341	0.855042
StdD. of the values of Model1 in the column	0.031197	0.158415	0.089168	0.03844
Avg. of the values of Model2 in the column	0.281014	0.604424	0.847648	0.914717
StdD. of the values of Model2 in the column	0.007085	0.090754	0.128236	0.077324
Avg. of the values of Model3 in the column	0.321394	0.667062	0.786878	0.928012
StdD. of the values of Model3 in the column	0.041328	0.086295	0.07002	0.108799
Avg. of the values of Model4 in the column	0.307202	0.473512	0.533975	0.688385
StdD. of the values of Model4 in the column	0.032327	0.068099	0.127089	0.12188

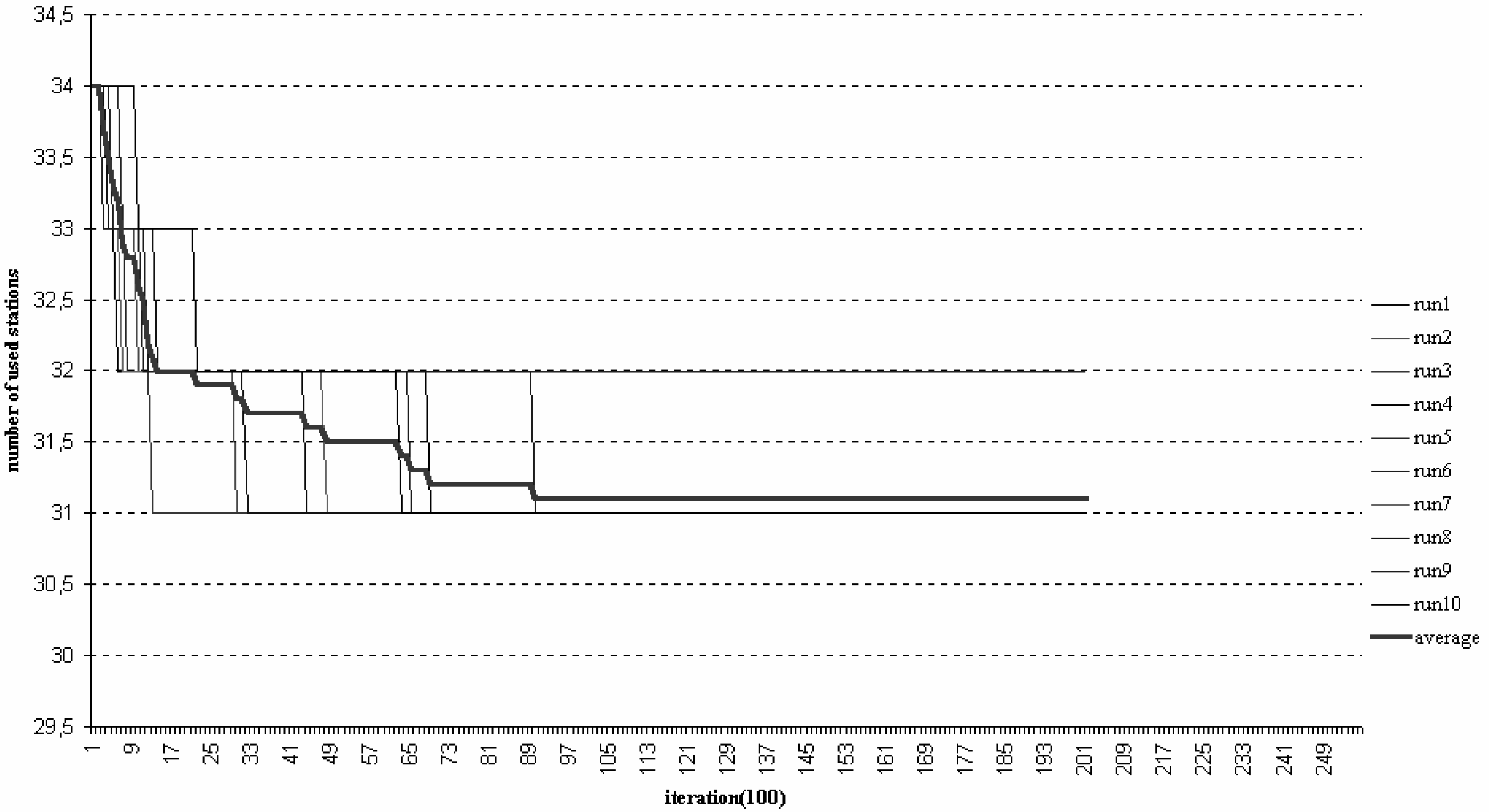


Figure E.1 Model1-number of used stations

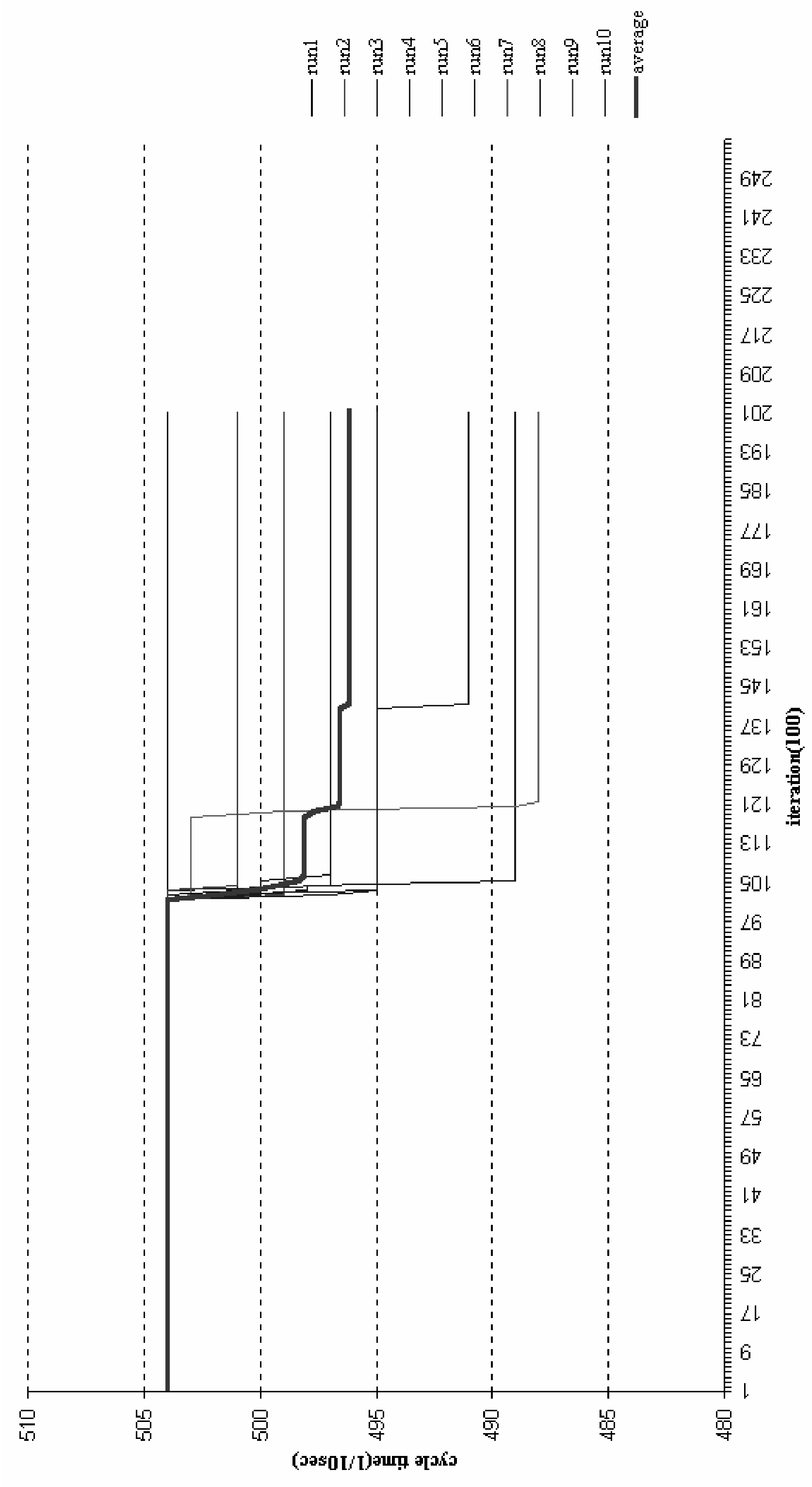


Figure E.2 Model1-cycle times

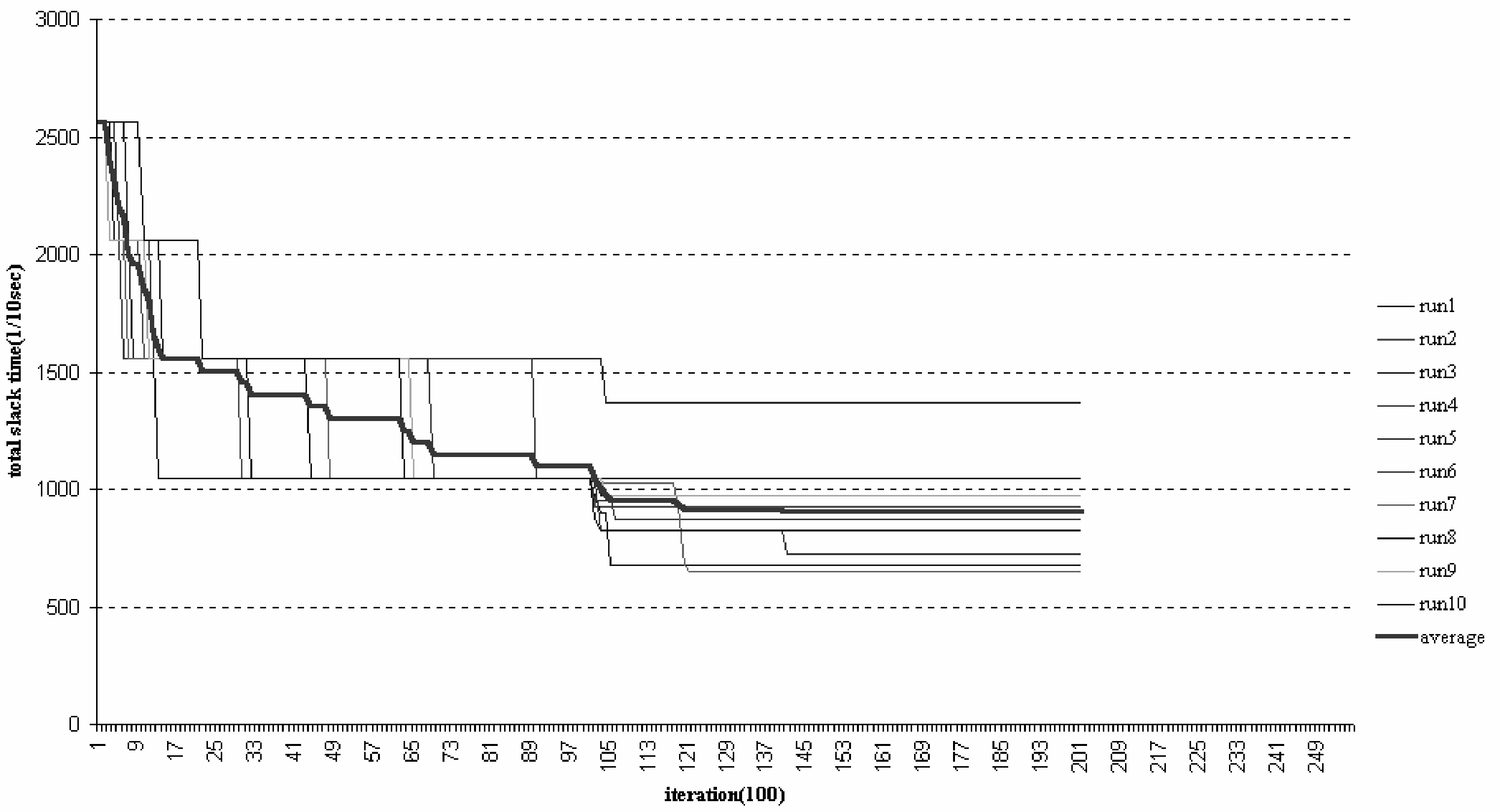


Figure E.3 Model1-total slack times

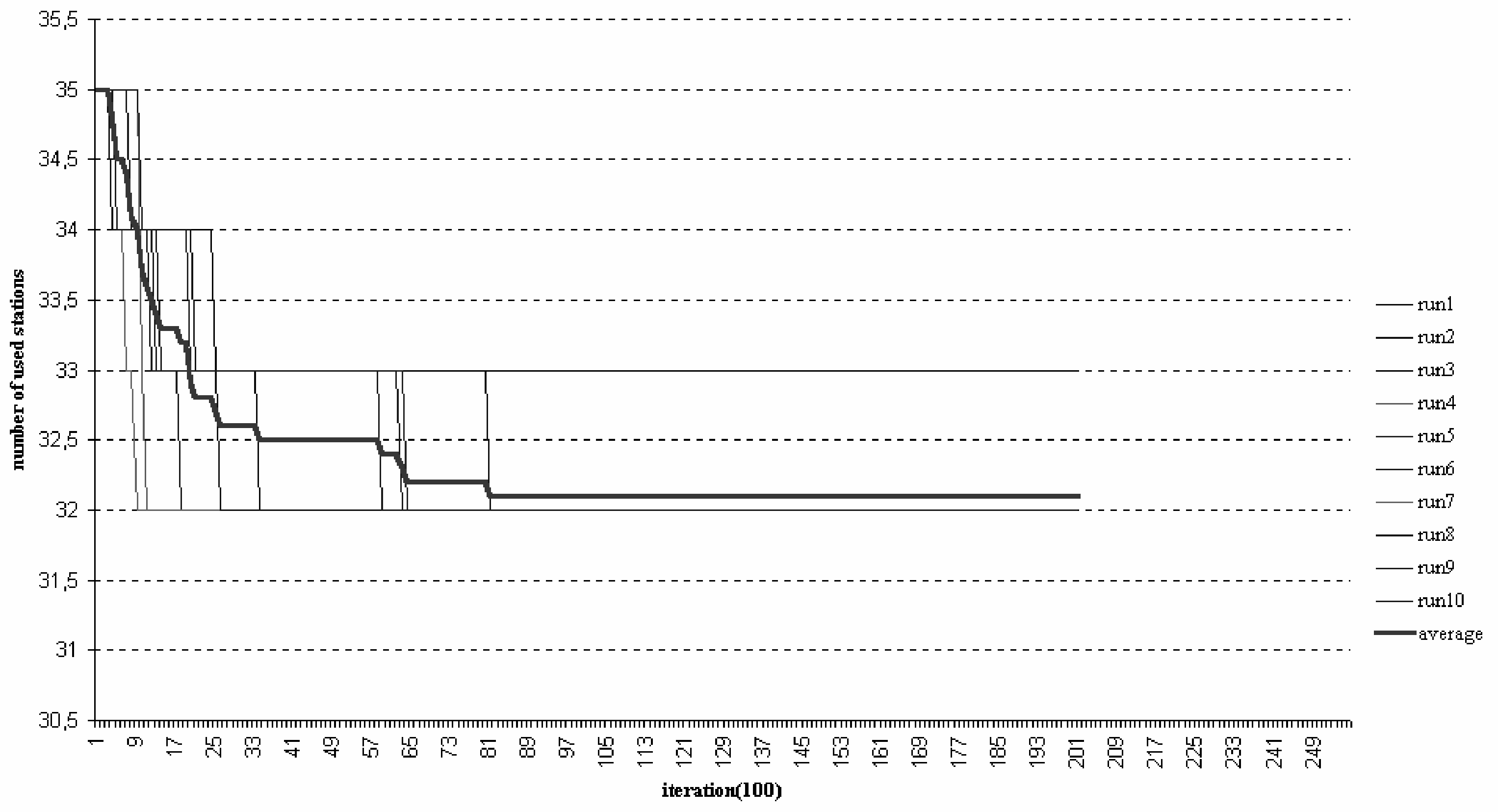


Figure E.4 Model2-number of used stations

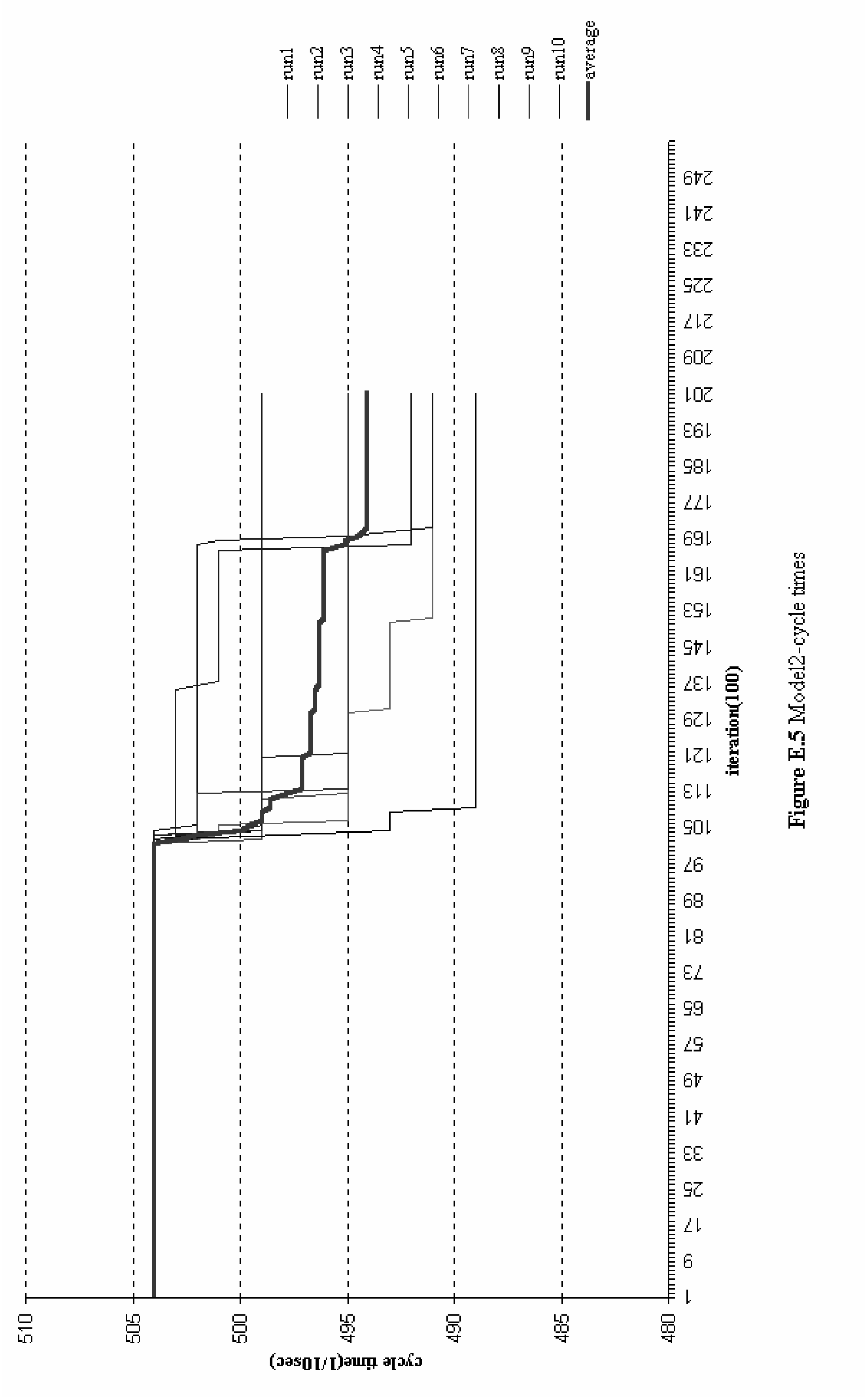


Figure E.5 Model2-cycle times

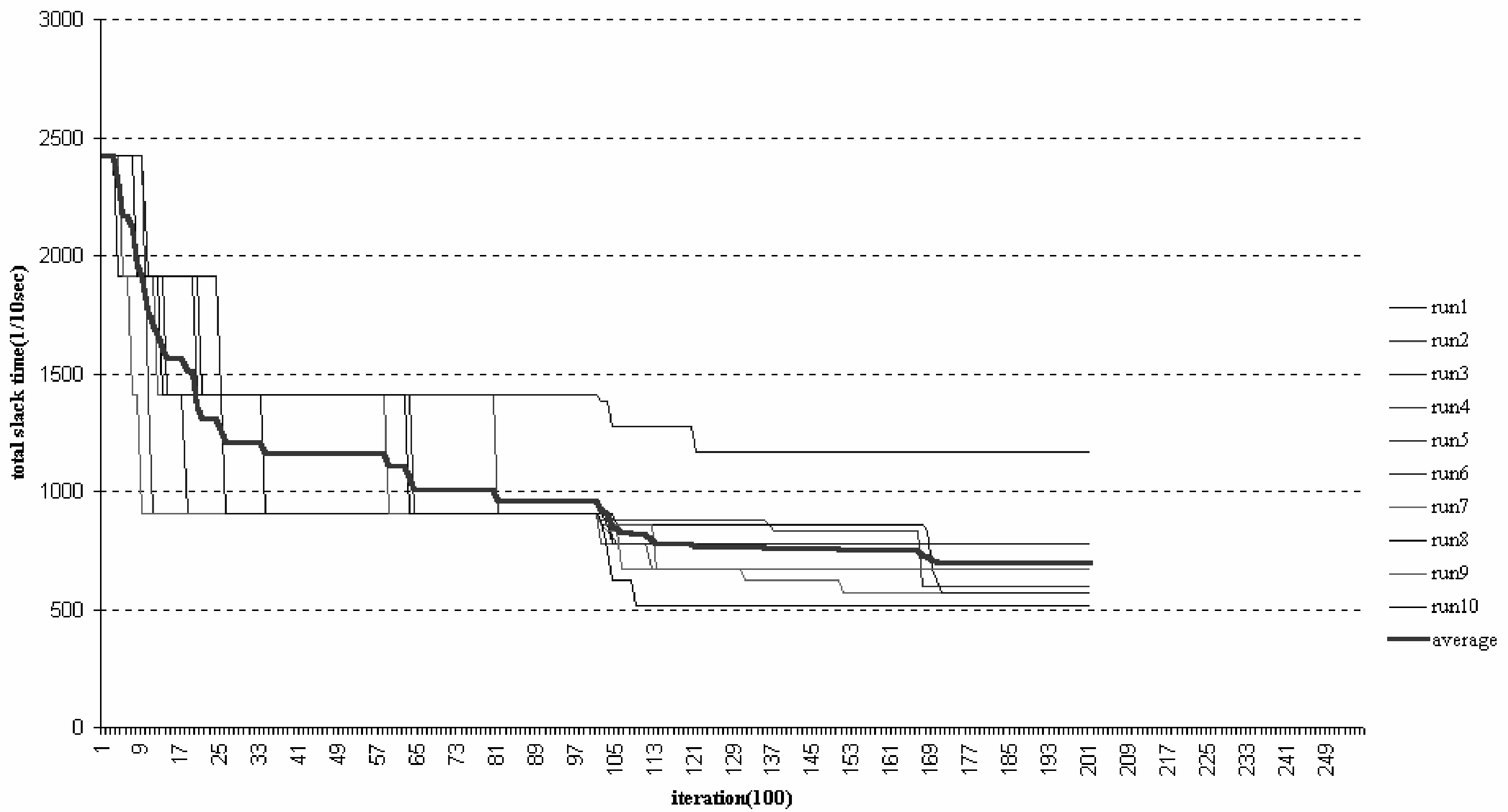


Figure E.6 Model2-total slack times

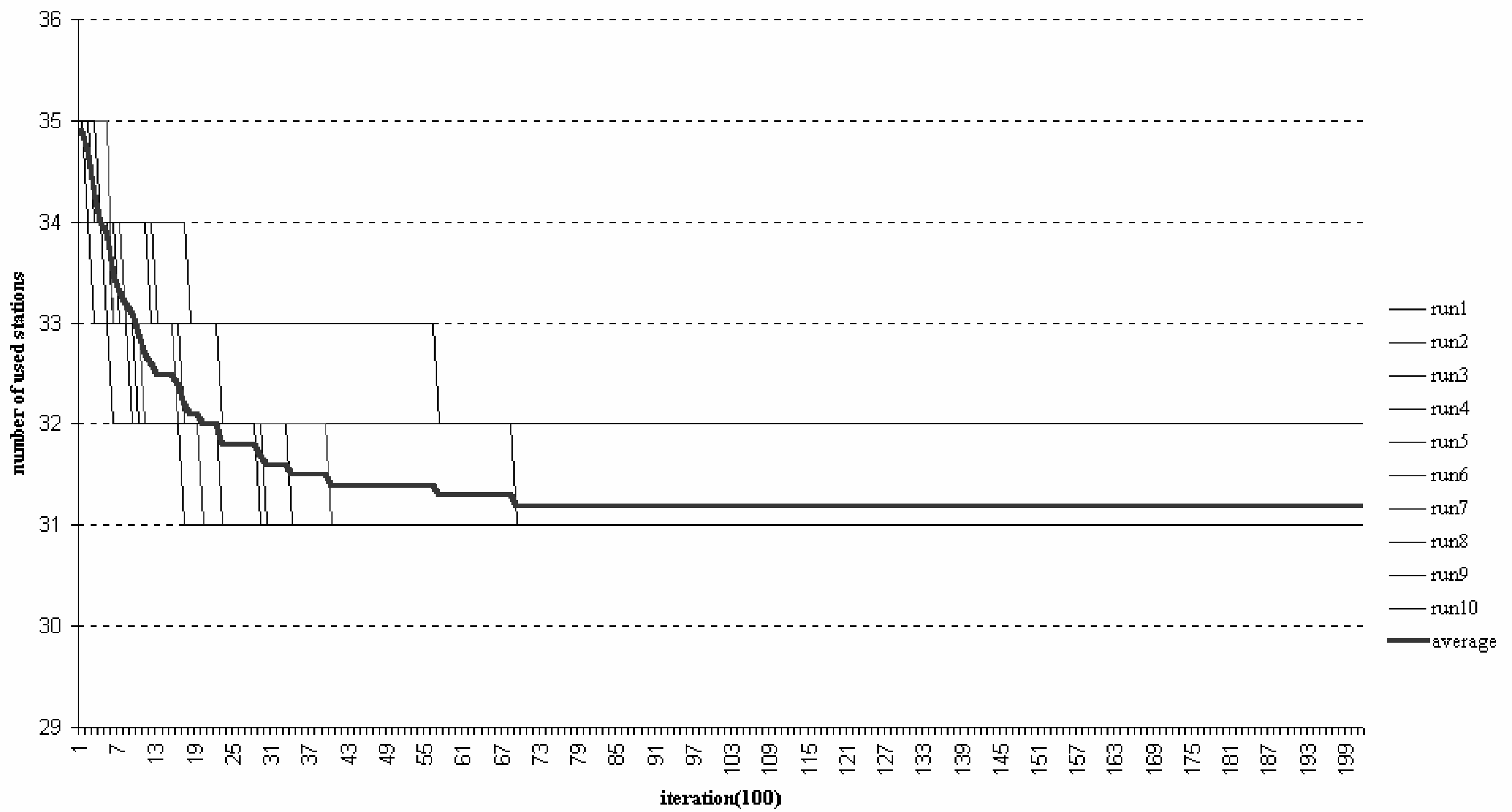


Figure E.7 Model3-number of used stations

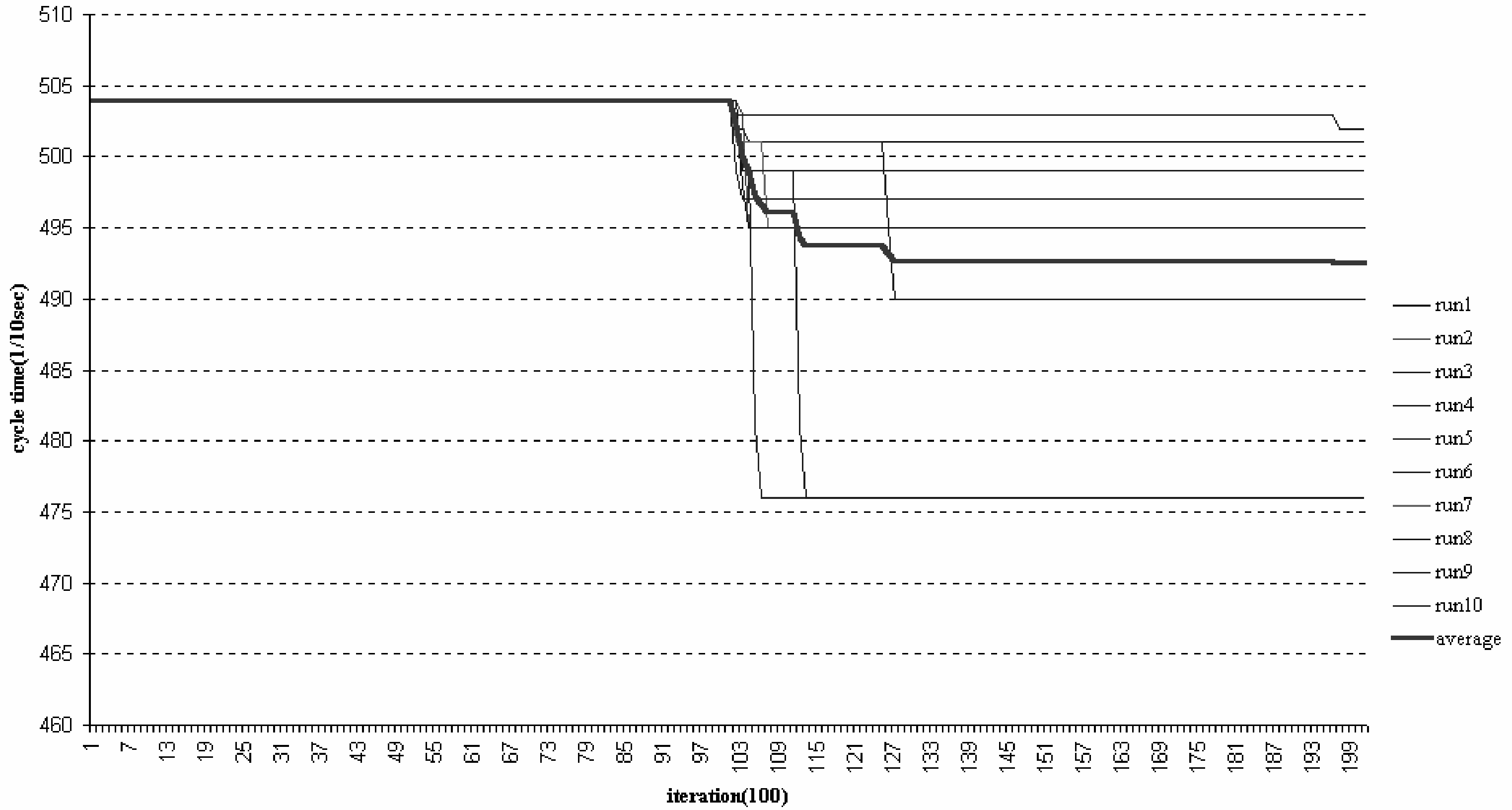


Figure E.8 Model3-cycle times

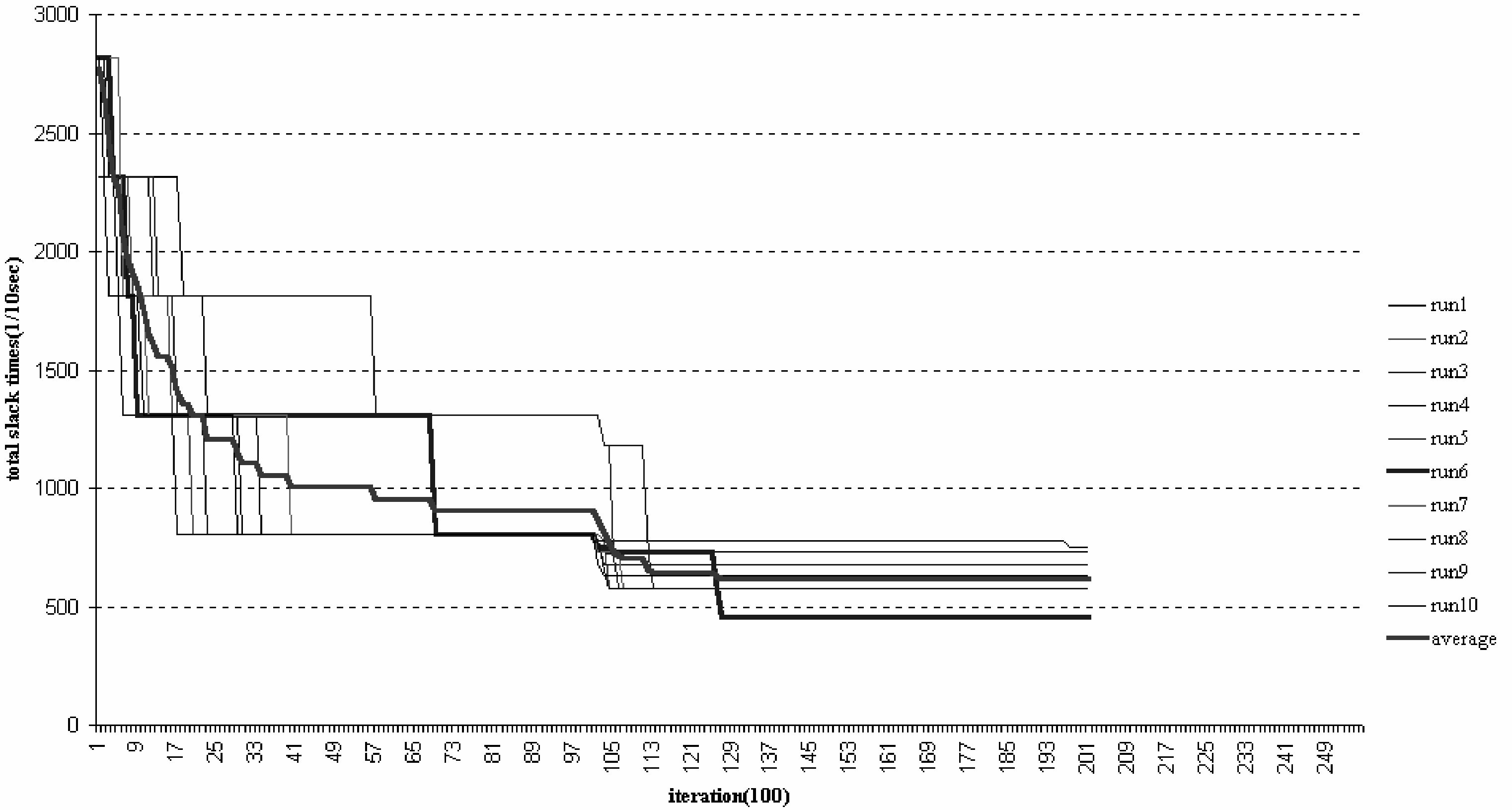


Figure E.9 Model3-total slack times

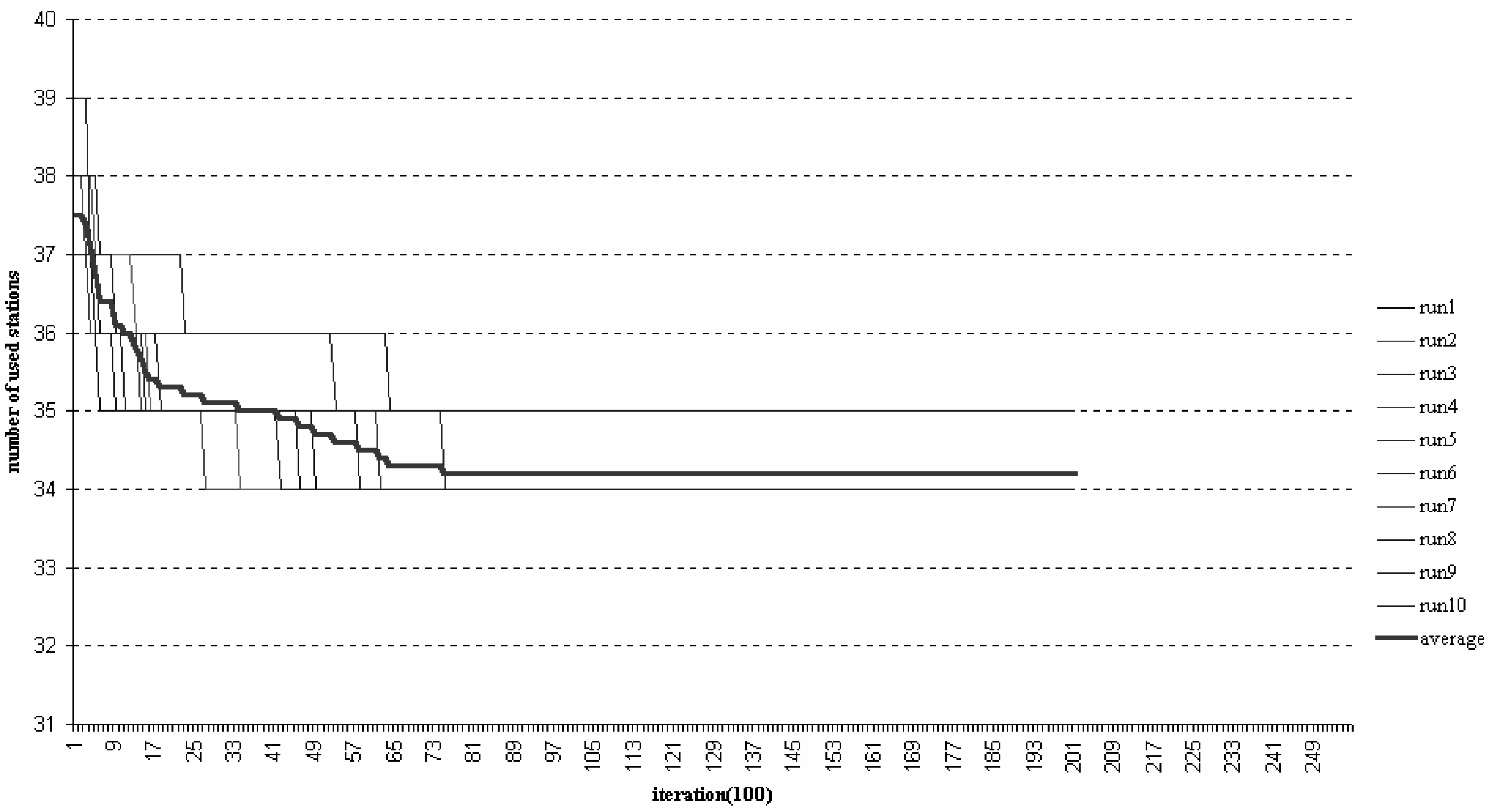


Figure E.10 Model4-number of used stations

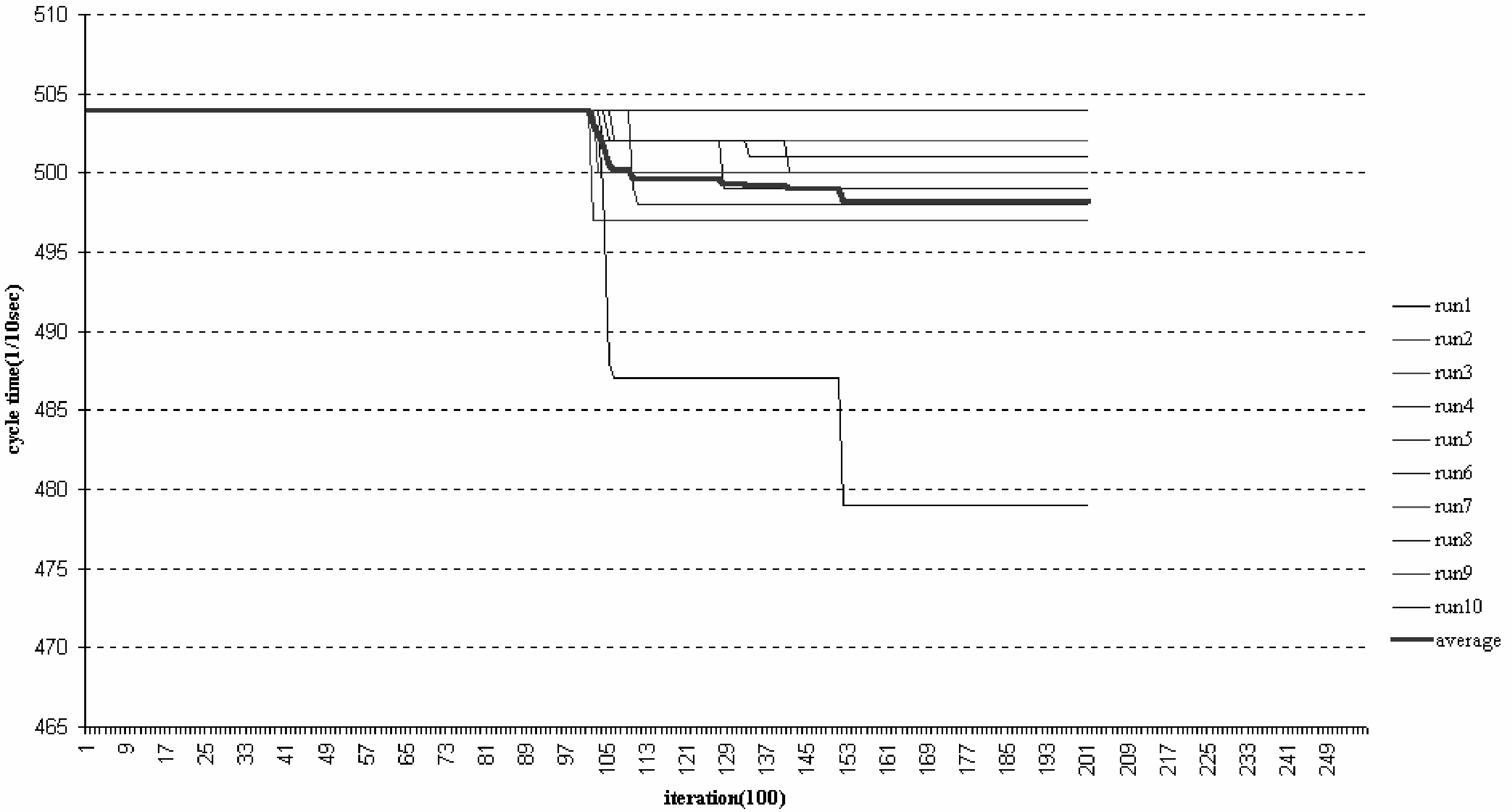


Figure E.11 Model4-cycle times

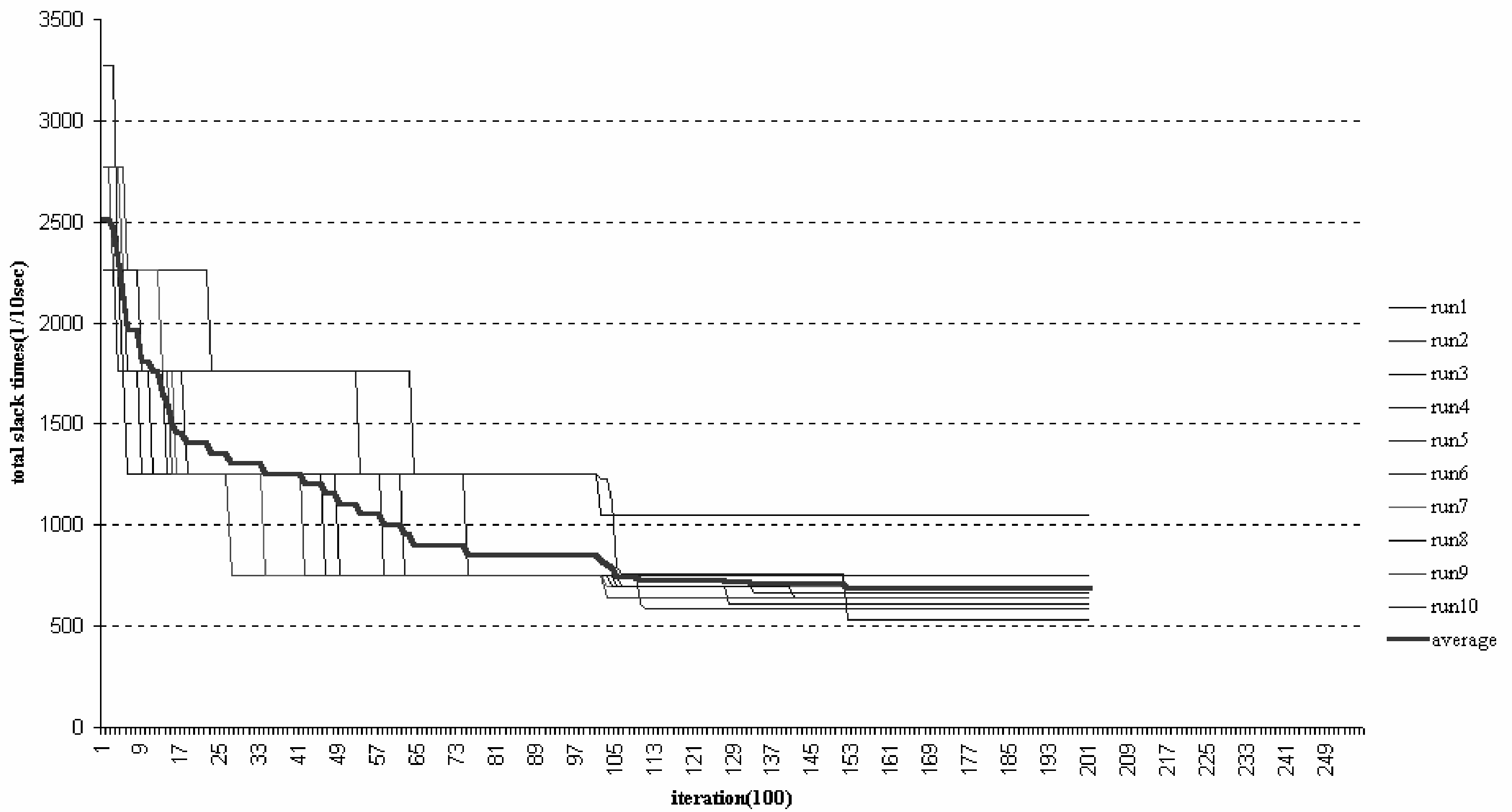


Figure E.12 Model4-total slack times

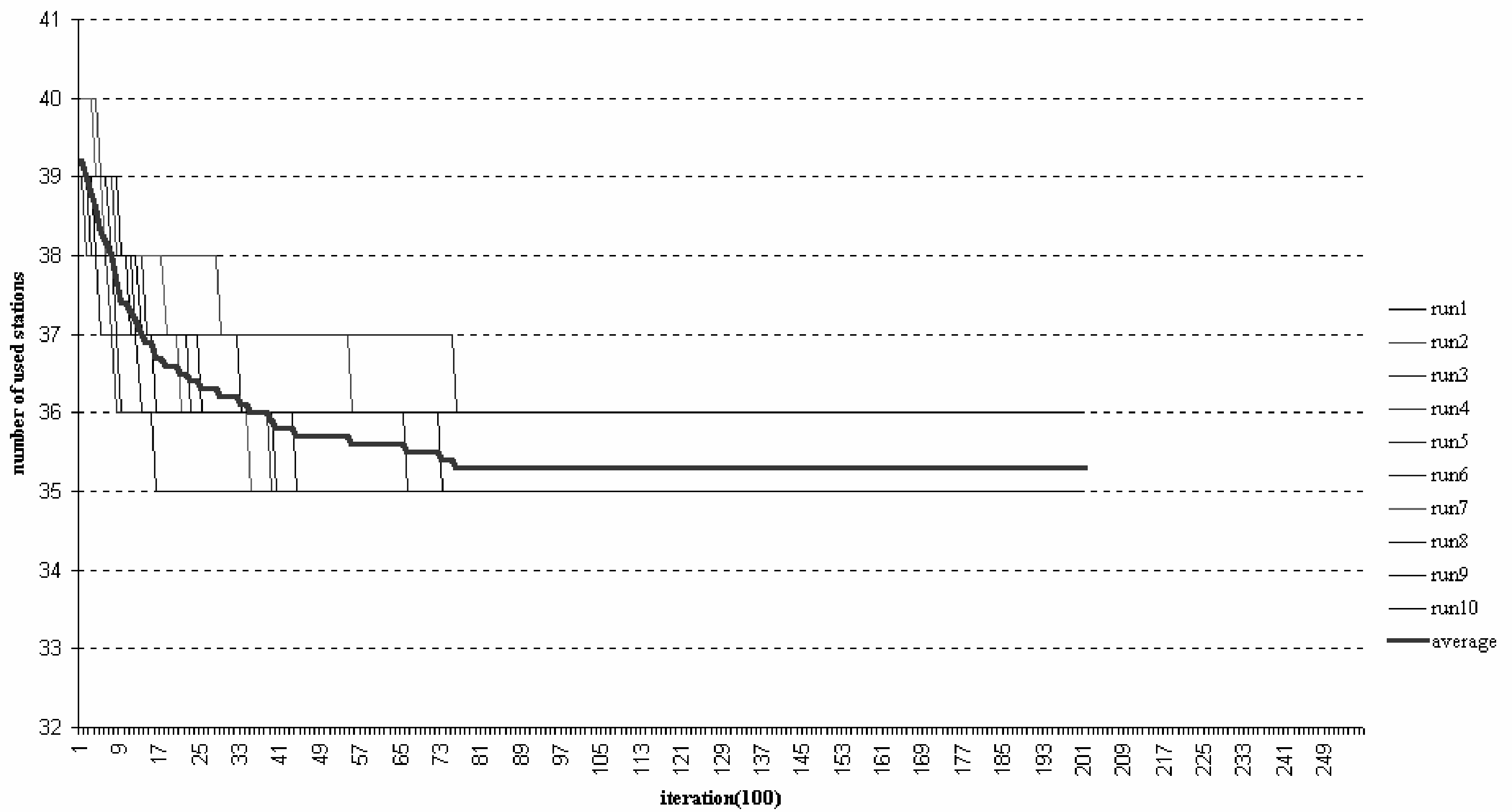


Figure E.13 Combined-number of used stations

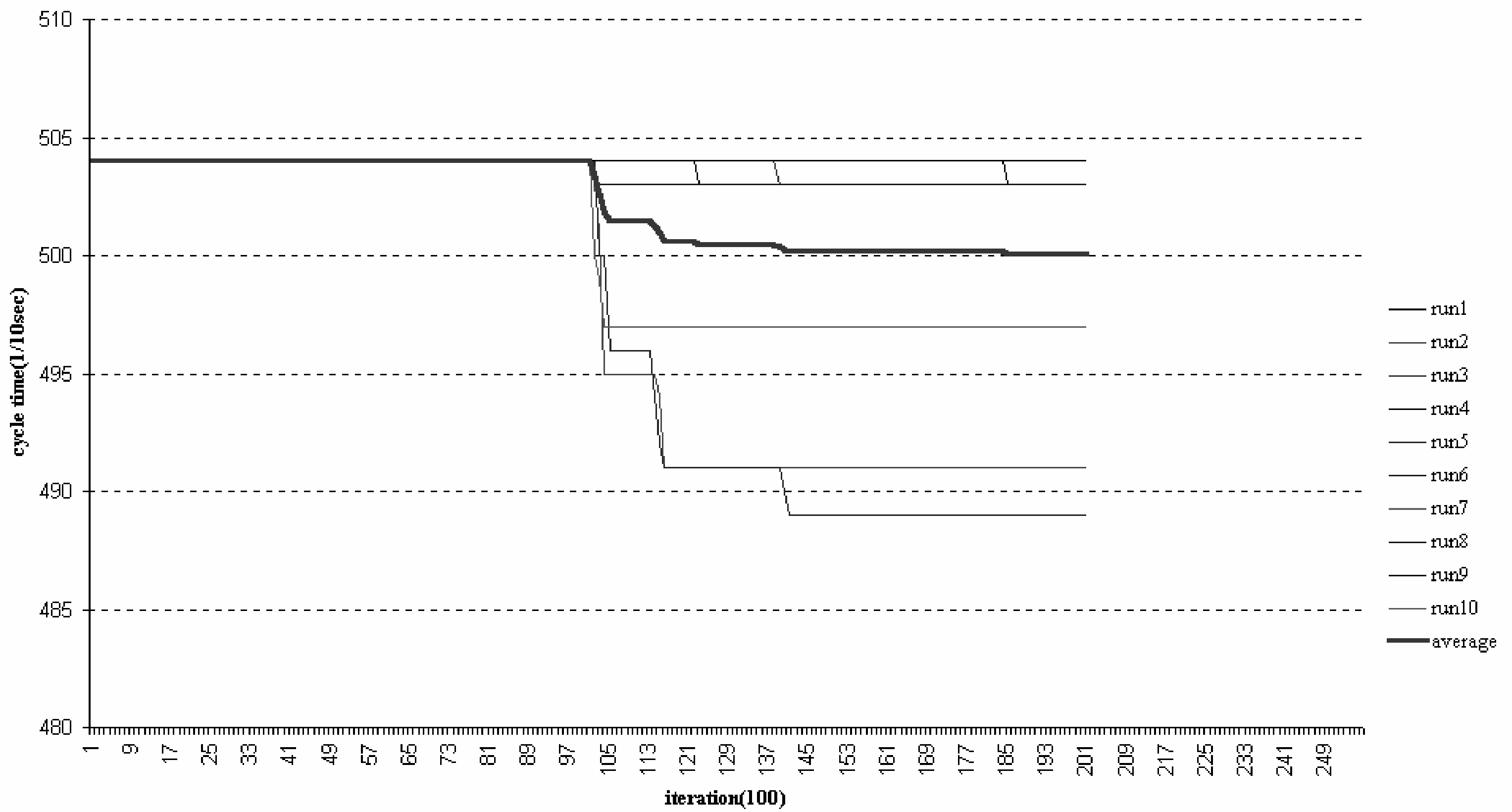


Figure E.14 Combined-cycle times

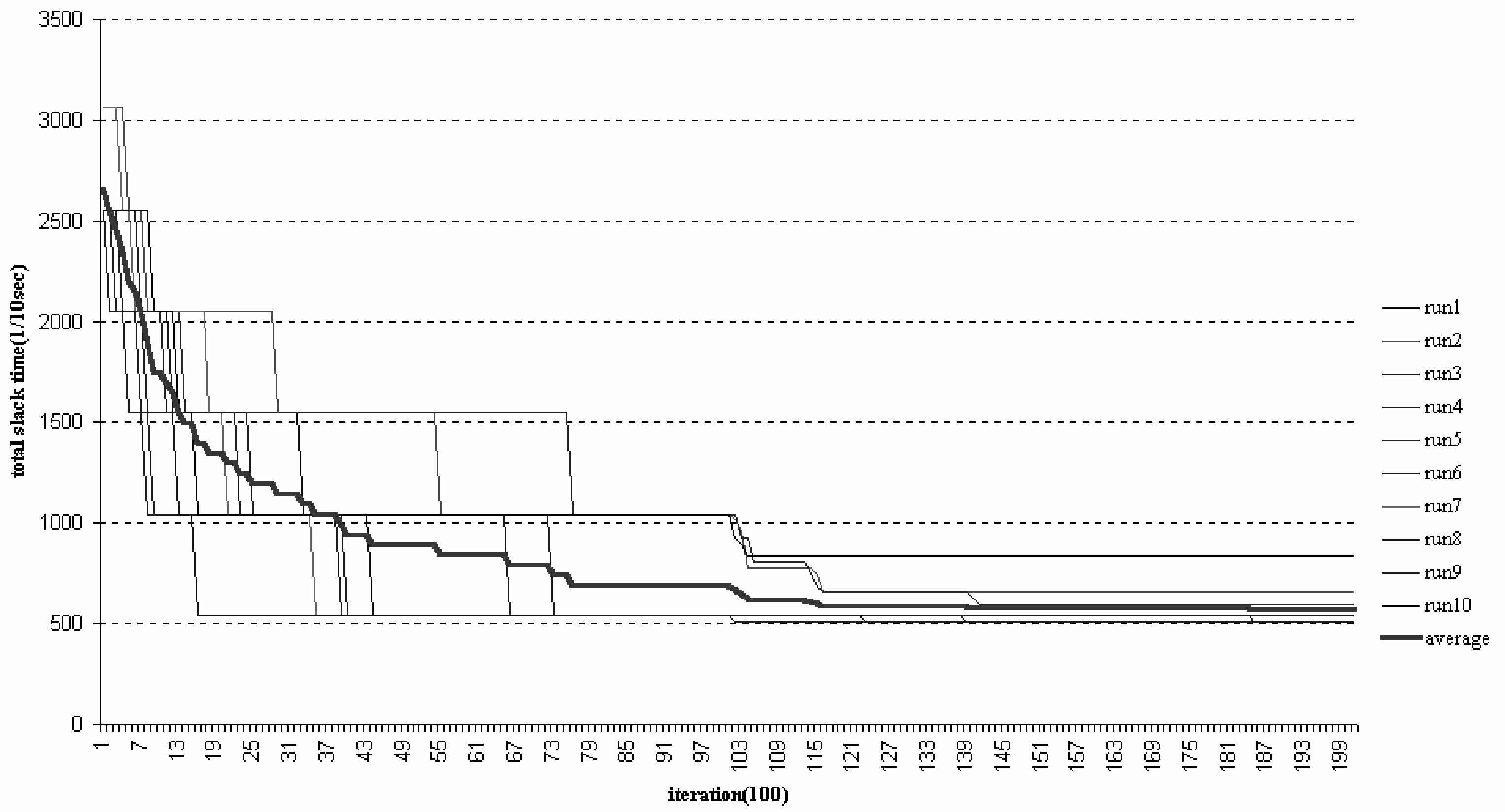


Figure E.15 Combined-total slack times

APPENDIX F

CURRENT AND SUGGESTED ASSIGNMENTS

Table F.1 Current and suggested assignments

	Number of Station That the Task Assigned (Current)				Number of Station That the Task Assigned (Suggested Multi-Model)				Number of Station That the Task Assigned (Suggested Mixed-Model)			
TASK CODE	**MODEL1**	**MODEL2**	**MODEL3**	**MODEL4**	**MODEL1**	**MODEL2**	**MODEL3**	**MODEL4**	**MODEL1**	**MODEL2**	**MODEL3**	**MODEL4**
1	1	1	1	1	1	1	1	1	1	1	1	1
2	3	3	3	3	12	12	12	12	1	1	1	1
3	2	2	2	2	4	4	4	4	1	1	1	1
4	2	2	2	2	2	2	2	2	1	1	1	1
5	5	5	5	5	1	1	1	4	4	4	4	4
6	3	3	3	3	1	1	1	1	1	1	1	1
7	1	1	1	1	4	4	4	20	2	2	2	2
8	1	1	1	1	11	11	11	20	12	12	12	12
9	5	5	5	5	20	20	20	20	20	20	20	20
10	0	0	0	1	0	0	0	1	0	0	0	2
11	0	0	0	3	0	0	0	2	0	0	0	4
12	11	11	11	11	11	11	11	11	11	11	11	11
13	11	11	11	11	11	11	11	11	11	11	11	11
14	11	11	11	11	11	11	11	11	11	11	11	11
15	11	11	11	11	11	11	11	11	11	11	11	11
16	11	11	11	11	11	11	11	11	11	11	11	11
17	11	11	11	11	11	11	11	11	11	11	11	11
18	11	11	11	11	11	11	11	11	11	11	11	11
19	0	1	1	1	0	1	50	1	0	21	21	21
20	11	11	11	11	11	11	11	11	11	11	11	11
21	12	12	12	12	12	12	12	11	11	11	11	11
22	12	12	12	12	12	12	12	12	12	12	12	12
23	12	12	12	12	12	12	12	12	12	12	12	12

Table F.1 (Continued)

24	0	21	21	21	0	23	23	23	0	11	11	11
25	11	11	11	11	11	11	11	11	12	12	12	12
26	11	11	11	11	11	11	11	11	12	12	12	12
27	3	3	3	3	4	4	4	4	1	1	1	1
28	5	5	5	5	4	4	4	12	2	2	2	2
29	5	5	5	5	12	12	12	12	18	18	18	18
30	3	3	3	4	4	4	4	4	5	5	5	5
31	5	5	5	5	4	4	4	4	5	5	5	5
32	5	5	5	5	4	4	4	4	5	5	5	5
33	1	1	0	0	4	4	0	0	2	2	0	0
34	3	3	0	0	4	4	0	0	2	2	0	0
35	2	2	2	2	2	2	2	2	5	5	5	5
36	2	2	2	2	1	1	1	1	2	2	2	2
37	2	2	2	2	2	2	2	2	2	2	2	2
38	2	2	2	2	4	4	4	4	4	4	4	4
39	0	0	3	4	0	0	4	4	0	0	5	5
40	0	0	3	4	0	0	1	4	0	0	4	4
41	5	5	0	0	4	4	0	0	5	5	0	0
42	12	12	0	0	4	4	0	0	5	5	0	0
43	12	12	0	0	12	12	0	0	11	11	0	0
44	0	0	12	12	0	0	4	12	0	0	12	12
45	12	12	12	12	12	12	12	12	12	12	12	12
46	0	3	3	4	0	12	12	12	0	12	12	12
47	0	3	3	4	0	11	11	11	0	5	5	5
48	5	5	5	5	12	12	12	12	12	12	12	12
49	2	2	2	2	2	2	2	2	2	2	2	2
50	0	0	0	18	0	0	0	28	0	0	0	21
51	0	0	0	18	0	0	0	28	0	0	0	24
52	0	0	0	20	0	0	0	30	0	0	0	25
53	0	0	0	24	0	0	0	33	0	0	0	32
54	0	0	0	34	0	0	0	33	0	0	0	44
55	0	0	0	20	0	0	0	44	0	0	0	34
56	0	0	0	38	0	0	0	44	0	0	0	38
57	18	18	18	18	1	1	1	1	18	18	18	18
58	3	3	3	4	1	1	1	1	5	5	5	5
59	18	18	18	18	20	20	20	20	18	18	18	18
60	18	18	18	18	19	19	19	19	20	20	20	20
61	19	19	19	19	2	2	2	23	2	2	2	2
62	18	18	18	18	20	20	20	20	20	20	20	20
63	20	20	20	20	25	25	25	25	20	20	20	20
64	20	0	0	0	20	0	0	0	23	0	0	0
65	0	21	21	21	0	23	23	23	0	18	18	18
66	21	21	21	21	20	20	20	20	20	20	20	20

Table F.1 (Continued)

67	18	18	18	18	23	23	23	23	20	20	20	20
68	19	19	19	19	23	23	23	23	21	21	21	21
69	23	23	23	23	20	20	20	20	21	21	21	21
70	20	20	20	20	20	20	20	20	20	20	20	20
71	18	18	18	18	23	23	23	23	21	21	21	21
72	17	17	17	17	17	17	17	17	17	17	17	17
73	0	0	0	3	0	0	0	1	0	0	0	4
74	0	0	0	3	0	0	0	2	0	0	0	4
75	11	11	11	0	11	11	11	0	12	12	12	0
76	18	18	18	18	19	19	19	19	20	20	20	20
77	19	19	19	19	19	19	19	19	18	18	18	18
78	19	19	19	19	19	19	19	19	18	18	18	18
79	20	20	20	20	19	19	19	19	18	18	18	18
80	20	20	20	20	19	19	19	19	20	20	20	20
81	18	18	18	18	19	19	19	19	18	18	18	18
82	20	20	20	20	26	19	19	19	24	24	24	24
83	21	21	21	21	20	20	20	20	20	20	20	20
84	21	21	21	21	20	20	20	20	21	21	21	21
85	21	21	21	21	20	20	20	20	21	21	21	21
86	23	23	23	23	23	23	23	23	23	23	23	23
87	23	23	23	23	26	24	24	24	24	24	24	24
88	24	24	24	24	25	25	25	25	23	23	23	23
89	19	19	19	19	19	19	19	19	20	20	20	20
90	20	20	20	20	23	23	23	23	20	20	20	20
91	23	23	23	23	23	23	23	23	23	23	23	23
92	24	24	24	24	24	24	24	24	23	23	23	23
93	23	23	23	23	25	25	25	25	27	27	27	27
94	24	24	24	24	24	24	24	24	25	25	25	25
95	24	24	24	24	25	25	25	25	27	27	27	27
96	23	23	23	23	23	23	23	23	23	23	23	23
97	24	24	24	24	24	24	24	24	23	23	23	23
98	24	24	24	24	24	24	24	24	24	24	24	24
99	26	26	26	26	24	24	24	24	25	25	25	25
100	23	23	0	0	23	23	0	0	27	27	0	0
101	23	23	0	0	23	23	0	0	26	26	0	0
102	23	23	23	0	26	26	26	0	26	26	26	0
103	26	26	26	26	26	26	26	26	27	27	27	27
104	26	26	26	26	26	26	26	26	27	27	27	27
105	23	0	23	0	23	0	23	0	23	0	23	0
106	28	28	28	28	27	33	27	33	34	34	34	34
107	55	55	55	55	55	55	55	55	55	55	55	55
108	23	23	23	23	23	23	23	23	23	23	23	23
109	24	24	24	24	26	25	25	25	24	24	24	24

Table F.1 (Continued)

110	27	27	27	27	28	25	25	25	24	24	24	24
111	25	25	25	25	28	30	30	30	27	27	27	27
112	26	26	26	26	30	30	30	30	25	25	25	25
113	27	27	27	27	26	26	26	26	24	24	24	24
114	27	27	0	0	26	27	0	0	27	27	0	0
115	19	19	19	19	23	23	23	23	25	25	25	25
116	30	30	30	30	28	25	25	25	27	27	27	27
117	0	27	0	27	0	25	0	25	0	28	0	28
118	24	24	24	24	26	26	26	26	26	26	26	26
119	26	26	26	26	27	26	26	26	27	27	27	27
120	0	0	0	25	0	0	0	26	0	0	0	24
121	21	21	21	21	28	20	20	20	20	20	20	20
122	2	2	2	2	12	12	12	12	25	25	25	25
123	0	24	0	24	0	26	0	26	0	26	0	26
124	0	25	0	25	0	27	0	27	0	28	0	28
125	25	25	25	25	27	27	27	27	26	26	26	26
126	25	25	25	25	28	27	27	27	24	24	24	24
127	25	25	25	25	28	27	27	27	26	26	26	26
128	25	25	25	25	27	27	27	27	30	30	30	30
129	30	0	30	0	28	0	25	0	25	0	25	0
130	0	0	0	25	0	0	0	27	0	0	0	25
131	30	30	30	30	30	30	30	30	30	30	30	30
132	32	32	32	32	32	32	32	32	33	33	33	33
133	30	30	30	30	30	30	30	30	30	30	30	30
134	31	31	31	31	30	30	30	30	30	30	30	30
135	30	30	30	30	30	30	30	30	31	31	31	31
136	31	31	31	31	30	30	30	30	30	30	30	30
137	31	31	31	31	30	30	30	30	31	31	31	31
138	30	30	30	30	30	30	30	30	30	30	30	30
139	30	30	30	30	30	30	30	30	30	30	30	30
140	31	31	31	31	30	30	30	30	30	30	30	30
141	31	31	31	31	30	30	30	30	31	31	31	31
142	27	27	27	0	30	30	30	0	30	30	30	0
143	33	33	33	33	38	38	38	38	32	32	32	32
144	19	19	19	19	24	24	24	24	20	20	20	20
145	21	21	21	21	27	31	31	31	27	27	27	27
146	30	30	30	30	30	30	30	30	31	31	31	31
147	31	31	31	31	31	31	31	31	31	31	31	31
148	31	31	31	31	31	31	31	31	31	31	31	31
149	31	31	31	31	31	31	31	31	31	31	31	31
150	31	31	31	31	31	31	31	31	31	31	31	31
151	38	38	38	38	50	33	44	33	38	38	38	38
152	38	38	38	38	38	38	38	38	38	38	38	38

Table F.1 (Continued)

153	32	32	32	32	31	31	31	31	32	32	32	32
154	33	33	33	33	31	32	31	32	33	33	33	33
155	33	33	33	33	32	32	32	32	33	33	33	33
156	0	32	0	32	0	31	0	31	0	32	0	32
157	0	33	0	33	0	33	0	33	0	33	0	33
158	0	33	0	33	0	33	0	33	0	34	0	34
159	0	34	0	34	0	33	0	33	0	34	0	34
160	55	55	55	55	55	55	55	55	55	55	55	55
161	55	55	55	55	55	55	55	55	55	55	55	55
162	34	34	34	0	32	33	32	0	34	34	34	0
163	34	34	34	0	32	33	32	0	34	34	34	0
164	31	31	31	31	31	31	31	31	31	31	31	31
165	32	32	32	32	31	31	31	31	31	31	31	31
166	32	32	32	32	32	32	32	32	32	32	32	32
167	32	32	32	32	32	32	32	32	32	32	32	32
168	0	32	0	32	0	31	0	31	0	32	0	32
169	0	32	0	32	0	32	0	32	0	32	0	32
170	33	33	33	33	32	32	32	32	32	32	32	32
171	33	33	33	33	32	32	32	32	33	33	33	33
172	34	34	34	34	32	32	32	32	33	33	33	33
173	34	34	34	34	32	33	32	33	38	38	38	38
174	34	34	34	34	32	38	32	38	38	38	38	38
175	34	34	34	34	38	38	38	38	38	38	38	38
176	34	34	34	34	38	38	38	38	38	38	38	38
177	38	38	38	38	38	38	38	38	38	38	38	38
178	34	34	34	34	32	33	32	33	38	38	38	38
179	38	38	38	38	38	38	38	38	38	38	38	38
180	38	38	38	38	38	38	38	38	38	38	38	38
181	44	44	44	44	44	38	44	38	38	38	38	38
182	23	23	23	23	24	24	24	24	23	23	23	23
183	25	25	25	25	24	24	24	24	25	25	25	25
184	26	26	26	26	24	24	24	24	23	23	23	23
185	26	26	26	26	24	24	24	24	25	25	25	25
186	27	27	27	27	25	25	25	25	26	26	26	26
187	27	27	27	27	24	24	24	24	25	25	25	25
188	27	27	27	27	25	26	26	26	28	28	28	28
189	28	28	28	28	27	33	27	33	34	34	34	34
190	50	50	50	50	51	50	51	50	51	51	51	51
191	38	38	38	38	51	52	51	52	44	44	44	44
192	53	53	53	53	53	52	53	52	53	53	53	53
193	53	53	53	53	53	52	53	52	53	53	53	53
194	50	50	50	50	51	50	51	50	51	51	51	51
195	43	43	43	43	43	43	43	43	43	43	43	43

Table F.1 (Continued)

196	38	38	38	38	25	25	25	25	32	32	32	32
197	28	28	28	28	25	25	25	25	26	26	26	26
198	28	28	28	28	26	26	26	26	28	28	28	28
199	28	28	28	28	27	33	27	33	34	34	34	34
200	28	28	28	28	27	33	27	33	34	34	34	34
201	28	28	28	28	27	33	27	33	34	34	34	34
202	28	28	28	28	27	33	27	33	34	34	34	34
203	0	28	0	28	0	33	0	33	0	34	0	34
204	0	0	0	26	0	0	0	28	0	0	0	26
205	0	0	0	24	0	0	0	28	0	0	0	24
206	0	0	0	26	0	0	0	28	0	0	0	26
207	44	44	44	44	44	44	44	44	44	44	44	44
208	44	44	44	44	44	44	44	44	44	44	44	44
209	44	44	44	44	44	44	44	44	44	44	44	44
210	44	44	44	44	44	44	44	44	44	44	44	44
211	44	44	44	44	44	44	44	44	44	44	44	44
212	44	44	44	44	44	44	44	44	44	44	44	44
213	38	38	38	38	38	38	38	38	38	38	38	38
214	44	44	44	44	44	44	44	44	44	44	44	44
215	0	0	0	27	0	0	0	28	0	0	0	28
216	44	44	44	44	44	44	44	44	44	44	44	44
217	49	49	49	49	49	49	49	49	50	50	50	50
218	49	49	49	49	49	49	49	49	50	50	50	50
219	49	49	49	49	49	49	49	49	50	50	50	50
220	49	49	49	49	49	49	49	49	50	50	50	50
221	0	0	0	26	0	0	0	28	0	0	0	24
222	49	49	49	49	49	49	49	49	50	50	50	50
223	49	49	49	49	49	49	49	49	50	50	50	50
224	49	49	49	49	49	49	49	49	50	50	50	50
225	49	49	49	49	49	49	49	49	50	50	50	50
226	49	49	49	49	49	49	49	49	50	50	50	50
227	49	49	49	49	49	49	49	49	50	50	50	50
228	49	49	49	49	49	49	49	49	50	50	50	50
229	49	49	49	49	49	49	49	49	50	50	50	50
230	49	49	49	49	50	50	50	50	51	51	51	51
231	49	49	49	49	52	49	52	49	52	52	52	52
232	50	50	50	50	52	50	52	50	52	52	52	52
233	50	50	50	50	52	51	52	51	52	52	52	52
234	0	0	0	44	0	0	0	44	0	0	0	44
235	38	38	38	38	52	19	52	19	51	51	51	51
236	1	1	1	1	2	2	2	2	21	21	21	21
237	19	19	19	19	2	2	2	51	5	5	5	5
238	0	0	50	50	0	0	56	51	0	0	49	49

Table F.1 (Continued)

239	44	44	44	44	49	44	44	44	49	49	49	49
240	51	51	51	51	50	49	49	51	49	49	49	49
241	51	51	51	51	50	50	50	51	50	50	50	50
242	52	52	52	52	51	51	51	51	50	50	50	50
243	0	0	44	44	0	0	44	44	0	0	44	44
244	44	44	44	44	44	44	44	44	49	49	49	49
245	51	51	51	51	44	44	50	49	49	49	49	49
246	51	51	51	51	49	44	50	50	49	49	49	49
247	49	49	49	49	49	44	49	44	49	49	49	49
248	53	53	53	53	53	52	53	52	53	53	53	53
249	0	0	0	4	0	0	0	19	0	0	0	21
250	52	52	52	52	50	50	50	50	51	51	51	51
251	51	51	51	51	50	51	50	51	52	52	52	52
252	50	50	50	50	51	50	51	50	51	51	51	51
253	50	50	50	50	51	50	51	50	51	51	51	51
254	50	50	50	50	51	50	51	50	51	51	51	51
255	50	50	50	50	51	50	51	50	51	51	51	51
256	50	50	50	50	51	50	51	50	51	51	51	51
257	50	50	50	50	51	50	51	50	51	51	51	51
258	50	50	50	50	51	50	51	50	51	51	51	51
259	54	54	54	54	54	54	54	54	54	54	54	54
260	0	0	0	4	0	0	0	28	0	0	0	34
261	50	50	50	50	51	50	51	50	51	51	51	51
262	50	50	50	50	51	50	51	50	51	51	51	51
263	50	50	50	50	51	50	51	50	51	51	51	51
264	50	50	50	50	51	50	51	50	51	51	51	51
265	50	50	50	50	51	50	51	50	51	51	51	51
266	28	28	28	28	26	26	26	26	28	28	28	28
267	28	28	28	28	27	27	27	27	28	28	28	28
268	28	28	28	28	27	27	27	27	28	28	28	28
269	30	30	30	30	28	27	27	27	30	30	30	30
270	30	30	30	30	27	27	27	27	30	30	30	30
271	32	32	32	32	38	38	38	38	33	33	33	33
272	52	52	52	52	52	51	52	52	52	52	52	52
273	52	52	52	52	52	51	52	52	52	52	52	52
274	52	52	52	52	52	51	52	52	52	52	52	52
275	52	52	52	52	52	51	52	52	52	52	52	52
276	31	31	31	31	38	38	38	38	31	31	31	31
277	38	38	38	38	53	52	53	52	53	53	53	53
278	38	38	38	38	52	52	52	52	53	53	53	53
279	52	52	52	52	52	51	52	52	52	52	52	52
280	52	52	52	52	52	51	52	52	52	52	52	52
281	53	53	53	53	53	52	53	56	53	53	53	53

Table F.1 (Continued)

282	53	53	53	53	53	52	53	56	53	53	53	53
283	53	53	53	53	53	52	53	56	53	53	53	53
284	55	55	55	55	55	55	55	55	55	55	55	55
285	55	55	55	55	55	55	55	55	55	55	55	55
286	55	55	55	55	55	55	55	55	55	55	55	55
287	55	55	55	55	55	55	55	55	55	55	55	55
288	55	55	55	55	55	55	55	55	55	55	55	55
289	45	45	45	45	45	45	45	45	45	45	45	45
290	55	55	55	55	55	55	55	55	55	55	55	55
291	55	55	55	55	55	55	55	55	55	55	55	55
292	55	55	55	55	55	55	55	55	55	55	55	55
293	56	56	56	56	56	56	56	56	56	56	56	56
294	56	56	56	56	56	56	56	55	56	56	56	56
295	56	56	56	56	56	56	56	55	56	56	56	56
296	55	55	55	55	55	55	55	55	55	55	55	55
297	56	56	56	56	56	56	56	55	56	56	56	56
298	29	29	29	29	29	29	29	29	29	29	29	29
299	29	29	29	29	29	29	29	29	29	29	29	29
300	29	29	29	29	29	29	29	29	29	29	29	29
301	29	29	29	29	29	29	29	29	29	29	29	29
302	0	0	0	29	0	0	0	29	0	0	0	29
303	29	29	29	29	29	29	29	29	29	29	29	29
304	29	29	29	29	29	29	29	29	29	29	29	29
305	29	29	29	29	29	29	29	29	29	29	29	29
306	29	29	29	29	29	29	29	29	29	29	29	29
307	29	29	29	29	29	29	29	29	29	29	29	29
308	29	29	29	29	29	29	29	29	29	29	29	29
309	29	29	29	29	29	29	29	29	29	29	29	29
310	22	22	22	22	22	22	22	22	22	22	22	22
311	0	0	0	29	0	0	0	29	0	0	0	29
312	53	53	53	53	53	52	53	56	53	53	53	53
313	53	53	53	53	53	52	53	56	53	53	53	53