

**Assembly Line Balancing Problem with Stochastic
Sequence-Dependent Setup Times**

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In
Industrial Engineering
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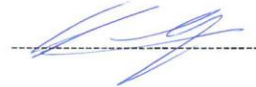
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ABSTRACT

ASSEMBLY LINE BALANCING PROBLEM WITH STOCHASTIC SEQUENCE-DEPENDENT SETUP TIMES

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M. Sc. in Industrial Engineering

Supervisor: Assoc. Prof. Dr. Kürşad AĞPAK

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When studies on the assembly line balancing problem taking into account the setup times are analyzed, a few papers are observed. However, studies showed that setup time plays an important role in total production time. Besides, in these studies, the setup times are assumed to be deterministic. Considering deterministic setup times decrease proximity of problem to real life application. Because the operation and setup times may vary in real applications due to human factors, machine breakdowns, lack of equipment and environmental factors. Therefore, in this thesis, assembly line balancing problem is investigated taking into account the sequence-dependent stochastic setup times. Mathematical model is proposed for solving the problem and computational analysis is conducted on test problems. The mathematical model can find solution for small-size test problems. However, for large scale test problems it doesn't give solution within acceptable computation time. For this reason, a heuristic approach based on COMSOAL is presented for solving large sized test problems.

Keywords: Assembly line, Setup time, Stochastic, Sequence-dependent

ÖZET

STOKASTİK SIRA BAĞIMLI HAZIRLIK ZAMANLI MONTAJ HATTI DENGELEME PROBLEMİ

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Montaj hattı dengeleme problemi üzerine yapılan çalışmalar incelendiğinde hazırlık zamanlarını dikkate alan az sayıda makaleye rastlanılmaktadır. Ancak, yapılan araştırmalar hazırlık zamanlarının toplam üretim zamanı içerisinde önemli bir payı olduğunu göstermiştir. Bunun yanında bu çalışmalarda hazırlık zamanlarının deterministik olduğu varsayılmıştır. Zamanların deterministik olarak kabul edilmesi problemi gerçek uygulamalardan uzaklaştırabilir. Çünkü gerçek uygulamalarda görev ve hazırlık zamanları insan faktörü, makine arızaları, ekipman eksikliği ve çevre faktörü gibi nedenlerden dolayı değişkenlik gösterebilmektedir. Bu nedenle, bu çalışmada sıra bağımlı stokastik hazırlık zamanlarını da dikkate alarak montaj hattı dengeleme problemi incelenmiştir. Problemin çözümüne yönelik matematiksel model önerilerek test problemleri üzerinde hesaplama analizleri yapılmıştır. Matematiksel model küçük boyutlu test problemleri için çözüme ulaşmıştır. Büyük boyutlu test problemleri için ise kabul edilebilir zaman aralığında çözüme ulaşamamıştır. Bu sebeple büyük boyutlu test problemleri için COMSOAL algoritması sunulmuştur.

Anahtar Kelimeler: Montaj hattı, Hazırlık zamanı, Stokastik, Sıra bağımlı

To My Parents

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LIST OF ABBREVIATIONS

AL	Assembly line
ALB	Assembly line balancing
ALBPs	Assembly line balancing problems
MIP	Mixed integer program
SA	Simulated annealing
COMSOAL	Computer Method of Sequencing Operations for Assembly Lines
PSO	Particle swarm optimization
BA	Bees algorithm
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

CHAPTER I

INTRODUCTION

An assembly line (AL) is an arrangement of machines, workers and tools. Traditionally, on this line a type of product is assembled serially and each worker performs on a specific task or tasks. An AL consists of workstations connected to each other with a conveyor belt. Station is a place in which workers perform on a specific task or tasks. Each station has a cycle time which is needed so as to perform on a task or tasks in this station. Henry Ford altered the type of manufacturing system by introducing a moving belt in a facility for the first time in 1913. This change provided lots of improvements in manufacturing of assembly products. By this way, a new study field which is called assembly line balancing has come into being in industry and literature. Assembly line balancing problems have increased the importance over the years and several studies have been carried out on assembly line balancing (ALB) since then.

Assembly line balancing problems (ALBPs) can be classified into several parts in terms of the number of model, complexity of problem, the line design and processing time aspects. On the basis of the number of model, it is separated three parts as single-model, multi-model and mixed-model. In single-model line, one type of product is manufactured with high volume. However, different models of a product are produced in a line simultaneously in mixed-model. Different models of same product or different products can be also produced on a line. This case is called as multi-model.

In terms of type of line ALBP can be divided into four parts. These are one-sided, two-sided, U-line and parallel lines. Traditional assembly lines are known as serial or straight layout of assembly lines. In these types of lines, workstations are organized along a conveyor belt serially and workers carry out tasks on continues portion of the line (Scholl, 1999). Layouts of this type are generally preferred because it can be easily placement and it reduces cost of production.

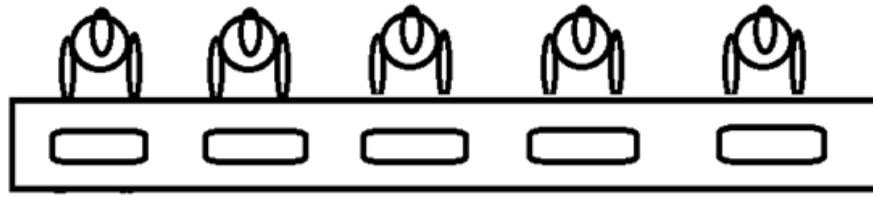


Figure1.1. One-sided assembly line

Two-sided assembly lines are usually organized to produce large-sized products, such as buses, automobiles and trucks. In this lines, both right-side and left-side of the line are used in parallel (Özcan and Toklu, 2010). Tasks can be performed on the left side, right side or both sides on the line. Two-sided assembly lines have several advantages compared with one-sided assembly lines. These are: (i) assembly line length can be shorter than the one-sided assembly line length, (ii) it can reduce material handling cost, setup time, workers motion and the amount of throughput time; and (iii) it can also reduce cost of fixtures and tools (Bartholdi, 1993).

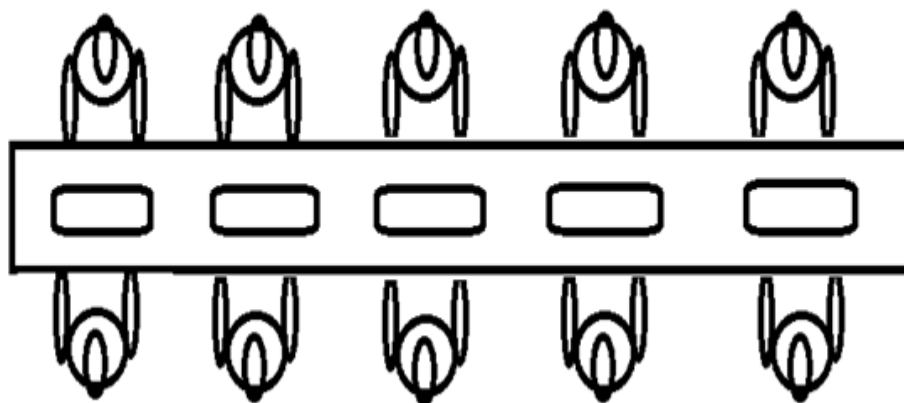


Figure 1.2. Two-sided assembly line

A U-line organizes tasks around a U-shaped production line and arranges them into workstations that worker can cross from one side of the line to the other. U-lines improve communication and visibility between operators on the line. This advantage provides problem-solving facility and quality improvement. Also, U-lines can

decrease the total number of required operators on the line and rebalance the line easier compared to the traditional production line (Guerriero and Miltenburg, 2003).

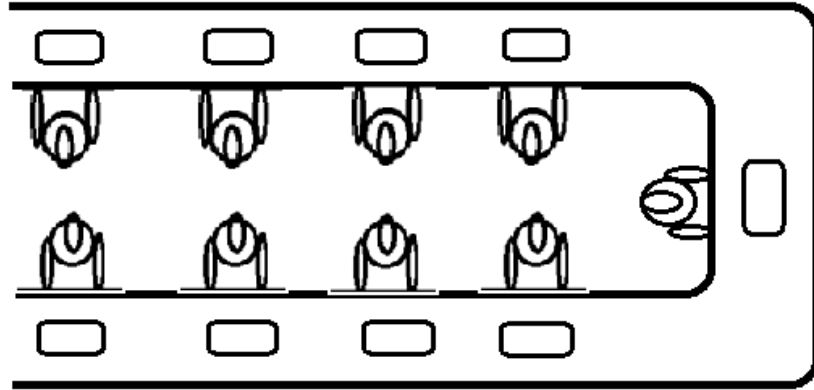


Figure 1.3. U-type assembly line

Most production plants can include one or more ALs. If the demand is high, it will be suitable to prefer parallel ALs. One of the advantages of parallel ALs is shortening the AL, but it may cause more tools and equipment requirement. The other advantage of parallel ALs is observed while station breakdowns. If lack of equipment occurs at a line, other lines can go on to run. A single serial line cannot be run whenever there is a lack of equipment at any station (Gökçen et al., 2006).

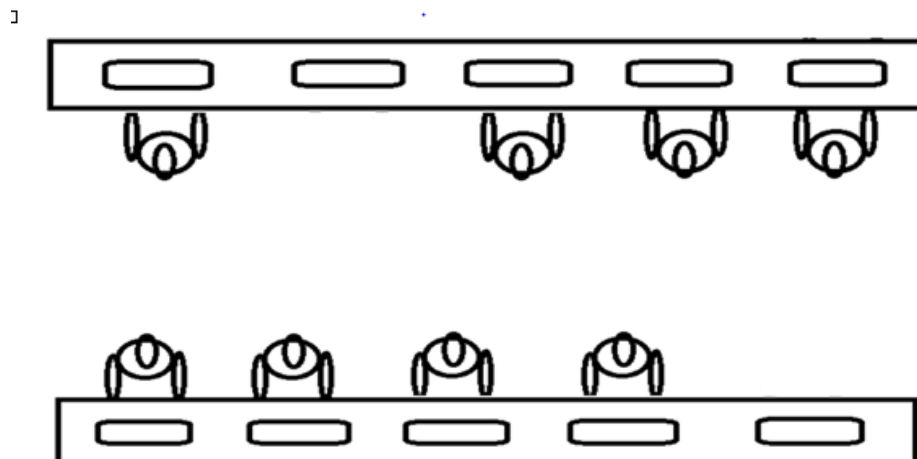


Figure 1.4. Parallel lines

Considering processing times, ALBP is classified into three groups: deterministic, stochastic and fuzzy processing times. In deterministic ALBP, processing times are constant. But in many real life implementations, particularly in manual ALs, it is not always possible. Human factors can cause changeable processing times because of the loss of motivation, non-qualified operators, and lack of training. In addition, machine breakdowns, complex tasks and environment may vary the processing times (Özcan, 2010). Also, Shin (1990) highlighted the task time may be random due to worker fatigue, defects in raw materials, low skill levels, poorly maintained equipment, job dissatisfaction and so on. Thus, considering stochastic times is a more realistic approach for ALB. In cases where times cannot be expressed by a probability distribution, fuzzy processing times can occur. Fuzzy set theory allows for the consideration of the ambiguity involved in assigning processing and cycle times and the uncertainty contained within such time variables (Fonseca et al., 2005).

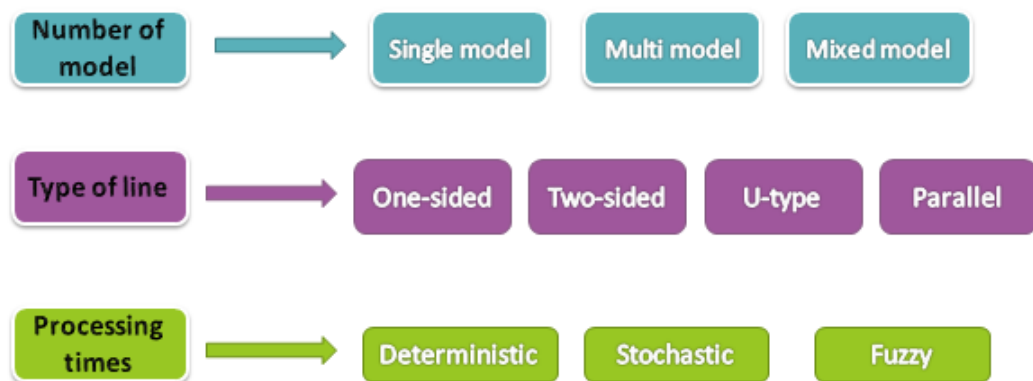


Figure 1.5. Classification of assembly line balancing problem

Another important classification type in ALs is with or without sequence-dependent setup times. Although researches often assume that the setup time between jobs is sequence-independent, studies show that setup time is sequence-dependent because of setup time differs depending on which job is operated next (Kim and Bobrowski, 1997). If setup time depends on the job to be operated, it is called sequence-independent. However, setup time is called sequence-dependent if it depends on both the immediate preceded job and the job to be processed (Allahverdi, 2006).

Setup times generally consist of walking distance, withdrawal times, turning and lifting processes, cooling or curing processes and changing tools which are used

between two consecutive tasks (Scholl et al., 2013). Many studies in literature disregarded the sequence-dependent setup times. Because setup times have very low value compared to processing time (Andres et al., 2008). However, a research at a German car manufacturer has shown that withdrawal and walking times quantity to about 10-15% of total production time. Also, if cycle time is low, setup times can represent a high rate of it (Andres et al., 2008). For example, when walking speed is typically supposed to be about 1m/s (Barnes 1959), walking related setup times can be accepted between 0 and 10s per setup. Concerning cycle times of about 60-90s, this is a very critical aspect (Scholl et al., 2013). Robotic lines involve setup times, as well. Often the robot removes the real tool, choose a new tool and make settings before starting next job. The time for the tool settings can vary and depends on the sequence of jobs. Sometimes processes such as lifting, turning, cooling and curing cause a sequence-dependent setup times. Consequently, it is essential to consider these times in a sequence-dependent manner (Scholl et al., 2013). If these times are disregarded, differences can occur between real situations and studies in literature and so methods which are developed may not provide the desired results in real life applications.

Such as operation times, setup times may show stochastic structure, as well. Especially, setups such as walking, turning, lifting, preparing the machine and changing tool depend on human factor and therefore setup times can vary. Setup times are uncertain due to the variation in skill levels of setup crews, unexpected breakdowns of fixtures and tools and temporary shortage of equipment, tools and setup crews (Wang and Choi, 2010). In addition to this, technological variety can cause uncertain setup times (Kim and Bobrowski, 1997).

Importance of stochastic system and proximity of it to the real life was expressed above. Also, significance of setup times and proportion in total production time was mentioned. Although there are studies about ALB, stochastic ALB and ALB with sequence-dependent setup times in literature separately, there is not any study involves these subjects together. At the same time though stochastic setup time exists in scheduling problem, to our best knowledge it has not been considered in ALBP. Thus, in this study ALBP with stochastic sequence-dependent setup times was scrutinized. We aimed to proximate problem to real life application and focused on

stochastic sequence-dependent setup times. Because setup times exist in real manufacturing system and vary due to human factor, machine breakdowns, lack of equipment and etc. Therefore, it is strongly necessary to consider stochastic concept on setup times.

1.1 Thesis Organization

Chapter 2: the literature review is presented in this chapter. We especially focused on ALBP with sequence-dependent setup times and stochastic ALBP. Previous studies are examined and given detailed information about them.

Chapter 3: deterministic and stochastic ALBP are defined in this chapter and given information about specific qualities of them. Assumptions of each problem are described and dissimilarities of stochastic ALBP from deterministic ALBP are expressed. Then ALBP with stochastic sequence-dependent setup times is defined in detail. Forward and backward setup times are described and expressed through figure and formulation.

Chapter 4: two mathematical models as deterministic and stochastic ALBP are presented in this chapter. Similarities and dissimilarities of them are discussed.

Chapter 5: solution methods are represented to solve ALBP. COMSOAL which is an efficient heuristic method for ALBP is selected among them and explained with an example.

Chapter 6: results and their effects on performance of proposed mathematical models and COMSOAL method is analyzed in this chapter.

Chapter 7: the summary of the study and the conclusions are given in the last chapter. Also some aspects for the future work are discussed.

CHAPTER II

LITERATURE REVIEW

ALBP has being studied for more than 50 years and many studies on the ALBP have been made during this time. In this section especially ALBP with sequence dependent setup times and ALBP with stochastic task time were analyzed in detail. Scheduling problems with stochastic setup times were analyzed for this thesis but they weren't mentioned in this section because of out of scope the problem. It can be seen Wurman and Wellman (1996), Kim and Bobrowski (1997), Chandra and Grabis (2003), Allahverdi A. (2005), Zhu and Wilhelm (2005), Mei and Winands (2007), Samaddar and Whalen (2007), Wang and Choi (2010), Lin et al. (2013)'s studies for detailed information.

2.1 ALBP with Sequence-dependent Setup Times

Andres et al. (2008) considered the sequence-dependent setup times in the simple ALBP first time in literature. Necessity of considering sequence-dependent setup times is mentioned and given detailed information. Also, considering sequence-dependent setup times can proximate problems to real life. A mathematical model is proposed and solved by using eight different heuristic rules. Heuristic rules' results were compared with GRASP algorithm's results. It is seen that scheduling of tasks must be considered in addition to balancing because of the existence of sequence-dependent setup times.

Özcan and Toklu (2010) took into consideration balancing of two-sided ALs with sequence-dependent setup times. In this study, sequence-dependent setup times between tasks firstly were considered for two-sided ALs. Primary objective of study is minimizing the number of the mated-stations and secondary objective is minimizing the number of the workstations for a given cycle time. So as to provide this, mixed integer program (MIP) is proposed and COMSOAL which is a heuristic approach is presented for large size problems. Results have showed that COMSOAL was very effective for the problem.

Seyed-Alagheband et al. (2010) proposed a mathematical model and Simulated Annealing (SA) algorithm for balancing the AL type-II problem with sequence-dependent setup times. Different from Andres et al. (2008)'s study, it is minimized cycle time instead of the number of the station.

Hamta et al. (2011) proposed a mathematical model for multi-objective ALBP. They assumed that operation times are unknown variables and only known information is the upper and lower bounds of operation times. This type of operation time is named bounded processing time. Also, operation times of tasks change according to worker(s) (or machine(s)) learning and sequence-dependent setup time exists between tasks. In addition to this, a new solution technique which is a hybrid particle swarm optimization (PSO) is proposed by Hamta et al.(2013) for the same study.

Yolmeh and Kianfar (2011) presented a hybrid genetic algorithm for the line balancing problem with sequence-dependent setup times. Task sequence has effect on the total operation time in a station due to sequence-dependent setup times between tasks.

Akpınar et al. (2012) proposed a new hybrid algorithm which combines genetic algorithm and ant colony optimization for mixed-model ALBP with sequence-dependent setup times. The problem was expanded by adding low, medium, and high variability of setup times.

Scholl et al. (2013) presented a mathematical model for ALB and scheduling problem with sequence-dependent setup times and solve it by using heuristic methods. Scholl et al. (2013) extended Andres et al. (2008)'s approach by adding forward and backward setup concept. Important information is given about necessity of considering setup times and percentage in total production time.

Akpınar and Baykasoğlu (2014a) developed a new mathematical programming model for mixed-model ALBP considering zoning constraints, parallel workstations and sequence-dependent setup times. The proposed model takes into account both the setups because of the model switches in any station and the setups between the tasks of the same model. This problem is an extension of classical mixed-model ALBP. The aim of study is finding optimum value of the number of the station. Many studies in literature disregarded setups due to low proportion compared with

task times. However, different schedules can cause different workloads, therefore effectiveness of line decreases. Besides, if cycle time is low, setup times may have high proportion of cycle time. Thereby, considering sequence-dependent setup times becomes important.

Akpinar and Baykasoğlu (2014b) dealt with mixed-model ALBP by applying bees algorithm (BA) and the problem was extended by adding low, medium and high variability of setup times. Presented multiple colony algorithm was conducted on test problems and compared with single colony algorithm in terms of computational times and solution quality. Results have shown that proposed algorithm has quite good performance.

Studies dealt with sequence-dependent setup times for ALBP claim that setup times exist between two consecutive tasks and should be taken into consideration. Setup times are neglected in many studies due to low proportion within total operation time. However, researches have shown that setup times may have high proportion in total operation time. In addition, even though many studies assume setup times to be sequence-independent, amount of setup time differs depending on what type of job is processed next. Therefore, it is essential to consider sequence-dependent setup times for ALBP.

2.2 Stochastic ALBP

When the assembly line balancing literature is examined, it is seen that most of the studies consider times to be deterministic. There are a few studies related to the stochastic situation. The main reason of this is complex mathematical structure of the problem.

Sarin and Erel (1990) developed a new cost model for single model stochastic ALBP and showed the use of dynamic programming model in their study. Results are compared with Kottas and Lau technique and it is seen that applied procedure is better than Kottas and Lau technique.

Sarin et al. (1999) dealt with the single-model, stochastic ALBP in their study. The objective of the study is minimizing the expected incompleteness cost and the total labor cost. It was presented an initial dynamic programming based solution and improved it using branch-and-bound procedure. Obtained results were compared

with those by the Kottas and Lau method (1981) and it was seen that their results are better than Kottas and Lau's within acceptable computation times.

Ağpak (2004) analyzed stochastic U-type ALBP under two different purposes and developed chance-constraint mathematical models for this purpose. Also, COMSOAL algorithm is proposed for large scale problems.

Gamberini et al. (2005) considered the single-model stochastic version of AL re-balancing problem. It was proposed a new heuristic which combines of Kottas and Lau (1973) heuristic approach and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). Processing times were accepted stochastic and normally distributed.

Erel et al. (2005) proposed beam search for stochastic U-type ALBP. It is the first study propose a heuristic method for stochastic U-type ALBP. Objective of proposed method is to minimize total expected cost. This cost includes total expected incompleteness cost and total labor cost. Heuristic method was conducted on straight line test problems and it was seen that U-line construction are better than their straight lines for stochastic ALBP. Task times display stochastic structure because of performing of tasks manually. In addition, task times are assumed to be distributed normally.

Gamberini et al. (2006) proposed an integrated heuristic method which consists of Kottas and Lau approach and TOPSIS for stochastic AL re-balancing problem. Proposed algorithm aims to minimize the two performance criterion. These performance criteria are re-assignment of tasks and costs of expected unit incompleteness and unit labour. In order to evaluate performance of proposed algorithm, it was compared with Kottas and Lau approach. Results have shown that proposed algorithm has advantages in terms of completion costs and workload re-assignment. Task times were accepted stochastic because of manually assembled of productions and flexible nature of workers.

Zhao et al. (2007) dealt with the stochastic mixed-model AL. In a mixed-model AL, processing times may be different for different models. For example, if it is produced cars which have engines with different horse powers, processing times will be different. Thus, processing times will display stochastic structure. It was said that

overload times were essential to measure performance of mixed-model ALs. Therefore, objective of study investigating the overload times for stochastic mixed-model ALs and it was proposed a method in order to achieve this objective. Calculations showed that proposed approach achieved satisfactory results.

Gamberini et al. (2009) considered AL re-balancing problem with stochastic task times and proposed multiple single pass heuristic algorithm for the problem. Task times were considered stochastic because of manually assembled of productions. The aim of study is to minimize task reassignments and assembly costs. In addition, a multi-objective genetic algorithm was improved and compared with proposed heuristic algorithm. Results have shown that proposed algorithm dominated the genetic algorithm. Besides, proposed procedure was applied in a case study and it was seen that algorithm provided benefits for line balancing.

Özcan U. (2010) studied on stochastic task times firstly for two sided assembly line balancing. The aim of study minimizing the number of mated station, and it is developed chance-constrained, piecewise-linear and mixed integer program (CPMIP). SA algorithm is proposed for large size problems and compared with COMSOAL (Computer Method of Sequencing Operations for Assembly Lines) which is an effective heuristic approach. Reasons such as machine breakdowns, lack of training, complex tasks, loss of motivation, environment, non-qualified operators may cause stochastic structure. It is assumed the task times are distributed normally and as a secondary objective the number of stations was also minimized.

Cakir et al. (2011) took into consideration multi-objective optimization of a single model stochastic ALBP with parallel workstations. First objective is minimization of the smoothness index and the second is minimization of the design cost. A new approach is proposed based on a SA algorithm called m_SAA. The aim of study is to obtain Pareto-optimal solutions for the single model stochastic ALBPs different from the studies in literature. Results are compared with SA's results and it is seen that m_SAA was more effective than SA.

Studies related to stochastic ALBP were examined above and reasons of stochastic structure were explained in detail. Even though task times are considered to be stochastic in these studies, situation that the setup times to be stochastic is not

considered for ALBP. However, setup times can display stochastic structure just as task times because of the same reasons.

CHAPTER III

PROBLEM DEFINITION

In this chapter ALBP with stochastic sequence-dependent setup times is defined and analyzed. The objective function is to minimize number of station under given cycle time. Chapter starts with definition of deterministic and stochastic ALBP and continues with definition of basic problem and problem assumptions.

3.1 Deterministic ALBP

Processing times are constant in deterministic ALBP. Assumptions of the problem are as follows:

- i. Operation times are known and constant.
- ii. Precedence diagram is known.
- iii. Division of tasks is not allowed.
- iv. All workers have same specification and gain equal wage.
- v. If task i is before task p in precedence diagram, task p cannot be performed without task i assigned to previous or same station.

Under these assumptions problem is defined simple deterministic ALBP. With relaxation of some assumption new problem types can be defined. For example, it can be allowed to sharing task more than one station through relaxation of assumption (iii) and paralleling one station through relaxation of assumption (iv).

There are three alternative cases, under minimization of idle time objective for deterministic ALBP. They are:

- i. Minimization of station number for a given cycle time.
- ii. Cycle time minimization for given number of station.
- iii. Number of workstations and cycle time minimization together.

Constraints for cases are as follows:

- i. All tasks must be done.
- ii. One task cannot be assigned to more than one station.
- iii. Total time of tasks which are performed in one station cannot be more than cycle time.
- iv. If task i is before task p in precedence diagram, task p cannot be performed without task i assigned to previous or same station.

3.2 Stochastic ALBP

Stochastic ALBP occurs through relaxation of assumption (i) in deterministic ALBP. Assumption of constant operation times becomes invalid, if it is considered human factor. In other words, human factor can cause variability of operation times. Reasons of variability may be lack of training, the loss of motivation, non-qualified operators, machine breakdowns, complex tasks and environment (Özcan, 2010). These cases may cause total time of tasks assigned to one station exceed cycle time and unfinished tasks within the border of station. Furthermore, next task which has precedence relation with previous task may not be started. Especially, taking into account precedence relations, some tasks may not be started.

Assumptions for stochastic ALBP are as follows:

- i. Operation times are uncertain.
- ii. One task cannot be assigned to more than one station.
- iii. Precedence diagram is known.
- iv. Keep in stock is not allowed between the workstations.
- v. One task can start after all predecessors of it finish.
- vi. All workers have same specification and gain equal wage.

Assumptions (ii), (iii), (iv), (v), (vi) are the same with deterministic ALBP. Assumption (i) represents the stochastic case. In ALBP literature, normal probability distribution is generally used for presenting uncertainty of task times. (Sarin et al., 1999, Boysen et al. 2007).

3.3 Problem definition

Tasks which assign to a station on the assembly line are performed in an order by considering the precedence relationship. In ALBP with sequence-dependent setup times, each task can be performed after a setup dependent to preceded task. In other words, if task i is immediate predecessor of task p and they are assigned to the same station; it can require a setup for task p after task i is performed. Therefore, when calculating the station time, setup time (tsu_{ip}) between task i and p must be taken into account in the same cycle. This is called forward setup time. If task p is the last task and task i is the first task assigned to the same station, a setup can be required before task i is performed in the next cycle. This is called backward setup time ($tsub_{ip}$). In this case total station time will be as follows:

$tsub_{ip}$	i	tsu_{ip}	p
-------------	-----	------------	-----

Figure 3.1. Presentation of forward and backward setup times

$$\text{Total station time} = tsub_{ip} + t_i + tsu_{ip} + t_p$$

Andres et al. (2008) accepted these setup times same for both cycles and only considered forward setup time in their study. However, Scholl et al. (2013), considered forward and backward setup time together by extending Andres et al. (2008)'s study. In this study, problem is considered for the case forward and backward setup times are expressed by a probability distribution. It is assumed that operation and setup time conform normal probability distribution. Problem assumptions are presented below.

- Precedence relations between tasks are known.
- A task cannot be assigned to more than one station.
- Setups occur between tasks and setup time is sequence-dependent.
- Task and setup times are normally distributed with known mean and variance.
- Tasks cannot be taken to pieces and they must be done.
- One side of the line is used.

In this thesis, ALBP with stochastic sequence-dependent setup times is considered. We extend the study of Andres et al. (2008) by adding stochastic concept to operation and setup times. Andres et al. (2008) considered firstly the sequence-dependent setup times between tasks for ALBP. Importance of considering sequence-dependent setup times and proximity to real life problems are emphasized in their study. Kim and Bobrowski (1997), emphasized that setup variation as well as sequence dependency plays an important role on real world production systems. In order to increase proximity of the problem to the real life, stochastic and sequence-dependent setup times were considered together. It was highlighted in introduction that operation and setup times may show stochastic structure because of skill variation levels of setup crews, tools and setup crews, the loss of motivation, temporary shortage of equipment, lack of training, environment, unexpected breakdowns of fixtures and tools, complex tasks and non-qualified operators by inspiring studies of Özcan U. (2009), Wang and Choi (2010) and Kim and Bobrowski (1997).

CHAPTER IV

MATHEMATICAL MODELS

In this chapter mathematical model which is developed by Andres et al. (2008) is given firstly. Then modified constraints by adding forward and backward setups and new constraints are analyzed. Finally, transforms are done with the help of chance constraint programming and presented mathematical model for ALBP with stochastic sequence-dependent setup times which is defined in previous chapter.

4.1 Deterministic mathematical model

Andres et al. (2008) are the first who considered sequence-dependent setup times for ALBP. Mathematical model which is developed by Andres et al. (2008) is given in below.

Objective function

$$\text{Min } Z = \sum_{j=m_{\min}+1}^{m_{\max}} j \cdot y_j \quad (5.1)$$

Subject to:

$$\sum_{j=E_i}^{Nm_j} x_{ijs} = 1 \quad \forall i, \quad (5.2)$$

$$x_{ijs} \leq 1 \quad (\forall j; s = 1, \dots, Nm_j), \quad (5.3)$$

$$x_{ij,s+1} \leq x_{ijs} \quad (\forall j; s = 1, \dots, Nm_j - 1), \quad (5.4)$$

$$\sum_{j=E_i}^{Nm_j} (NT_m \cdot j - 1 + s) \cdot x_{ijs} \leq \sum_{j=E_k}^{Nm_j} (NT_m \cdot j - 1 + s) \cdot x_{kjs} \quad \forall i, k \in P, \quad (5.5)$$

$$\sum_{\forall i \in T_j}^{Nm_j} t_i \cdot x_{ijs} + \sum_{\forall i, k \mid i \neq k \wedge i, k \in T_j} tsu_{ik} \cdot z_{ikj} \leq TC \quad j = 1, \dots, m_{min}, \quad (5.6)$$

$$\sum_{\forall i \in T_j}^{Nm_j} t_i \cdot x_{ijs} + \sum_{\forall i, k \mid i \neq k \square i, k \in T_j} tsu_{ik} \cdot z_{ikj} \leq TC * y_j \quad j = m_{min} + 1, \dots, m_{max}, \quad (5.7)$$

$$x_{ijs} + x_{kj, s+1} \leq 1 + z_{ikj} \quad (\forall j; s = 1, \dots, Nm_j - 1; \forall (i, k) / (i \neq k) \square (i, k \in T_j) \square (k \notin PT_i)), \quad (5.8)$$

$$x_{ijs} - \sum_{\forall k \in T_j (i \neq k) \square k \notin PT_i} x_{ij, s+1} \leq w_{ij} \quad \forall j; s = 1, \dots, Nm_j - 1; \forall i \in T_j, \quad (5.9)$$

$$w_{ij} + x_{kj1} \leq 1 + z_{ikj} \quad \forall j; \forall i, k \mid (i \neq k) \wedge i, k \in T_j \wedge i \notin PT_k, \quad (5.10)$$

Table 4.1 Notations

i,k	Task
j	Station
s	Position within the sequence of a station
N	Task set ($i=1, \dots, N$)
m_{min}	Lower bound for station number
m_{max}	Upper bound for station number
t_i	Operation time of task i
TC	Cycle time
E_i, L_i	Earliest and Latest station where task i can be assigned
T_j	Set of tasks that can be assigned to station j
P	Set of pairs of tasks (i,k) in which i is immediate predecessor of k
PT_i	Set of tasks all predecessors of task i , consisting non immediate predecessors.
ST_i	Set of tasks all successors of task i
Nm_j	Maximum task number that can be assigned to station j
NT_m	Maximum task number that can be assigned to any station $NT_m = \max_j(Nm_j)$
tsu_{ik}	Forward setup time when task k is performed just after task i inside the same station
$tsub_{ik}$	Backward setup time when task k is performed just after task i inside the same station

$x_{ijs} \in \{0,1\}$	1 if task i is assigned to station j in position s of its schedule
$y_j \in \{0,1\}$	1 if any task is assigned to station j
$z_{ikj} \in \{0,1\}$	1 if task i immediate predecessor of task k in the station j in the same cycle
$z_{b_{ikj}} \in \{0,1\}$	1 if task i immediate predecessor of task k in the station j in the next cycle
$w_{ij} \in \{0,1\}$	1 if task i is the last one in the sequence of tasks assigned to station j
$W_{\max}$	Big number
μ_i	Mean time of task i
μs_{ik}	Mean of forward setup time where task i immediate predecessor of task k in the same station in the same cycle
$\mu s_{b_{ik}}$	Mean of backward setup time where task i immediate predecessor of task k in the same station in the next cycle
σ_i	Variance of task i
σs_{ik}	Variance of forward setup time where task i immediate predecessor of task k in the same station in the same cycle
$\sigma s_{b_{ik}}$	Variance of backward setup time where task i immediate predecessor of task k in the same station in the next cycle

Minimization of the number of workstations is provided by objective function (5.1). The assignment constraint (5.2) provides that every task must be assigned to only one position inside only one station. Constraint (5.3) provides that more than one task can't be assigned to every position inside every station. Constraint (5.4) provides that the tasks assigned to same station should be sequenced in increasing positions in the schedule of every station. Constraint (5.5) is the precedence constraint and considers both the assignment of tasks to different workstations and positions inside the same station. Constraints (5.6) and (5.7) provide that the total time in every station, containing both operation and setup times, does not exceed the cycle time. Constraint (5.8) provides that if tasks i and k are assigned to positions s and $s+1$ respectively, then z_{ikj} is equal to 1. Constraint (5.9) provides that if task i is assigned to the last position in the schedule of station j , the variable w_{ij} is equal to 1. Constraint (5.10) provides that if task i is assigned to the last position and task k to the first one in the schedule of station j , the variable z_{ikj} is equal to 1.

Andres et al. (2008) considered only forward setup in their study. However, a setup can be needed before starting the first task assigned to station. Taking into account this situation Andres et al. (2008)'s study is extended by adding forward and backward setups. In addition, new constraints are added in order to increase effectiveness. The modified and new added constraints for deterministic ALBP with sequence-dependent setup times are presented below.

$$\sum_{j=1}^{m_{max}} \sum_{s=1}^{Nm_j} x_{ijs} = 1 \quad \forall i, \quad (5.11)$$

$$\sum_{j=1}^{m_{max}} \sum_{s=1}^{Nm_j} (NT_{m \cdot j} - 1 + s) \cdot x_{ijs} \leq \sum_{j=1}^{m_{max}} \sum_{s=1}^{Nm_j} (NT_{m \cdot j} - 1 + s) \cdot x_{kjs} \quad \forall i, k \in P, \quad (5.12)$$

Constraints (5.11) and (5.12) don't include E_i and L_i different from (5.2) and (5.5).

$$\begin{aligned}
& Nm_j \\
& \forall i \in T_j \quad s=1 \\
& t_i \cdot x_{ijs} + \quad \quad \quad tsu_{ik} \cdot z_{ikj} + \quad \quad \quad tsub_{ik} \cdot zb_{ikj} \\
& \quad \quad \quad \forall i, k \quad i \neq k \quad \square \quad i, k \in T_j \quad \quad \quad \forall i, k \quad (i \neq k) \quad \square \quad (i, k \in T_j) \\
& \leq TC * y_j \quad j = 1, \dots, m_{max} ,
\end{aligned} \tag{5.13}$$

$$w_{ij} + x_{kj1} \leq 1 + zb_{ikj} \quad (\forall j; \forall i, k \mid (i \neq k) \square (i, k \in T_j) \square (i \notin ST_i)), \tag{5.14}$$

Constraint (5.6) is removed and cycle time constraint is expressed by one form in new mathematical model. Constraint (5.7) carries out the same mission with (5.6). Therefore, constraint (5.6) isn't needed. Constraints (5.7) and (5.10) are modified by considering backward setup time and new constraints are constraints (5.13) and (5.14).

$$\begin{aligned}
& X_{ijs} \cdot -W_{max} \cdot y_j \leq 0 \quad \forall (j) \in J \\
& s \in Nm_j \quad \forall i \in T_j
\end{aligned} \tag{5.15}$$

$$y_{j+1} \leq y_j \quad j = 1, \dots, m_{max} - 1 , \tag{5.16}$$

$$\begin{aligned}
& m_{max} \quad N \\
& z_{ikj} \leq 1 \quad \forall i \\
& j=1 \quad \forall k \mid tsu_{ik} > 0 \wedge k \notin PT_i
\end{aligned} \tag{5.17}$$

$$\begin{aligned}
& m_{max} \quad N \\
& zb_{ikj} \leq 1 \quad \forall i \\
& j=1 \quad \forall k \mid tsub_{ik} > 0 \wedge k \notin ST_i
\end{aligned} \tag{5.18}$$

Finally, new added constraint (5.15) checks whether station open or not; constraint (5.16) provides opening workstations sequentially. (5.17) and (5.18) prevent z to take unnecessary value. It is expected that new added constraints will be positive effect on solution capability of the model.

4.2 Chance constraint MIP model

In stochastic situation, times receive values according to a certain probability distribution and in deterministic situation receive constant values for ALBP. This is

the main difference between stochastic situation and deterministic situation in ALBP. In this thesis, Andres et al. (2008)'s study is extended by using chance-constraint technique for ALBP with stochastic sequence-dependent setup times. Thus, probabilistic structure of the problem has been converted into equivalent deterministic case.

The main objective of 0-1 integer programming model with chance constraint is to determine deterministic equivalents of probabilistic constraints. Model ensures the possibility of exceeding the cycle time of total time of assigned tasks in a station to remain below determined probability level (α).

Task time t_i is taken $Y = t_i$ when $t_i \sim N(\mu_i, \sigma_i^2)$, it turns into $z \sim N(0,1)$ with the help of $Y \sim N(\mu_i, \sigma_i^2)$, $z = \frac{Y - \mu_i}{\sqrt{\sigma_i^2}}$.

Probability of exceeding cycle time of station time can be equal at most α , it can be written $P(Y > C) \leq \alpha$. If some regulation is done, this equivalent turns into $1 - P(Y \leq C) \leq \alpha$ or $P(Y \leq C) \geq 1 - \alpha$. Then, if z-transforms is done, the following equation is obtained:

$$P\left(z \leq \frac{C - \mu_i}{\sqrt{\sigma_i^2}}\right) \geq 1 - \alpha \quad (5.19)$$

$P(z \leq z_{1-\alpha}) = 1 - \alpha$ provides to obtain (5.20) and (5.21) from (5.19).

$$z_{1-\alpha} \leq \frac{C - \mu_i}{\sqrt{\sigma_i^2}} \quad (5.20)$$

$$\mu_i + z_{1-\alpha} \sqrt{\sigma_i^2} \leq C \quad (5.21)$$

When mean and variance of setup are added to (5.21), (5.22) is obtained. This constraint replaces with (5.7) in which deterministic model.

$$\begin{aligned}
& \sum_{\forall i \in T_j} \sum_{s=1}^{Nm_j} \mu_i \cdot x_{ijs} + \sum_{\forall (i,k)(i \neq k) \wedge (i,k \in T_j)} \mu s_{ik} \cdot z_{ikj} + \sum_{\forall (i,k)(i \neq k) \wedge (i,k \in T_j)} \mu s b_{ik} \cdot z_{ikj} + \\
& z_{1-\alpha} \sqrt{\sum_{\forall (i,k)(i \neq k) \wedge (i,k \in T_j)} \sigma_i^2 \cdot x_{ijs} + \sum_{\forall (i,k)(i \neq k) \wedge (i,k \in T_j)} \sigma s_{ik}^2 \cdot z_{ikj} + \sum_{\forall (i,k)(i \neq k) \wedge (i,k \in T_j)} \sigma s b_{ik}^2 \cdot z_{ikj}} \leq TC \cdot y_j \\
& (j = 1, \dots, m_{\max}) \tag{5.22}
\end{aligned}$$

Stochastic structure of problem is expressed by Constraint (5.22). This constraint guarantees the possibility of exceeding the cycle time of total time of assigned tasks in a station to remain below determined probability level (α). In this study, based on applicability and classical cycle time constraint, probability level (α) is assumed greater and equal than 0.5.

CHAPTER V

HEURISTIC PROCEDURE

Methods developed for the solution of ALB problems can be divided into two parts. They are:

- Optimal methods
- Heuristic methods

Optimal methods require a very long time to achieve a solution due to the combinatorial structure of the problem. This situation eliminates the applicability of these methods. Heuristic methods are generally used in solving the ALB problem. These methods reach to solution in a very short time but do not guarantee an optimal solution. In this study well known COMSOAL algorithm is adapted for solving ALBP with stochastic sequence-dependent setup times.

5.1 COMSOAL

COMSOAL is a computer-based method based on random search. Method uses a simple record keeping system that allows testing numerous of appropriate sequences quickly. Sequences are generated by selecting randomly from set of appropriate assigned tasks. Throughout the solution desired trial can be made and the line design is obtained as each trial, as well. The first exact sequence(workstations and tasks assigned to workstations) which method provides is preserved as first solution by the system and if the new exact sequence is better than the previous, old solution is ignored and new solution is kept by the system.

Arcus (1966) has developed 9 sampling and adopted in various combinations so as to increase the effectiveness of the method and provide a good performance in large scale problems in the same study.

Although COMSOAL does not have complicated mathematical structure, it has many advantages. It can be encoded in a computer language simply and more likely to achieve the optimal solution in long working hours. Restrictions could be modeled into the algorithm easily. Also, it has rapid access to possible sequence.

These advantages also show that why COMSOAL heuristic is used in this study. The main consideration of this algorithm produces so many numbers of feasible solutions randomly, and also selecting the best one among produced feasible solution. The traditional COMSOAL algorithm can be continued in 6 steps as follows:

Step 1 Precedence diagram is created. Then, Construct a list (list A), in one column, all the work elements, and in an adjacent column, operation time and number of predecessors.

Step 2 From list A, construct list B, constituted of the tasks which have zero predecessors.

Step 3 Add to C list the tasks in the B list whose time is less than or equal idle time of station.

Step 4 A task is selected randomly from the C list. (This random selection causes the formation of different balances.)

Step 5 If the C list is empty, a new station opens and C list is created again, return 4.

Step 6 Selected task is removed from the precedence diagram. If all tasks assigned to a station, balancing has been completed. If there are tasks which are not assigned, return to Step 1.

The above steps are repeated as many times as desired by the user. The solution in each case is compared with the previous one, if there is a improvement, the best solution is updated.

5.2 COMSOAL for ALBP with Deterministic Sequence-dependent Setup Times.

Proposed heuristic approach for deterministic model is based on COMSOAL by adding some constraint. Forward and backward setup times are added to traditional COMSOAL algorithm in order to solve ALBP with deterministic sequence-dependent setup times.

Assumptions for presented heuristic algorithm are summarized as follows:

- Parameters of heuristic are known.
- Objective function is to minimize the number of station.
- Task and setup times are known.
- Task and setup times are assumed to be deterministic.

Number of iteration is defined as iteration number = $150 \times \text{number of tasks}$ for each problem. Iteration number is occurred after a specific number of trial. The general procedure steps of the proposed approach which is based on COMSOAL algorithm for deterministic model are summarized below:

Step 1 Precedence diagram and setup time between tasks are created. Then, Construct a list (list A), in one column, all the work elements, and in an adjacent column, operation time and number of predecessors.

Step 2 From list A, construct list B, constituted of the tasks which have zero predecessors. If the task is first assigned task in the station, return Step 3. Otherwise, return Step 4.

Step 3 Add to C list the tasks in the B list whose time is less than or equal idle time of station. Continue Step 5.

Step 4 Add to C list the task in the B list if the sum of task time, forward setup times and backward setup between tasks is less than or equal idle time of station.

Step 5 If the C list is empty, a new station opens and return step 3. Otherwise continue.

Step 6 A task is selected randomly from the C list. (This random selection causes the formation of different balances.)

Step 7 Selected task is removed from the precedence diagram and update idle time in the station. If all tasks assigned to a station, balancing has been completed. If there are tasks which are not assigned, return to Step 1.

For this study, our priority is to find solutions as good as the best existing procedures provide for the test problems and to keep the solution time at the minimum level.

Large test problems (SBF2-data sets) are solved by using COMSOAL which is an effective heuristic for ALBP. The results are presented in Appendix A.

5.3 An Illustrative Example

An example is solved for deterministic ALBP with stochastic sequence-dependent setup times to understand the stages of COMSOAL algorithm. Precedence diagram of 11 task test problem is shown in Figure 5.1. Cycle time for balancing is taken as 13 units. Operation time of tasks, forward and backward setup times are given in Table 5.1, Table 5.2 and Table 5.3.

Example

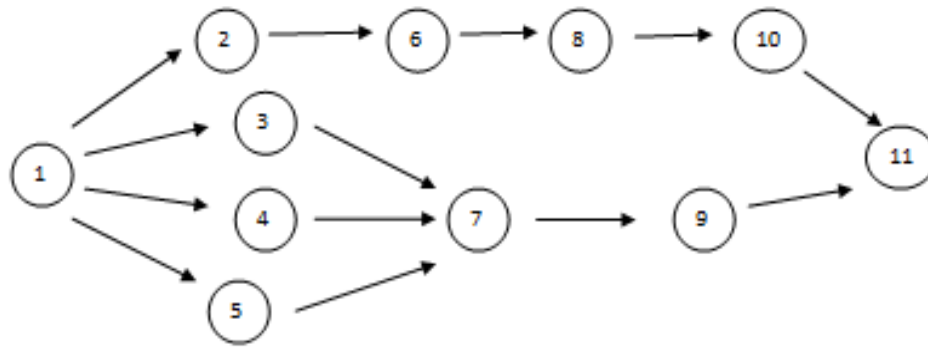


Figure 5.1. An example of precedence diagram with 11 tasks

Table 5.1 Operation time of tasks

task	1	2	3	4	5	6	7	8	9	10	11
tt	6	2	5	7	1	2	3	6	5	5	4

tt: task time

Table 5.2 Forward setup times between tasks

	1	2	3	4	5	6	7	8	9	10	11
1	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	1	0	0	1	0	0
3	0	0	0	0	0	1	0	1	0	0	0
4	0	0	0	0	0	1	0	1	0	0	0
5	0	0	0	0	0	1	0	1	0	0	0
6	0	0	1	1	1	0	1	0	0	0	0
7	0	0	0	0	0	1	0	1	1	0	0
8	0	0	1	1	1	0	1	0	0	1	0
9	0	1	0	0	0	0	0	0	0	1	1
10	0	0	0	0	0	0	0	0	1	0	0
11	0	0	0	0	0	0	0	0	0	0	0

Table 5.3 Backward setup times between tasks

	1	2	3	4	5	6	7	8	9	10	11
1	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	1	0	0
3	0	0	0	0	0	1	0	1	0	0	0
4	0	0	0	0	0	1	0	1	0	0	0
5	0	0	0	0	0	1	0	1	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	1	0	1	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	1	0	1	1	0	0
11	0	0	0	0	0	1	0	1	1	0	0

Table 5.4 Solution stage of COMSOAL algorithm for ALBP with deterministic sequence-dependent setup times

A list	
Tasks	The number of predecessors of task i
1	0
2	1
3	1
4	1
5	1
6	2
7	4
8	3
9	5
10	4
11	10

B list
Tasks which don't have immediate predecessor
1

C list
Tasks whose time is less than or equal idle time of station
1*

Task 1 is assigned to station1.

$S_1 = \{1\} = 6$

Idle time=7.

Task 1 is removed from the priority diagram. A, B and C list are generated again.

Table 5.4 (Continued)

A list	
2	0
3	0
4	0
5	0
6	1
7	3
8	2
9	4
10	3
11	9

B list
2
3
4
5

C list
2
3
4
5*

Task 5 is selected randomly from C list.

$S_1 = \{1, 5\} = 7$

Idle time=6

Task 5 is removed from the priority diagram and process continues.

Table 5.4 (Continued)

A list	
2	0
3	0
4	0
6	1
7	2
8	2
9	3
10	3
11	8

B list
2
3
4

C list
2
3*
4

Task 3 is selected randomly from C list.

$$S_1 = \{1, 5, 3\} = 12$$

Idle time=1

Task 3 is removed from the priority diagram and process continues.

Table 5.4 (Continued)

A list	
2	0
4	0
6	1
7	1
8	2
9	3
10	3
11	7

B list
2
4

C list
0

The new C list
2
4*

Because the C list is empty, a new station is opened and C list is created again. Task 4 is selected randomly from C list.

$$S_2 = \{4\} = 7$$

Idle time=6

Task 4 is removed from the priority diagram and process continues.

Table 5.4 (Continued)

A list	
2	0
6	1
7	0
8	2
9	1
10	3
11	6

B list
2
7

C list
2*
7

Task 2 is selected randomly from C list.

$$S_2 = \{4, 2\} = 7$$

Idle time=4

Task 2 is removed from the priority diagram and process continues.

Table 5.4 (Continued)

A list	
6	0
7	0
8	1
9	1
10	2
11	5

B list
6
7

C list
6
7*

Because setup exist between task 2 and task 6, task 7 is selected from C list.

$$S_2 = \{4, 2, 7\} = 12$$

Idle time=1

Task 7 is removed from the priority diagram and process continues.

Table 5.4 (Continued)

A list	
6	0
8	1
9	0
10	2
11	4

B list
6
9

C list
0

The new C list
6*
9

Because the C list is empty, a new station is opened and C list is created again.

Task 6 is selected from C list.

$$S_3 = \{6\} = 2$$

Idle time=11, Task 6 is removed from the priority diagram and process continues.

Table 5.4 (Continued)

A list	
8	0
9	0
10	1
11	3

B list
8
9

C list
8*
9

Task 8 is selected from C list.

$$S_3=\{6,8\}=8$$

Idle time=5

Task 8 is removed from the priority diagram and process continues.

Table 5.4 (Continued)

A list	
9	0
10	0
11	2

B list
9
10

C list
9*
10

Task 9 is selected from C list.

$$S_3=\{6,8,9\}=13$$

Idle time=0

Task 9 is removed from the priority diagram and process continues.

Table 5.4 (Continued)

A list	
10	0
11	1

B list
10

C list
0
The new C list
10*

A new station is opened and task 10 is assigned to new station.

Task 11 remains and it can be assigned to same station with task 10.

$$S_4=\{10,11\}=9$$

5.4 COMSOAL for ALBP with Stochastic Sequence-dependent Setup Times.

Stochastic cycle time constraint is added to traditional COMSOAL algorithm in order to solve ALBP with stochastic sequence-dependent setup times. Besides, algorithm includes forward and backward setup times together.

Assumptions of the presented heuristic algorithm for stochastic model different from deterministic model are summarized as follows:

- Task and setup times are assumed to be stochastic.
- All tasks and setup times are considered to normally distributed.

Variances for the test problems are generated randomly between (0~0.6). While generating variances, Guerriero and Miltenburg (2003) study is taken into account.

Different from deterministic COMSOAL algorithm, only step 3 and step 4 is changed which are given below.

Step 3 Add to C list the tasks in the B list, possibility of exceeding the cycle time of total station time with this task's operation time and variance less than or equal determined probability level(α).

Step 4 Add to C list the task in the B list possibility of exceeding the cycle time of total station time with this task's operation time, setups and variances less than or equal determined probability level(α).

For stochastic model, a new data set which is based on SBF2-data set is generated. The main objective is to minimize the number of station. Another objective is to proximate problem to the real life applications. Proposed COMSOAL for stochastic model is solved for large sized test problems. The results are presented in Appendix A.

CHAPTER VI

COMPUTATIONAL RESULTS

6.1 Mathematical models' results

In computational analysis, models were tested taking into account minimization the number of workstations objective. Proposed models were solved considering both deterministic and stochastic task and setup times. Test problems for deterministic model were taken from Scholl et al. (2013)'s study (SBF2-data sets). Four different levels for setup time (0.25, 0.5, 0.75, and 1.0) were determined in this data set and for this thesis "1.0" level was selected in order to run models on test problems. Scholl et al. (2013)'s study can be examined for more information.

The same data set which tasks and setup times were assumed as average (mean) times was used for stochastic ALBP with stochastic setup times. The variance of the tasks and setup time was determined by generating random numbers, fitting uniform distribution. The lower bounds (LB) were taken from the study of Scholl et al. (2013) for deterministic model. The solution time was limited within 3600 seconds. Upper bound for station number was calculated by adding 2 workstations to optimal number of workstations.

The proposed mathematical models were solved by a computer Intel Xeon 4 Core 2.40 GHz dual processor and 8.00 GB memories. GAMS/CPLEX-12 and GAMS/DICOPT solvers are used to solve linear and non-linear models respectively. For CPLEX 3600 CPU time and for DICOPT 3600 CPU time and 360 iteration limit is taken. The test results deterministic and stochastic models were given in Tables 6.1 and 6.2.

Table 6.1 Test results of mathematical model of ALBP with deterministic sequence-dependent setup time

Problem	Cycle Time	Station numbers	CPU	LB
P7	6	6	0.063	5
	7	5	0.062	5
	8	5	0.141	4
	10	3	0.094	3
	15	2	0.063	2
	18	2	0.110	2
P8	20	5	0.094	5
P9	6	8	0.062	7
	7	7	0.125	6
	8	6	0.140	6
	10	4	0.094	4
	18	3	0.141	3
P11	48	4	1.872	4
	62	3	2.808	3
	94	2	0.358	2
P11	7	8	0.437	7
	9	6	0.530	6
	10	5	0.437	5
	13	4	12.979	4
	14	4	0.905	4
	21	3	0.499	3
P21	14	8	109.684	8
	15	8	92.742	7
	21	5	179.588	5
	26	5	168.154	5
	35	3	14.773	3
	39	3	105.753	3

LB: Lower bound

Table 6.1 shows the results of deterministic model. Deterministic model solved the test problems up to 21 tasks and found optimal solution. However, it can't be reached to optimal solution for large-sized problems within an acceptable time. Optimal results of several test problems are equal to lower bound.

Table 6.2 Test results of mathematical model of ALBP with stochastic task and sequence-dependent setup time

Problem	Cycle time	Station number	CPU
P8	20	6	19.312
P11	48	6	570.966
	62	5	433.355
	94	4	115.877
P21	14	*	+3600
	15	*	+3600
	21	8	+3600
	26	8	+3600
	35	5	+3600
	39	5	+3600

Results of mathematical model with stochastic task and setup time were given in Table 2. Integer solutions were reached for selected test problems except P21/C14 and P21/C15. Stochastic model compared with deterministic model and it was seen that station numbers were different each other. This situation occurred due to stochastic structure and it was reflected to station number. However, this situation may increase applicability of problem.

6.2 Heuristic procedure's results

In this section, the test problems are solved with different cycle time. Four different levels for setup time (0.25, 0.5, 0.75 and 1.0) were determined in SBF2 data set and for this thesis level "0.5, 0.75 and 1.0" were selected in order to run heuristic method on test problems. Deterministic and stochastic models were solved for each level. 269-tests are done for each problem type and level and also compared with the results of Scholl's computational results for deterministic model. 6 levels and 1601 test problems are considered in total including 3 levels deterministic and 3 levels stochastic structure.

The proposed heuristic algorithm was solved by a computer with MATLAB Intel(R) Core(TM) i7-2630QM 2.0 GHz dual processor and 6.00 GB memories for certain test problems.

A few results of deterministic model for level 0.5 are given in the following. Also, it is compared with Scholl et al. (2013)'s results. The results of whole test problems are presented in Appendix A.

Table 6.3 Comparison of deterministic model (0.50) according to number of station

Problem	cycletime	BEST	CPU	LB
Arc83	3786	23	38,607	21
	3985	22	38,690	20
	4206	21	38,925	19
	4454	19	38,681	18
	4732	18	38,809	17
	5048	17	38,483	16
	5408	16	38,911	15
	5824	15	39,504	14
	5853	15	38,952	14
	6309	14	39,038	13
	6842	13	39,203	12
	6883	13	38,480	12
	7571	11	0,003	11
	8412	10	0,003	10
	8898	9	16,009	9
	10816	8	0,003	8
arc111	5755	30	84,319	27
	5785	29	84,826	27
	6016	28	84,540	26
	6267	27	84,298	25
	6540	26	83,778	24
	6837	25	83,590	23
	7162	24	84,156	22
	7520	23	83,805	21
	7916	22	84,102	20
	8356	21	84,234	19
	8847	20	84,324	18
	9400	18	84,892	17
	10027	17	84,561	16
	10743	16	84,823	15
	11378	15	84,680	14
	11570	15	84,926	13
	17067	10	85,422	9

LB: Lower Bound

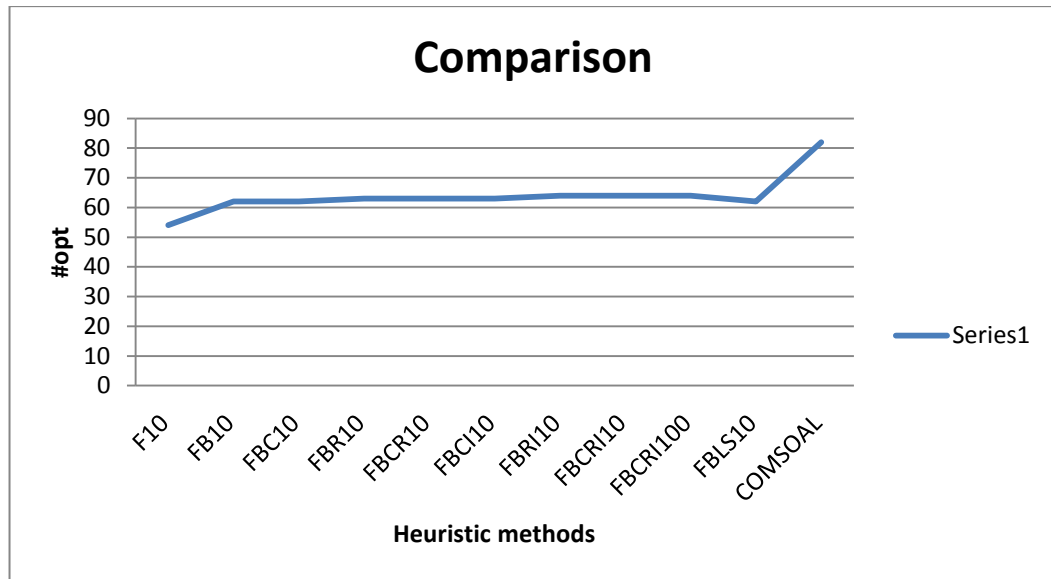


Figure 6.1. Comparison of Scholl et al.(2013) and COMSOAL results for deterministic model

Graphical representation of COMSOAL and Scholl's results for deterministic model are given above for different test problems and levels. Levels and test problems are selected randomly. Comparisons are done according to number of station and it is seen that 82 stations are equal to optimal station number for deterministic model in 267 test problems for level 0.50. However Scholl et al.(2013) finds 64 stations are equal to optimal station number. In level 0.75, 79 stations are equal to optimal station number in 269 test problems, while Scholl et al.(2013) finds 61 stations. Finally, for level 0.1 it exists 74 stations which are equal to optimal station number in 269 test problems, while Scholl et al.(2013) finds 61 stations.

In order to show differences between deterministic and stochastic model results a few test problems are selected randomly. The two model results are compared with each other in terms of station number and CPU time. Graphical representation of comparisons are given in below.

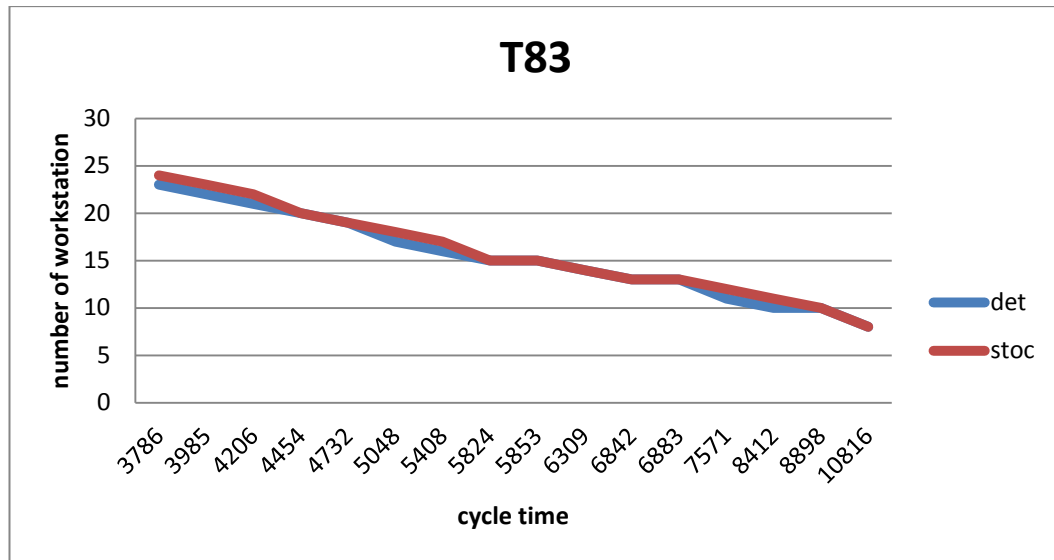


Figure 6.2. Comparison of deterministic and stochastic model results according to number of station for T83 in level 0.50

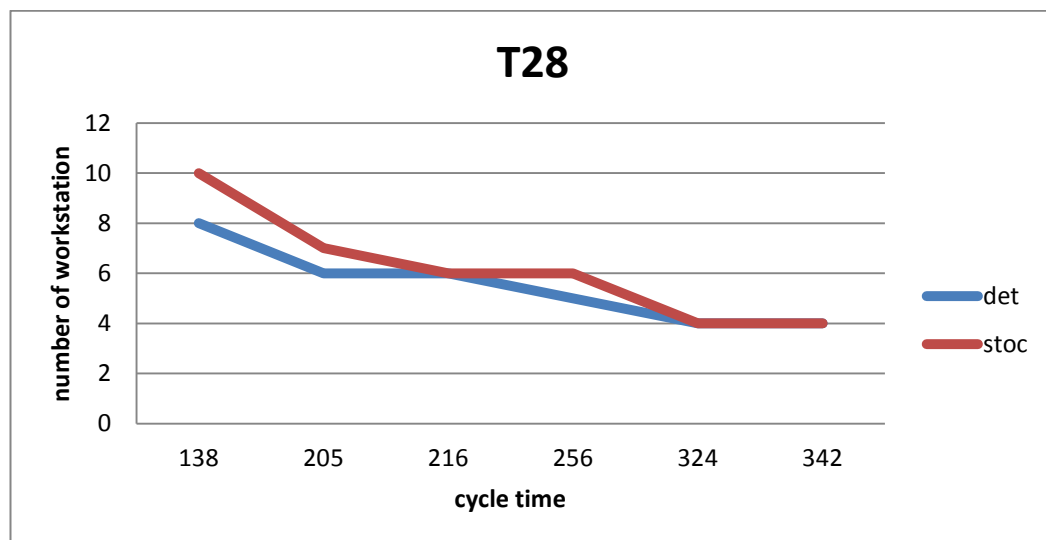


Figure 6.3. Comparison of deterministic and stochastic model results according to number of station for T28 in level 0.50

In figures 6.2 and 6.3, deterministic and stochastic models are compared according to number of station for 83 and 28-task test problem in level 0.50. It is seen that number of workstations for stochastic model are more than deterministic model. This situation results from stochastic structure of problem.

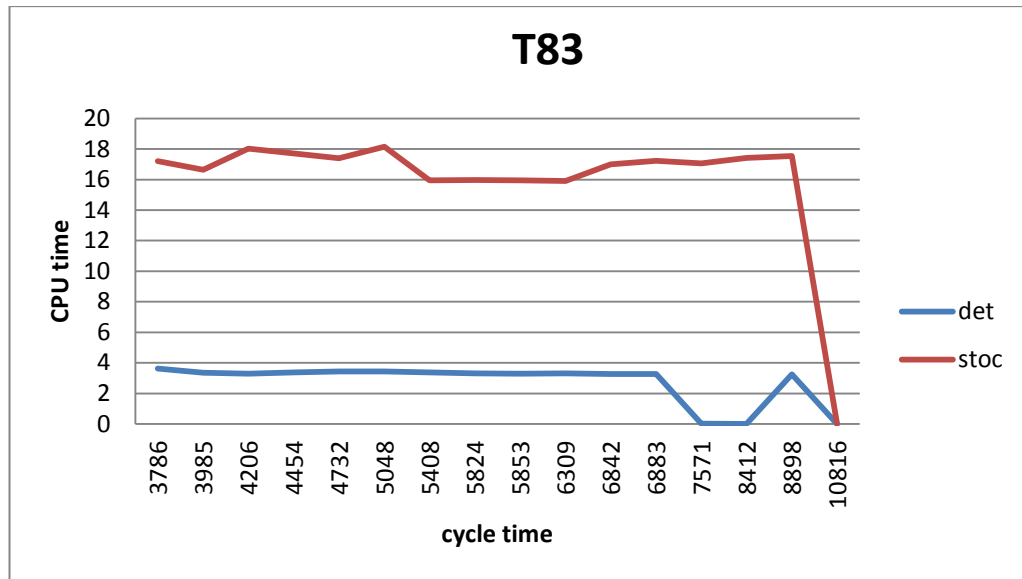


Figure 6.4. Comparison of deterministic and stochastic model results according to CPU time for T83 in level 0.50

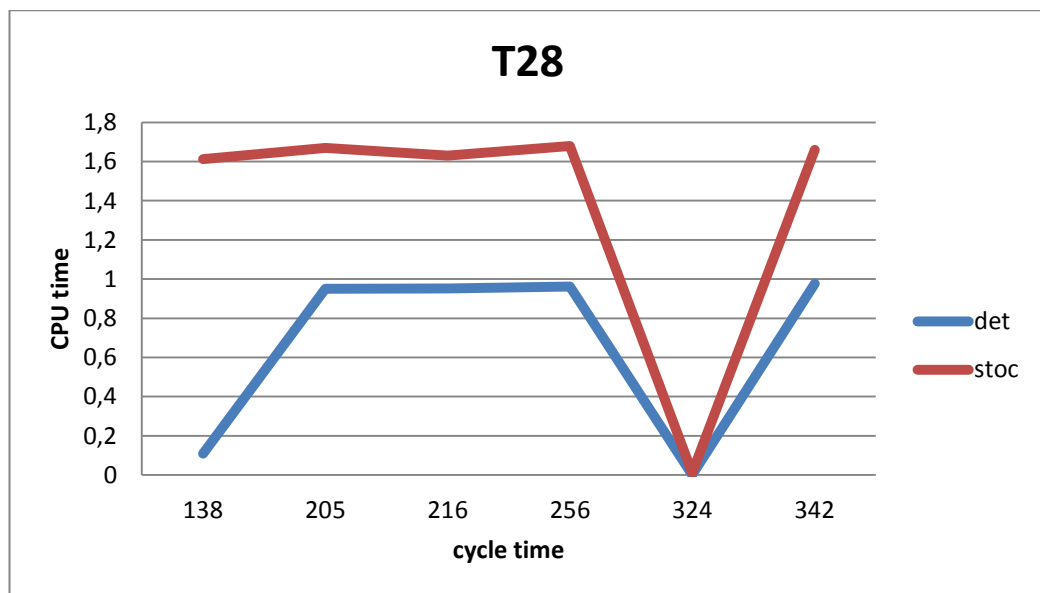


Figure 6.5. Comparison of deterministic and stochastic model results according to CPU time for T28 in level 0.50

When deterministic and stochastic models are compared for 83 and 28-task test problem in level 0.50 according to CPU time, it is seen that CPU times of stochastic model exceed the deterministic model's CPU times. This is an expected case. Stochastic systems are more complicated than deterministic systems. Therefore, it takes time to reach solution in stochastic model.

CHAPTER VII

CONCLUSIONS

In this thesis, mathematical models are proposed for ALBP with deterministic and stochastic sequence-dependent setup times and computational analysis is conducted on test problems. When studies on the assembly line balancing problem are examined and it is found that there are a few studies taking into account the setup times. However, studies showed that setup time plays an important role in total production time. Besides, in these studies the setup times are assumed to be deterministic. Considering setup times to be deterministic may cause to fall short of reality. Because in many real life applications, the operations are performed manually and manual systems may cause variation in task and setup times. The variation in skill levels of setup crews, temporary shortage of tools, setup crews and equipment, unexpected breakdowns, lack of equipment and environmental factors may bring about task and setup times display stochastic structure, as well. Thus, in this thesis for the first time stochastic and sequence-dependent concept are considered together for ALBP with setup times in order to proximate problem to real life applications.

Proposed mathematical models are solved in GAMS, firstly. Results have shown that deterministic model reached to optimal solution up to 21 tasks test problem except a few test problems. Stochastic model has given integer solutions up to 21 tasks test problem.

An effective heuristic approach COMSOAL is proposed for large size test problems. The algorithm is solved in MATLAB. Results have shown that algorithm is very effective for deterministic model. Especially, compared with results of Scholl et al. (2013)'s study, quite a lot of good results have been found for deterministic model. In addition, it is seen that number of workstations for stochastic model are more than deterministic model as it is expected. Complex structure of stochastic model and variances of task and setup times causes this situation.

To the best of our knowledge, this study is the first attempt to solve ALBP with sequence-dependent stochastic setup times. We hope our study helps to open new research areas related with stochastic setup times for ALBP. For large test problems, more efficient heuristic based on branch and bound such as beam search can be improved to solve this problem.

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APPENDIX A. RESULTS OF HEURISTIC APPROACH

Table A.1 Results of deterministic model for level 0.50

Problem	cycletime	BEST	CPU	LB
Arc83	3786	23	38,607	21
	3985	22	38,690	20
	4206	21	38,925	19
	4454	19	38,681	18
	4732	18	38,809	17
	5048	17	38,483	16
	5408	16	38,911	15
	5824	15	39,504	14
	5853	15	38,952	14
	6309	14	39,038	13
	6842	13	39,203	12
	6883	13	38,480	12
	7571	11	0,003	11
	8412	10	0,003	10
	8898	9	16,009	9
	10816	8	0,003	8
arc111	5755	30	84,319	27
	5785	29	84,826	27
	6016	28	84,540	26
	6267	27	84,298	25
	6540	26	83,778	24
	6837	25	83,590	23
	7162	24	84,156	22
	7520	23	83,805	21
	7916	22	84,102	20
	8356	21	84,234	19
	8847	20	84,324	18
	9400	18	84,892	17
	10027	17	84,561	16
	10743	16	84,823	15
	11378	15	84,680	14
	11570	15	84,926	13
	17067	10	85,422	9
barthol2_148	84	59	200,049	51

Table A.1 (Continued)

barthol2_148	85	57	200,714	51
	87	57	200,047	49
	89	56	200,045	49
	91	54	199,643	47
	93	54	200,910	47
	95	52	202,112	45
	97	51	199,993	44
	99	50	200,695	43
	101	49	200,435	42
	104	48	200,024	41
	106	46	199,944	40
	109	45	199,897	39
	112	44	199,902	38
	115	43	200,689	37
	118	42	200,307	36
	121	41	200,837	35
	125	39	200,494	34
	129	38	199,837	33
	133	37	200,544	32
	137	36	201,118	31
	142	34	201,687	30
	146	33	201,433	29
	152	32	201,365	28
	157	31	200,614	27
	163	30	201,379	26
	170	28	201,729	25
barthold148	403	16	202,104	14
	434	15	203,161	13
	470	13	202,010	12
	513	12	202,846	11
	564	11	203,553	10
	626	10	202,759	9
	705	9	203,185	8
	805	8	202,321	7
bowman8	20	5	0,000	5
buxey29	27	14	3,882	13
	30	12	2,747	12
	33	12	3,780	11
	36	10	0,005	10
	41	8	1,420	8
	47	8	3,966	7
	54	7	0,001	7
gunther35	41	14	2,083	14

Table A.1 (Continued)

gunther35	44	12	0,814	12
	49	11	0,002	11
	54	10	5,739	9
	61	9	0,001	9
	69	8	0,003	8
	81	7	0,001	7
hahn53	2004	8	0,004	8
	2338	7	1,771	7
	2806	6	0,002	6
	3507	5	0,002	5
	4676	4	0,002	4
heskia28	138	8	1,271	8
	205	6	3,755	5
	216	6	3,742	5
	256	5	3,748	4
	324	4	0,001	4
	342	4	3,831	3
jackson11	7	8	0,001	8
	9	6	0,000	6
	10	5	0,000	5
	13	4	0,001	4
	14	4	0,000	4
	21	3	0,000	3
jaeschke9	6	8	0,000	8
	7	7	0,000	7
	8	6	0,000	6
	10	4	0,000	4
	18	3	0,000	3
kilbrid45	56	11	10,231	10
	57	11	10,131	10
	62	10	10,065	9
	69	9	9,998	8
	79	8	10,187	7
	92	7	9,940	6
	110	6	0,002	6
	111	6	10,024	5
	138	5	10,248	4
	184	4	10,163	3
lutz1_32	1414	11	0,026	11
	1572	10	0,059	10
	1768	9	0,002	9
	2020	8	0,011	8
	2357	7	0,001	7

Table A.1 (Continued)

lutz1_32	2828	6	0,001	6
lutz2_89	11	51	47,384	49
	12	47	46,734	44
	13	43	46,094	40
	14	39	46,187	37
	15	36	46,391	34
	16	34	46,082	31
	17	32	46,336	29
	18	30	46,562	28
	19	28	46,491	26
	20	26	46,646	25
	21	25	46,769	24
lutz3_89	75	25	46,156	23
	79	24	45,829	22
	83	23	45,327	21
	87	22	45,564	20
	92	20	46,113	19
	97	19	46,258	18
	103	18	45,762	17
	110	17	45,307	15
	118	15	45,568	14
	127	14	0,017	14
	137	13	0,624	13
	150	12	0,004	12
mansoor11	48	4	0,003	4
	62	3	0,001	3
	94	2	0,001	2
mertens7	6	6	0,000	6
	7	5	0,000	5
	8	5	0,000	5
	10	3	0,000	3
mitchell21	14	9	1,983	8
	15	8	0,038	8
	21	5	0,115	5
	26	5	0,001	5
	35	3	0,010	3
	39	3	0,001	3
mukherje94	176	28	59,445	25
	183	26	59,384	24
	192	26	59,713	23
	201	24	59,693	22
	211	23	59,526	21
	222	22	60,053	20

Table A.1 (Continued)

mukherje94	234	20	61,212	19
	248	20	60,252	18
	263	18	59,814	17
	281	17	60,077	16
	301	16	60,052	15
	324	15	60,344	14
	351	14	60,300	13
roszieg25	14	10	0,008	10
	16	9	2,853	8
	18	8	0,001	8
	21	6	0,082	6
	25	6	0,001	6
	32	4	0,066	4
sawyer30	25	14	1,324	14
	27	14	4,206	13
	30	12	0,093	12
	33	11	1,194	11
	36	10	0,001	10
	41	9	4,242	8
	47	8	4,187	7
	54	7	0,001	7
	75	5	0,001	5
Scholl297	1394	58	1843,56	50
	1422	57	1850,45	49
	1452	56	1820,37	48
	1483	55	1850,933	47
	1515	54	1845,430	46
	1548	52	1846,147	45
	1584	53	1844,443	44
	1620	50	1844,528	43
	1659	49	1844,607	42
	1699	48	1843,770	41
	1742	47	1842,649	40
	1787	45	1845,148	39
	1834	44	1845,186	38
	1883	43	1845,441	37
	1935	42	1843,484	36
	1991	41	1845,287	35
	2049	40	1845,277	34
	2111	38	1845,200	33
	2177	37	1845,331	32
	2247	36	1845,462	31
	2322	34	1845,593	30

Table A.1 (Continued)

Scholl297	2402	33	1845,430	29
	2488	32	1846,147	28
	2580	31	1843,770	27
	2680	30	1842,649	26
	2787	29	1842,846	25
Tonge70	160	25	26,878	23
	168	24	27,337	22
	176	23	27,446	21
	185	22	26,930	20
	195	21	26,976	19
	207	19	27,040	18
	220	18	27,319	17
	234	17	27,154	16
	251	16	26,837	14
	270	15	27,149	14
	293	14	26,851	13
	320	12	26,894	11
	364	11	26,906	10
	410	10	27,006	9
	468	9	26,974	8
	527	8	26,979	7
warnecke58	54	35	17,939	31
	56	32	17,804	29
	58	31	17,728	29
	60	30	17,671	27
	62	29	17,614	27
	65	28	17,637	25
	68	27	17,619	24
	71	26	17,670	23
	74	25	17,654	22
	78	23	17,608	21
	82	22	17,582	20
	86	21	17,630	19
	92	19	17,579	17
	97	18	17,685	17
	104	17	17,578	15
	111	16	17,595	14
wee-mag75	28	63	1,918	63
	29	63	1,687	63
	30	62	1,200	62
	31	62	0,033	62
	32	61	0,150	61
	33	61	0,003	61

Table A.1 (Continued)

wee-mag75	34	61	0,030	61
	35	60	0,039	60
	36	60	0,006	60
	37	60	0,003	60
	38	60	0,003	60
	39	60	0,003	60
	40	60	0,003	60
	41	59	0,009	59
	42	55	6,751	55
	43	50	3,642	50
	45	41	32,736	38
	46	39	32,705	34
	47	36	32,500	33
	49	34	32,520	32
	50	33	32,809	32
	52	33	33,027	31
	54	32	32,961	31
	56	31	32,907	30

Table A.2 Results of deterministic model for level 0.75

Problem	cycletime	BEST	CPU	LB
Arc83	3786	23	39,19672	21
	3985	22	38,89223	20
	4206	21	38,79291	19
	4454	20	39,79162	18
	4732	19	39,02556	17
	5048	17	39,08627	16
	5408	16	39,29223	15
	5824	15	39,5453	14
	5853	15	39,35598	14
	6309	14	39,46331	13
	6842	13	38,98984	12
	6883	13	39,08611	12
	7571	11	0,05557892	11
	8412	10	0,7598568	10
	8898	10	39,19825	9
	10816	8	0,003136502	8
arc111	5755	31	85,10284	27

Table A.2 (Continued)

arc111	5785	30	85,42912	27
	6016	29	84,73358	26
	6267	28	85,04222	25
	6540	27	84,57451	24
	6837	25	84,39935	23
	7162	25	84,68382	22
	7520	23	85,12719	21
	7916	22	84,83922	20
	8356	21	84,90573	19
	8847	21	84,89668	18
	9400	18	85,58941	17
	10027	18	84,72214	16
	10743	16	84,95818	15
	11378	16	85,46373	14
	11570	15	85,49208	13
	17067	10	86,21392	9
barthol2_148	84	60	200,6196	51
	85	60	201,3387	51
	87	59	200,7426	49
	89	57	200,2131	49
	91	56	200,173	47
	93	55	200,6007	47
	95	54	200,0389	45
	97	53	200,2278	44
	99	52	201,1801	43
	101	51	200,7419	42
	104	49	200,0644	41
	106	48	200,3113	40
	109	47	199,979	39
	112	46	200,7648	38
	115	44	200,9134	37
	118	43	200,5032	36
	121	42	201,0635	35
	125	41	201,2321	34
	129	39	200,239	33
	133	38	201,1519	32
	137	37	201,1643	31
	142	36	201,305	30
	146	35	201,0848	29
	152	33	201,1154	28
	157	32	201,4039	27
	163	31	201,6651	26
	170	30	201,8318	25

Table A.2 (Continued)

barthold148	403	16	202,2665	14
	434	15	201,6221	13
	470	14	201,753	12
	513	13	202,2346	11
	564	11	202,6642	10
	626	10	203,962	9
	705	9	203,7032	8
	805	8	204,2114	7
bowman8	20	5	0,000421562	5
buxey29	27	14	3,994238	13
	30	12	1,844939	12
	33	12	3,925978	11
	36	10	0,1217245	10
	41	8	0,8365024	8
	47	8	3,790535	7
	54	7	0,002678623	7
gunther35	41	14	1,956417	14
	44	12	2,848081	12
	49	11	0,175437	11
	54	10	5,603636	9
	61	9	0,002208661	9
	69	8	0,02357911	8
	81	7	0,1317097	7
hahn53	2004	8	0,001796597	8
	2338	7	1,121459	7
	2806	6	0,001769638	6
	3507	5	0,001763772	5
	4676	4	0,001770895	4
heskia28	138	9	3,782919	8
	205	6	3,756782	5
	216	6	3,85111	5
	256	5	3,858697	4
	324	4	0,001021499	4
	342	4	3,810089	3
jackson11	7	8	0,000372464	8
	9	6	0,000371067	6
	10	5	0,00036534	5
	13	4	0,00036527	4
	14	4	0,000364362	4
	21	3	0,000370019	3
jaeschke9	6	8	0,00030807	8
	7	7	0,000306533	7
	8	6	0,000301645	6

Table A.2 (Continued)

jaeschke9	10	4	0,000301784	4
	18	3	0,000303111	3
kilbrid45	56	11	10,35821	10
	57	11	10,13322	10
	62	10	10,22626	9
	69	9	9,916193	8
	79	8	10,21392	7
	92	7	10,07935	6
	110	6	0,001576248	6
	111	6	10,15871	5
	138	5	10,42221	4
	184	4	10,19252	3
lutz1_32	1414	11	0,03985416	11
	1572	10	3,886778	10
	1768	9	0,003821226	9
	2020	8	0,01834158	8
	2357	7	0,001013048	7
	2828	6	0,001000406	6
lutz2_89	11	52	47,52215	49
	12	48	47,65249	44
	13	44	47,03469	40
	14	41	47,0204	37
	15	38	46,77662	34
	16	35	46,28751	31
	17	32	46,79235	29
	18	31	47,08791	28
	19	29	46,38599	26
	20	27	46,45867	25
	21	27	46,50679	24
lutz3_89	75	26	46,53014	23
	79	24	46,11975	22
	83	23	45,75288	21
	87	22	46,33484	20
	92	21	46,73464	19
	97	19	45,92348	18
	103	18	46,54832	17
	110	17	45,95225	15
	118	16	45,77125	14
	127	14	4,855165	14
	137	14	45,83549	13
	150	12	0,04702113	12
mansoor11	48	4	0,002905048	4
	62	3	0,003231975	3

Table A.2 (Continued)

mansoor11	94	2	0,000372464	2
mertens7	6	6	0,000250591	6
	7	5	0,00045774	5
	8	5	0,000250451	5
	10	3	0,000254921	3
	15	2	0,000253943	2
	18	2	0,00024633	2
mitchell21	14	9	1,89831	8
	15	8	0,03866762	8
	21	5	0,01453956	5
	26	5	0,000658813	5
	35	3	0,009794681	3
	39	3	0,000898159	3
mukherje94	176	28	59,38684	25
	183	27	59,76168	24
	192	26	59,71465	23
	201	25	59,56141	22
	211	23	59,42271	21
	222	22	59,86067	20
	234	21	59,88526	19
	248	20	59,64532	18
	263	19	59,75664	17
	281	17	60,10803	16
	301	17	60,11897	15
	324	15	60,04199	14
	351	14	59,82706	13
roszieg25	14	10	0,001349264	10
	16	8	2,714372	8
	18	8	0,000783619	8
	21	6	0,1205092	6
	25	6	0,000781175	6
	32	4	0,04670105	4
sawyer30	25	14	4,099323	14
	27	14	4,088579	13
	30	13	4,098603	12
	33	12	4,087765	11
	36	10	1,375656	10
	41	9	4,088129	8
	47	8	4,109379	7
	54	7	0,001060749	7
	75	5	0,001047479	5
Scholl297	1394	60	1845,43	50
	1422	59	1844,443	50

Table A.2 (Continued)

Scholl297	1452	57	1842,649	48
	1483	57	1843,484	47
	1515	57	1845,43	46
	1548	55	1844,443	45
	1584	54	1842,649	44
	1620	52	1843,484	43
	1659	51	1844,43	42
	1699	50	1844,93	41
	1742	49	1841,49	40
	1787	48	1843,44	39
	1834	46	1846,87	38
	1883	45	1844,443	37
	1935	44	1842,649	36
	1991	43	1843,84	35
	2049	42	1845,43	34
	2111	40	1844,23	33
	2177	39	1845,649	32
	2247	37	1843,484	31
	2322	36	1842,33	30
	2402	35	1844,443	29
	2488	33	1842,649	28
	2580	32	1841,84	27
	2680	31	1842,0935	26
	2787	30	1841,3303	25
Tonge70	160	26	27,22756	23
	168	24	26,81177	22
	176	24	27,06308	21
	185	22	27,1339	20
	195	21	27,37116	19
	207	20	26,98251	18
	220	19	26,9345	17
	234	18	26,68868	16
	251	16	27,28745	14
	270	15	27,17326	14
	293	14	27,76984	13
	320	13	27,47861	11
	364	11	27,5855	10
	410	10	26,664	9
	468	9	27,61823	8
	527	8	27,04634	7
warnecke58	54	35	17,89415	31
	56	33	17,76822	29
	58	32	18,0471	29

Table A.2 (Continued)

warnecke58	60	31	17,77333	27
	62	29	17,54839	27
	65	29	17,50288	25
	68	28	17,52297	24
	71	26	17,73415	23
	74	25	17,58957	22
	78	24	17,8332	21
	82	23	17,66094	20
	86	22	17,42646	19
	92	20	17,41001	17
	97	19	17,5242	17
	104	17	17,89989	15
	111	16	17,8202	14
wee-mag75	28	63	3,177546	63
	29	63	0,00934609	63
	30	62	0,3622057	62
	31	62	0,3942789	62
	32	61	0,1456183	61
	33	61	0,01243671	61
	34	61	0,03930646	61
	35	60	0,003039213	60
	36	60	0,003074483	60
	37	60	0,003244616	60
	38	60	0,0030228	60
	39	60	0,003026223	60
	40	60	0,002990045	60
	41	59	0,004630407	59
	42	55	1,775747	55
	43	51	33,64315	50
	45	42	33,38672	38
	46	38	32,37187	34
	47	38	32,55105	33
	49	34	32,20004	32
	50	34	33,33427	32
	52	33	32,67198	31
	54	32	33,21573	31
	56	32	33,50369	30

Table A.3 Results of deterministic model for level 1.00

Problem	cycletime	BEST	CPU	LB
Arc83	3786	24	39,02624	21
	3985	22	39,13741	20
	4206	22	38,58796	19
	4454	20	39,16143	18
	4732	19	39,17106	17
	5048	18	39,57239	16
	5408	17	39,92052	15
	5824	15	39,44383	14
	5853	15	38,86569	14
	6309	14	38,54561	13
	6842	13	38,80442	12
	6883	13	39,00915	12
	7571	12	38,68379	11
	8412	11	19,86911	10
	8898	10	0,009255	9
	10816	8	0,006288	8
arc111	5755	32	84,97163	27
	5785	31	84,65224	27
	6016	30	84,66075	26
	6267	28	85,18202	25
	6540	27	84,56458	24
	6837	27	84,61728	23
	7162	25	84,67345	22
	7520	24	84,84509	21
	7916	23	84,43663	20
	8356	22	84,75401	19
	8847	21	85,05639	18
	9400	19	84,98154	17
	10027	18	85,13811	16
	10743	17	85,35629	15
	11378	16	85,75163	14
	11570	15	85,78157	13
	17067	11	86,46309	9
barthol2_148	84	62	200,7004	51
	85	61	199,9656	51
	87	61	199,4012	49
	89	59	200,1413	49
	91	58	200,1446	47
	93	57	200,8524	47
	95	56	199,8239	45
	97	54	199,7118	44
	99	53	200,1997	43

Table A.3 (Continued)

barthol2_148	101	52	201,0441	42
	104	51	199,4454	41
	106	49	199,3881	40
	109	47	199,4598	39
	112	47	199,2099	38
	115	46	200,1805	37
	118	44	200,4238	36
	121	44	200,382	35
	125	42	200,1375	34
	129	40	200,756	33
	133	39	200,4699	32
	137	38	200,206	31
	142	37	200,5646	30
	146	36	199,5505	29
	152	34	200,242	28
	157	33	201,1759	27
	163	32	201,2809	26
	170	31	201,4643	25
barthold148	403	17	202,4044	14
	434	16	201,4057	13
	470	14	202,0191	12
	513	13	202,5609	11
	564	12	202,4527	10
	626	11	202,7606	9
	705	9	201,7617	8
	805	8	0,000454457	7
bowman8	20	5	0,000421632	5
buxey29	27	14	4,008138	13
	30	13	3,920658	12
	33	12	0,6416072	11
	36	10	1,233301	10
	41	8	3,818774	8
	47	8	0,02502741	7
	54	7	0,01709882	7
gunther35	41	14	0,4635536	14
	44	12	0,5145229	12
	49	11	0,06155615	11
	54	10	0,06213429	9
	61	9	0,08310651	9
	69	8	0,07137045	8
	81	7	0,006968833	7
hahn53	2004	8	0,02756356	8
	2338	7	0,001842553	7

Table A.3 (Continued)

hahn53	2806	6	0,001782908	6
	3507	5	0,001775295	5
	4676	4	0,001866089	4
heskia28	138	9	3,818775	8
	205	6	1,383992	5
	216	5	3,766525	5
	256	5	0,000980991	4
	324	4	0,002989067	4
	342	4	0,000745137	3
jackson11	7	8	0,000428965	8
	9	6	0,001712788	6
	10	5	0,001731575	5
	13	4	0,000607759	4
	14	4	0,000559987	4
	21	3	0,000465981	3
jaeschke9	6	8	0,000459276	8
	7	7	0,000452572	7
	8	6	0,000451035	6
	10	4	0,000450127	4
	18	3	0,000456972	3
kilbrid45	56	12	10,0814	10
	57	11	10,12365	10
	62	10	10,02477	9
	69	9	10,23679	8
	79	8	10,34261	7
	92	7	0,003090616	6
	110	6	0,002279969	6
	111	6	10,00377	5
	138	5	10,47347	4
	184	4	1,121131	3
lutz1_32	1414	11	0,2765897	11
	1572	10	0,01233167	10
	1768	9	0,007566115	9
	2020	8	0,00099028	8
	2357	7	0,001492718	7
	2828	6	0,001498375	6
lutz2_89	11	51	47,37788	49
	12	49	47,24362	44
	13	44	46,88844	40
	14	41	46,80825	37
	15	39	46,26165	34
	16	36	46,5559	31
	17	33	46,17578	29

Table A.3 (Continued)

lutz2_89	18	31	46,3469	28
	19	29	45,92218	26
	20	28	46,68289	25
	21	27	46,48408	24
lutz3_89	75	26	46,69261	23
	79	25	45,64962	22
	83	23	46,39451	21
	87	22	45,86658	20
	92	21	46,3177	19
	97	20	46,02433	18
	103	18	45,91833	17
	110	17	44,98794	15
	118	17	45,65255	14
	127	15	45,54734	14
	137	14	3,048588	13
	150	12	0,004459016	12
mansoor11	48	4	0,002242534	4
	62	3	0,001014514	3
	94	2	0,000250241	2
mertens7	6	6	0,000253105	6
	7	5	0,000253524	5
	8	5	0,000249892	5
	10	3	0,000252546	3
	15	2	0,000248914	2
	18	2	0,000248705	2
mitchell21	14	8	0,09007416	8
	15	8	0,009153817	8
	21	5	0,000716781	5
	26	5	0,001509829	5
	35	3	0,000686819	3
	39	3	0,005493296	3
mukherje94	176	29	58,84914	25
	183	28	59,0206	24
	192	27	59,57765	23
	201	25	59,42938	22
	211	24	58,89011	21
	222	23	59,582	20
	234	21	59,49575	19
	248	20	59,91162	18
	263	19	59,85999	17
	281	18	59,0921	16
	301	17	59,80112	15
	324	15	61,24524	14

Table A.3 (Continued)

mukherje94	351	14	0,02809617	13
roszieg25	14	10	0,01059632	10
	16	9	0,002377397	8
	18	8	0,001583162	8
	21	6	0,001785911	6
	25	6	0,003935067	6
	32	4	0,07635984	4
sawyer30	25	15	4,280556	14
	27	14	4,31347	13
	30	13	4,304351	12
	33	12	4,286946	11
	36	11	4,271853	10
	41	9	4,259944	8
	47	8	0,001048597	7
	54	7	0,001008368	7
	75	5	0,001953321	5
Scholl297	1394	62	1842,427	50
	1422	60	1842,198	50
	1452	59	1841,356	48
	1483	58	1840,729	47
	1515	59	1842,723	46
	1548	56	1842,108	45
	1584	57	1841,657	44
	1620	55	1840,736	43
	1659	53	1840,203	42
	1699	52	1839,561	41
	1742	51	1840,92	40
	1787	50	1842,279	39
	1834	48	1843,638	38
	1883	47	1840,997	37
	1935	46	1842,723	36
	1991	45	1842,108	35
	2049	43	1841,657	34
	2111	42	1841,667	33
	2177	41	1840,563	32
	2247	39	1840,306	31
	2322	37	1839,561	30
	2402	36	1840,92	29
	2488	35	1842,279	28
	2580	33	1841,894	27
	2680	32	1840,378	26
	2787	31	1841,837	25
Tonge70	160	26	26,62029	23

Table A.3 (Continued)

Tonge70	168	25	26,77697	22
	176	23	26,86078	21
	185	22	26,4677	20
	195	22	26,28928	19
	207	20	26,35083	18
	220	19	26,75687	17
	234	18	26,87418	16
	251	17	27,37869	14
	270	16	27,57221	14
	293	14	27,00552	13
	320	13	26,51374	11
	364	11	27,74267	10
	410	10	27,16356	9
	468	9	27,21841	8
	527	8	26,5127	7
warnecke58	54	35	17,57776	31
	56	33	17,32462	29
	58	32	17,77826	29
	60	31	17,47246	27
	62	30	17,49171	27
	65	30	17,26467	25
	68	28	17,23104	24
	71	27	17,50082	23
	74	26	17,26119	22
	78	24	17,25134	21
	82	23	17,33633	20
	86	22	17,47885	19
	92	20	17,44963	17
	97	19	17,24125	17
	104	17	17,19322	15
	111	17	17,72507	14
wee-mag75	28	63	0,9236992	63
	29	63	4,575001	63
	30	62	10,83686	62
	31	62	0,03126145	62
	32	61	0,1843913	61
	33	61	0,07552391	61
	34	61	0,05820146	61
	35	60	0,02916921	60
	36	60	0,003181131	60
	37	60	0,006183188	60
	38	60	0,003123931	60
	39	60	0,004605962	60

Table A.3 (Continued)

wee-mag75	40	60	0,004573277	60
	41	59	0,02225849	59
	42	55	1,521209	55
	43	51	33,35969	50
	45	42	32,46617	38
	46	38	32,91853	34
	47	38	32,50153	33
	49	35	31,69875	32
	50	34	32,26003	32
	52	33	32,20856	31
	54	33	32,13924	31
	56	32	32,17184	30

Table A.4 Results of stochastic model for level 0.50

Problem	cycletime	SR	BR	BEST	CPU
Arc83	3786	24	24	24	17,20574
	3985	23	23	23	16,64969
	4206	22	22	22	18,03201
	4454	20	20	20	17,70184
	4732	19	19	19	17,4008
	5048	18	18	18	18,15085
	5408	17	17	17	15,95119
	5824	15	15	15	15,96549
	5853	15	15	15	15,9432
	6309	14	14	14	15,89585
	6842	13	13	13	17,00291
	6883	13	13	13	17,21668
	7571	12	12	12	17,05795
	8412	11	11	11	17,41756
	8898	10	10	10	17,53136
	10816	8	8	8	0,020873
arc111	5755	32	32	32	37,57982
	5785	31	31	31	37,11942
	6016	29	29	29	34,95811
	6267	29	29	29	35,20024
	6540	27	27	27	34,97216
	6837	26	26	26	34,88374
	7162	25	25	25	34,81399
	7520	24	24	24	34,94369
	7916	22	22	22	34,91384

Table A.4 (Continued)

arc111	8356	21	21	21	34,87578
	8847	20	20	20	35,8033
	9400	19	19	19	35,04238
	10027	18	18	18	34,97006
	10743	16	16	16	34,96086
	11378	16	16	16	35,05495
	11570	15	15	15	35,22719
	17067	10	10	10	35,31065
barthol2_148	84	71	71	71	85,93677
	85	69	69	69	86,08178
	87	68	68	68	85,91066
	89	66	66	66	85,73234
	91	65	65	65	86,03258
	93	65	65	65	85,84411
	95	63	63	63	85,86175
	97	61	61	61	85,90887
	99	60	60	60	85,74994
	101	59	59	59	86,07516
	104	56	56	56	86,06968
	106	55	55	55	86,10426
	109	54	54	54	86,04016
	112	53	53	53	85,73062
	115	52	52	52	85,97619
	118	50	50	50	85,89295
	121	49	49	49	85,73393
	125	47	47	47	85,99306
	129	45	45	45	85,76229
	133	44	44	44	85,78374
	137	43	43	43	85,84179
	142	41	41	41	85,87545
	146	40	40	40	85,72542
	152	38	38	38	85,7889
	157	37	37	37	85,93009
	163	36	36	36	85,85686
	170	33	33	33	85,92324
barthold148	403	18	18	18	85,93573
	434	17	17	17	85,9139
	470	15	15	15	86,03694
	513	14	14	14	85,93314
	564	13	13	13	85,93522
	626	12	12	12	86,06997
	705	10	10	10	86,01128
	805	9	9	9	85,89477

Table A.4 (Continued)

bowman8	20	6	6	6	0,11311
buxey29	27	19	19	19	1,707396
	30	17	17	17	1,711213
	33	15	15	15	1,689345
	36	14	14	14	1,629849
	41	12	12	12	1,637913
	47	10	10	10	1,625047
	54	9	9	9	1,670189
gunther35	41	18	18	18	2,425427
	44	17	17	17	2,472952
	49	15	15	15	2,455344
	54	13	13	13	2,420244
	61	11	11	11	2,424536
	69	10	10	10	2,357262
	81	9	9	9	2,376525
hahn53	2004	9	9	9	5,718151
	2338	8	8	8	5,640058
	2806	6	6	6	0,004145
	3507	5	5	5	0,007916
	4676	4	4	4	0,007092
heskia28	138	10	10	10	1,611992
	205	7	7	7	1,669383
	216	6	6	6	1,630246
	256	6	6	6	1,67873
	324	4	4	4	0,01057
	342	4	4	4	1,659061
jackson11	9	9	9	9	0,220191
	10	9	9	9	0,223801
	13	6	6	6	0,219704
	14	6	6	6	0,216704
	21	4	4	4	0,217133
jaeschke9	7	9	9	9	0,145532
	8	8	8	8	0,141641
	10	8	8	8	0,141982
	18	4	4	4	0,137662
kilbrid45	56	14	14	14	4,310845
	57	14	14	14	4,28553
	62	13	13	13	4,328508
	69	11	11	11	4,281116
	79	10	10	10	4,277423
	92	9	9	9	4,320744
	110	7	7	7	4,306972
	111	7	7	7	4,347332

Table A.4 (Continued)

kilbrid45	138	6	6	6	4,28258
	184	4	4	4	4,387786
lutz1_32	1414	12	12	12	1,894236
	1572	11	11	11	1,926356
	1768	10	10	10	1,913047
	2020	9	9	9	1,919236
	2357	7	7	7	0,001371
	2828	6	6	6	0,009093
lutz2_89	11	70	70	70	19,83764
	12	67	67	67	19,69981
	13	64	64	64	19,68106
	14	62	62	62	19,50709
	15	58	58	58	19,47977
	16	53	53	53	19,2733
	17	50	50	50	19,35469
	18	47	47	47	19,19246
	19	45	45	45	19,08552
	20	42	42	42	19,04515
	21	39	39	39	19,07196
	75	32	32	32	18,80753
	79	30	30	30	18,78322
	83	29	29	29	18,77851
	87	27	27	27	18,64526
	92	25	25	25	18,70633
	97	25	25	25	18,64816
	103	23	23	23	18,66019
	110	21	21	21	18,63787
	118	19	19	19	18,54534
	127	18	18	18	18,60884
	137	17	17	17	18,68917
	150	15	15	15	18,55511
mansoor11	48	6	6	6	0,216555
	62	4	4	4	0,212634
	94	3	3	3	0,211768
mertens7	7	7	7	7	0,094487
	8	6	6	6	0,087528
	10	6	6	6	0,088992
mitchell21	14	13	13	13	0,854074
	15	13	13	13	0,812882
	21	9	9	9	0,800503
	26	7	7	7	0,785899
	35	5	5	5	0,80371
	39	4	4	4	0,826944

Table A.4 (Continued)

mukherje94	176	32	32	32	26,93101
	183	31	31	31	26,31733
	192	30	30	30	26,24898
	201	29	29	29	26,298
	211	26	26	26	26,11347
	222	25	25	25	26,30634
	234	24	24	24	26,22375
	248	23	23	23	26,26004
	263	21	21	21	26,29622
	281	19	19	19	26,33475
	301	18	18	18	26,23454
	324	17	17	17	26,3319
	351	16	16	16	26,24685
roszieg25	14	16	16	16	1,187401
	16	13	13	13	1,160105
	18	13	13	13	1,156627
	21	11	11	11	1,144871
	25	8	8	8	1,147948
	32	7	7	7	1,220073
sawyer30	27	19	19	19	1,855986
	30	18	18	18	1,774423
	33	16	16	16	1,792753
	36	14	14	14	1,776701
	41	12	12	12	1,773512
	47	10	10	10	1,75831
	54	9	9	9	1,757406
	75	6	6	6	1,744665
scholl297	1394	61	61	61	495,538
	1422	60	60	60	494,7643
	1452	59	59	59	495,3146
	1483	58	58	58	494,638
	1515	57	57	57	495,4288
	1548	56	56	56	494,2931
	1584	55	55	55	494,943
	1620	53	53	53	494,592
	1659	52	52	52	494,5174
	1699	51	51	51	495,0357
	1742	50	50	50	494,4046
	1787	49	49	49	495,2593
	1834	46	46	46	494,9824
	1883	45	45	45	495,0775
	1935	44	44	44	494,8572
	1991	43	43	43	496,2328

Table A.4 (Continued)

scholl297	2049	42	42	42	495,8382
	2111	41	41	41	494,7764
	2177	40	40	40	495,408
	2247	38	38	38	495,0039
	2322	36	36	36	495,0134
	2402	35	35	35	551,4801
	2488	34	34	34	497,7365
	2580	33	33	33	498,9852
	2680	31	31	31	498,548
	2787	30	30	30	496,1147
tonge70	160	29	29	29	11,40762
	168	28	28	28	11,44755
	176	27	27	27	11,40264
	185	25	25	25	11,43793
	195	25	25	25	11,38518
	207	23	23	23	11,38078
	220	21	21	21	11,46293
	234	20	20	20	11,37086
	251	18	18	18	11,53782
	270	17	17	17	11,38911
	293	16	16	16	11,42516
	320	14	14	14	11,37932
	364	12	12	12	11,54576
	410	11	11	11	11,40025
	468	10	10	10	11,37977
	527	9	9	9	11,48935
warnecke58	54	41	41	41	7,710386
	56	40	40	40	7,78938
	58	38	38	38	7,803804
	60	37	37	37	7,726768
	62	36	36	36	7,674682
	65	35	35	35	7,755941
	68	34	34	34	7,658589
	71	32	32	32	7,636301
	74	31	31	31	7,661804
	78	28	28	28	7,573599
	82	28	28	28	7,512716
	86	26	26	26	7,584347
	92	25	25	25	7,525269
	97	23	23	23	7,5554
	104	21	21	21	7,610419
	111	20	20	20	7,601248
wee-mag75	28	68	68	68	15,33003

Table A.4 (Continued)

wee-mag75	29	67	67	67	15,32496
	30	67	67	67	15,30693
	31	66	66	66	15,23924
	32	66	66	66	15,23721
	33	65	65	65	15,23561
	34	65	65	65	15,19639
	35	65	65	65	15,71974
	36	63	63	63	15,09213
	37	63	63	63	15,13072
	38	63	63	63	15,13082
	39	61	61	61	15,14685
	40	62	62	62	14,92997
	41	62	62	62	14,96103
	42	60	60	60	14,9647
	43	61	61	61	14,83189
	45	61	61	61	14,87987
	46	60	60	60	15,39957
	47	60	60	60	14,78948
	49	56	56	56	14,77274
	50	54	54	54	14,67005
	52	49	49	49	14,70543
	54	49	49	49	14,60523
	56	40	40	40	14,36419

Table A.5 Results of stochastic model for level 0.75

Problem	cycletime	SR	BR	BEST	CPU
arc83	3786	24	24	24	15,79983
	3985	23	23	23	15,74587
	4206	22	22	22	15,76161
	4454	21	21	21	15,79959
	4732	20	20	20	15,77392
	5048	19	19	19	15,80515
	5408	17	17	17	15,75821
	5824	15	15	15	15,76497
	5853	15	15	15	15,72629
	6309	14	14	14	15,81515
	6842	14	14	14	15,7006
	6883	14	14	14	15,82343
	7571	12	12	12	15,76179

Table A.5 (Continued)

arc83	8412	11	11	11	15,70624
	8898	10	10	10	15,74627
	10816	8	8	8	0,122139
arc111	5755	33	33	33	34,57986
	5785	33	33	33	34,56254
	6016	30	30	30	34,65113
	6267	29	29	29	34,67563
	6540	28	28	28	34,70759
	6837	27	27	27	34,45422
	7162	26	26	26	34,41112
	7520	25	25	25	34,64688
	7916	23	23	23	34,63116
	8356	22	22	22	34,55794
	8847	21	21	21	34,7516
	9400	20	20	20	34,88148
	10027	18	18	18	34,76943
	10743	17	17	17	34,76336
	11378	16	16	16	34,96521
	11570	16	16	16	34,88998
	17067	11	11	11	35,10713
barthol2_148	84	72	72	72	85,38557
	85	71	71	71	85,32283
	87	71	71	71	84,85181
	89	68	68	68	84,95058
	91	67	67	67	85,33265
	93	66	66	66	85,14066
	95	64	64	64	85,17588
	97	62	62	62	85,27376
	99	61	61	61	85,37937
	101	61	61	61	85,15196
	104	58	58	58	85,26898
	106	58	58	58	84,94893
	109	56	56	56	85,02654
	112	54	54	54	85,18709
	115	52	52	52	85,40831
	118	51	51	51	85,28914
	121	50	50	50	84,89162
	125	49	49	49	85,29496
	129	47	47	47	85,34599
	133	45	45	45	85,23206
	137	44	44	44	85,14287
	142	43	43	43	85,10796
	146	42	42	42	84,93108

Table A.5 (Continued)

barthol2_148	152	39	39	39	85,2312
	157	38	38	38	85,16401
	163	37	37	37	85,37583
	170	35	35	35	85,13951
	403	18	18	18	84,94411
	434	17	17	17	85,19239
	470	16	16	16	85,25706
	513	15	15	15	85,23173
	564	13	13	13	85,57941
	626	12	12	12	85,53679
	705	11	11	11	85,48644
	805	9	9	9	85,43434
bowman8	20	6	6	6	0,111576
buxey29	27	20	20	20	1,693323
	30	18	18	18	1,623094
	33	15	15	15	1,656034
	36	14	14	14	1,616122
	41	12	12	12	1,649663
	47	11	11	11	1,638475
	54	9	9	9	1,59449
gunther35	41	18	18	18	2,415431
	44	17	17	17	2,410145
	49	16	16	16	2,427705
	54	14	14	14	2,348791
	61	12	12	12	2,333929
	69	10	10	10	2,364461
	81	9	9	9	2,384983
hahn53	2004	9	9	9	5,601958
	2338	8	8	8	5,546012
	2806	6	6	6	0,002418
	3507	5	5	5	0,002425
	4676	4	4	4	0,002389
heskia28	138	10	10	10	1,605838
	205	7	7	7	1,606473
	216	6	6	6	1,647067
	256	5	5	5	1,657937
	324	4	4	4	0,195161
	342	4	4	4	1,667667
jackson11	9	9	9	9	0,222051
	10	9	9	9	0,221395
	13	7	7	7	0,2169
	14	7	7	7	0,214733
	21	4	4	4	0,214312

Table A.5 (Continued)

jaeschke9	7	9	9	9	0,142199
	8	9	9	9	0,142783
	10	8	8	8	0,139752
	18	4	4	4	0,13416
kilbrid45	56	15	15	15	4,279322
	57	15	15	15	4,274924
	62	13	13	13	4,292402
	69	12	12	12	4,269382
	79	10	10	10	4,257915
	92	9	9	9	4,233773
	110	7	7	7	4,245837
	111	7	7	7	4,232469
	138	6	6	6	4,259961
	184	5	5	5	4,299191
lutz1_32	1414	12	12	12	1,917744
	1572	11	11	11	1,84318
	1768	10	10	10	1,838216
	2020	9	9	9	1,871686
	2357	7	7	7	0,052465
	2828	6	6	6	0,008395
lutz2_89	11	72	72	72	19,54925
	12	71	71	71	19,40979
	13	67	67	67	19,46335
	14	64	64	64	19,25971
	15	60	60	60	19,28589
	16	59	59	59	19,188
	17	53	53	53	19,13374
	18	50	50	50	19,07584
	19	48	48	48	18,93245
	20	43	43	43	18,84414
	21	42	42	42	18,88657
lutz3_89	75	34	34	34	18,61308
	79	30	30	30	18,52824
	83	30	30	30	18,5427
	87	28	28	28	18,62697
	92	27	27	27	18,56961
	97	25	25	25	18,51969
	103	24	24	24	18,51543
	110	22	22	22	18,54451
	118	20	20	20	18,52519
	127	18	18	18	18,46946
	137	17	17	17	18,42284
	150	16	16	16	18,47161

Table A.5 (Continued)

mansoor11	48	6	6	6	0,211283
	62	5	5	5	0,210058
	94	3	3	3	0,219711
mertens7	7	7	7	7	0,089292
	8	7	7	7	0,090819
	10	6	6	6	0,088306
	15	3	3	3	0,085405
	18	3	3	3	0,085299
mitchell21	14	13	13	13	0,795287
	15	13	13	13	0,806834
	21	9	9	9	0,833137
	26	7	7	7	0,774688
	35	5	5	5	0,772987
	39	5	5	5	0,766901
mukherje94	176	34	34	34	26,3385
	183	32	32	32	26,25496
	192	31	31	31	26,05472
	201	30	30	30	26,06521
	211	27	27	27	25,93319
	222	26	26	26	26,01132
	234	25	25	25	26,11373
	248	24	24	24	26,09933
	263	22	22	22	26,10886
	281	20	20	20	26,25342
	301	19	19	19	25,96981
	324	18	18	18	26,08998
	351	16	16	16	26,1728
roszieg25	14	16	16	16	1,17865
	16	14	14	14	1,151218
	18	13	13	13	1,154103
	21	10	10	10	1,191476
	25	8	8	8	1,122672
	32	7	7	7	1,162813
sawyer30	27	19	19	19	1,797276
	30	19	19	19	1,759168
	33	16	16	16	1,756727
	36	15	15	15	1,756083
	41	12	12	12	1,756565
	47	11	11	11	1,758426
	54	9	9	9	1,746143
	75	7	7	7	1,735141
scholl297	1394	63	63	63	494,6895
	1422	63	63	63	493,8067

Table A.5 (Continued)

scholl297	1452	61	61	61	495,1568
	1483	60	60	60	494,6246
	1515	59	59	59	495,1576
	1548	58	58	58	493,5342
	1584	57	57	57	496,2063
	1620	56	56	56	494,2413
	1659	54	54	54	494,3787
	1699	53	53	53	494,6142
	1742	52	52	52	496,179
	1787	50	50	50	495,4342
	1834	48	48	48	496,2984
	1883	47	47	47	498,6003
	1935	46	46	46	497,9674
	1991	45	45	45	498,9157
	2049	44	44	44	500,6756
	2111	42	42	42	503,3535
	2177	41	41	41	496,9453
	2247	39	39	39	495,5599
	2322	38	38	38	497,9877
	2402	36	36	36	498,0622
	2488	35	35	35	496,4285
	2580	33	33	33	496,6047
	2680	32	32	32	498,0562
	2787	31	31	31	496,8594
tonge70	160	30	30	30	11,50122
	168	29	29	29	11,48442
	176	28	28	28	11,48377
	185	26	26	26	11,3895
	195	25	25	25	11,48804
	207	23	23	23	11,35603
	220	22	22	22	11,43034
	234	20	20	20	11,42385
	251	19	19	19	11,51792
	270	17	17	17	11,57136
	293	16	16	16	11,38553
	320	15	15	15	11,47947
	364	13	13	13	11,49238
	410	11	11	11	11,43217
	468	10	10	10	11,38605
	527	9	9	9	11,35096
warnecke58	54	41	41	41	7,771163
	56	40	40	40	7,750051
	58	39	39	39	7,705654

Table A.5 (Continued)

warnecke58	60	38	38	38	7,693252
	62	37	37	37	7,619864
	65	36	36	36	7,657175
	68	35	35	35	7,562871
	71	33	33	33	7,573607
	74	32	32	32	7,54628
	78	30	30	30	7,566696
	82	28	28	28	7,529716
	86	26	26	26	7,61613
	92	25	25	25	7,510884
	97	23	23	23	7,52861
	104	22	22	22	7,518475
	111	20	20	20	7,515006
wee-mag75	28	68	68	68	15,43476
	29	67	67	67	15,43509
	30	67	67	67	15,42678
	31	67	67	67	15,35356
	32	67	67	67	15,37723
	33	65	65	65	15,33921
	34	65	65	65	15,30509
	35	65	65	65	15,31248
	36	64	64	64	15,28581
	37	63	63	63	15,23617
	38	62	62	62	15,20857
	39	62	62	62	15,14276
	40	62	62	62	15,05521
	41	63	63	63	15,15408
	42	61	61	61	15,03671
	43	62	62	62	14,93912
	45	60	60	60	15,06418
	46	60	60	60	15,34879
	47	60	60	60	15,16045
	49	59	59	59	14,92133
	50	58	58	58	14,8703
	52	52	52	52	14,73248
	54	48	48	48	14,5944
	56	42	42	42	14,39977

Table A.6 Results of stochastic model for level 1.00

Problem	cycletime	SR	BR	BEST	CPU
arc83	3786	25	25	25	17,0406
	3985	23	23	23	16,62569
	4206	23	23	23	16,88339
	4454	22	22	22	16,69982
	4732	20	20	20	16,53317
	5048	19	19	19	16,35672
	5408	17	17	17	16,64403
	5824	16	16	16	16,34039
	5853	16	16	16	17,22871
	6309	15	15	15	16,74775
	6842	14	14	14	16,58663
	6883	14	14	14	16,43198
	7571	12	12	12	16,49475
	8412	11	11	11	16,5594
	8898	10	10	10	16,8106
	10816	8	8	8	8,373885
arc111	5755	33	33	33	36,63552
	5785	33	33	33	36,94591
	6016	31	31	31	36,3097
	6267	30	30	30	36,7266
	6540	29	29	29	36,1669
	6837	27	27	27	35,99646
	7162	26	26	26	36,77498
	7520	25	25	25	36,53932
	7916	24	24	24	38,42016
	8356	22	22	22	37,19458
	8847	22	22	22	36,90992
	9400	21	21	21	36,2788
	10027	19	19	19	36,36129
	10743	17	17	17	36,07246
	11378	17	17	17	36,17471
	11570	16	16	16	35,89648
	17067	11	11	11	36,28165
barthol2_148	84	72	72	72	88,00667
	85	73	73	73	87,54715
	87	74	74	74	87,17567
	89	70	70	70	87,71224
	91	70	70	70	87,47172
	93	67	67	67	87,15035
	95	65	65	65	87,90324
	97	64	64	64	87,36
	99	63	63	63	88,33424

Table A.6 (Continued)

barthol2_148	101	62	62	62	87,36903
	104	60	60	60	87,59032
	106	59	59	59	87,57106
	109	57	57	57	86,95418
	112	55	55	55	87,24389
	115	55	55	55	87,60536
	118	53	53	53	86,82643
	121	52	52	52	87,61041
	125	50	50	50	87,77015
	129	47	47	47	87,66533
	133	46	46	46	87,42529
	137	44	44	44	87,41149
	142	44	44	44	87,15909
	146	43	43	43	87,36246
	152	41	41	41	87,18862
	157	39	39	39	87,9879
	163	38	38	38	87,06886
	170	36	36	36	87,32858
	403	19	19	19	87,97605
	434	18	18	18	87,45953
	470	16	16	16	87,20757
	513	15	15	15	86,99051
	564	14	14	14	87,26773
	626	12	12	12	87,39999
	705	11	11	11	87,61609
	805	9	9	9	87,48769
bowman8	20	6	6	6	0,111809
buxey29	27	20	20	20	1,684614
	30	17	17	17	1,711822
	33	16	16	16	1,710827
	36	15	15	15	1,752085
	41	13	13	13	1,651571
	47	11	11	11	1,809971
	54	9	9	9	1,644477
gunther35	41	19	19	19	2,487306
	44	18	18	18	2,47384
	49	16	16	16	2,437998
	54	14	14	14	2,465446
	61	12	12	12	2,412859
	69	11	11	11	2,387959
	81	9	9	9	2,483694
hahn53	2004	9	9	9	6,000058
	2338	8	8	8	5,773291

Table A.6 (Continued)

hahn53	2806	6	6	6	0,007034
	3507	5	5	5	0,002515
	4676	4	4	4	0,008182
heskia28	138	11	11	11	1,640201
	205	7	7	7	1,839233
	216	7	7	7	1,69309
	256	6	6	6	1,737889
	324	4	4	4	0,588227
	342	4	4	4	1,676162
jackson11	9	9	9	9	0,22629
	10	9	9	9	0,224527
	13	7	7	7	0,220388
	14	7	7	7	0,221789
	21	4	4	4	0,217563
jaeschke9	7	9	9	9	0,145394
	8	9	9	9	0,147313
	10	8	8	8	0,142571
	18	4	4	4	0,139674
kilbrid45	56	15	15	15	4,389653
	57	15	15	15	4,53126
	62	13	13	13	4,52017
	69	12	12	12	4,34721
	79	10	10	10	4,426796
	92	9	9	9	4,354478
	110	8	8	8	4,394304
	111	7	7	7	4,335305
	138	6	6	6	4,396122
	184	5	5	5	4,36064
lutz1_32	1414	12	12	12	1,910162
	1572	11	11	11	1,949024
	1768	10	10	10	1,891183
	2020	10	10	10	1,968167
	2357	8	8	8	1,880219
	2828	6	6	6	0,346497
lutz2_89	11	75	75	75	20,22053
	12	70	70	70	20,03288
	13	68	68	68	20,00261
	14	63	63	63	20,1224
	15	60	60	60	20,1081
	16	59	59	59	19,91857
	17	53	53	53	19,75834
	18	51	51	51	19,54431
	19	48	48	48	19,55601

Table A.6 (Continued)

lutz2_89	20	44	44	44	19,6671
	21	43	43	43	19,77423
lutz3_89	75	34	34	34	19,32931
	79	31	31	31	19,53357
	83	31	31	31	19,3172
	87	29	29	29	19,49443
	92	27	27	27	19,24586
	97	25	25	25	19,27993
	103	24	24	24	19,07118
	110	22	22	22	19,06438
	118	20	20	20	19,09638
	127	18	18	18	19,07877
	137	18	18	18	18,96058
	150	16	16	16	19,06536
mansoor11	48	6	6	6	0,218361
	62	5	5	5	0,213296
	94	3	3	3	0,214483
mertens7	7	7	7	7	0,09064
	8	7	7	7	0,125274
	10	6	6	6	0,087834
	15	4	4	4	0,08784
	18	3	3	3	0,087457
mitchell21	14	13	13	13	0,817228
	15	13	13	13	0,86259
	21	9	9	9	0,79741
	26	7	7	7	0,836684
	35	5	5	5	0,794066
	39	5	5	5	0,792347
mukherje94	176	34	34	34	27,01136
	183	33	33	33	27,19035
	192	32	32	32	26,57875
	201	30	30	30	27,13786
	211	28	28	28	26,66774
	222	26	26	26	26,97807
	234	25	25	25	26,81379
	248	24	24	24	26,76957
	263	22	22	22	27,09354
	281	21	21	21	26,82837
	301	19	19	19	26,92261
	324	18	18	18	17126,93
	351	17	17	17	27,90256
roszieg25	14	17	17	17	1,248018
	16	14	14	14	1,251836

Table A.6 (Continued)

roszieg25	18	13	13	13	1,240939
	21	10	10	10	1,213463
	25	8	8	8	1,207249
	32	7	7	7	1,21729
sawyer30	27	19	19	19	1,931666
	30	18	18	18	1,889296
	33	17	17	17	1,888229
	36	15	15	15	1,87761
	41	12	12	12	1,865808
	47	11	11	11	1,839587
	54	10	10	10	1,860745
	75	7	7	7	1,840186
scholl297	1394	66	66	66	533,7921
	1422	65	65	65	496,8604
	1452	63	63	63	497,322
	1483	63	63	63	495,7856
	1515	61	61	61	497,2102
	1548	60	60	60	516,0644
	1584	59	59	59	537,204
	1620	57	57	57	538,5923
	1659	56	56	56	538,9106
	1699	55	55	55	538,637
	1742	53	53	53	539,5288
	1787	52	52	52	539,365
	1834	50	50	50	546,8564
	1883	49	49	49	542,256
	1935	47	47	47	545,8709
	1991	46	46	46	543,4856
	2049	45	45	45	545,0181
	2111	44	44	44	543,1216
	2177	43	43	43	547,5093
	2247	41	41	41	544,9415
	2322	39	39	39	545,6491
	2402	37	37	37	11439,06
	2488	37	37	37	536,6873
	2580	35	35	35	540,7223
	2680	33	33	33	536,2211
	2787	32	32	32	536,2229
tonge70	160	31	31	31	11,96047
	168	29	29	29	12,0454
	176	27	27	27	11,96166
	185	26	26	26	11,93619
	195	26	26	26	12,01772

Table A.6 (Continued)

tonge70	207	24	24	24	11,99873
	220	22	22	22	12,19608
	234	21	21	21	11,92201
	251	19	19	19	11,98546
	270	18	18	18	11,91595
	293	17	17	17	11,9294
	320	15	15	15	11,89461
	364	13	13	13	11,95034
	410	11	11	11	12,00144
	468	10	10	10	11,89471
	527	9	9	9	12,13105
	54	41	41	41	8,119652
warnecke58	56	41	41	41	8,143334
	58	40	40	40	8,169048
	60	38	38	38	8,097576
	62	38	38	38	8,006914
	65	36	36	36	8,044769
	68	35	35	35	7,989435
	71	34	34	34	8,021409
	74	31	31	31	7,962136
	78	30	30	30	7,945148
	82	29	29	29	7,907039
	86	27	27	27	7,957683
	92	25	25	25	7,938106
	97	23	23	23	7,897008
	104	22	22	22	7,859675
	111	21	21	21	7,886336
wee-mag75	28	68	68	68	16,12493
	29	68	68	68	16,14994
	30	68	68	68	16,09581
	31	67	67	67	15,92009
	32	66	66	66	16,0209
	33	67	67	67	16,04364
	34	65	65	65	15,8918
	35	64	64	64	15,93722
	36	64	64	64	15,86968
	37	64	64	64	15,90346
	38	62	62	62	15,83641
	39	62	62	62	15,72136
	40	62	62	62	15,7237
	41	61	61	61	15,8318
	42	62	62	62	15,77135
	43	61	61	61	15,62698

Table A.6 (Continued)

wee-mag75	45	60	60	60	15,69169
	46	61	61	61	15,75776
	47	60	60	60	15,6629
	49	60	60	60	15,65524
	50	59	59	59	15,78025
	52	52	52	52	15,39736
	54	50	50	50	15,33767
	56	43	43	43	15,25216

SR:Smallest Result BR:Biggest Result