DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MULTI OBJECTIVE META-HEURISTIC OPTIMIZATION TO BALANCE GENERALIZED ASSEMBLY LINES

by
Şebnem DEMİRKOL AKYOL

May, 2014
İZMİR

MULTI OBJECTIVE META-HEURISTIC OPTIMIZATION TO BALANCE GENERALIZED ASSEMBLY LINES

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Ph.D. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"MULTI OBJECTIVE META-HEURISTIC OPTIMIZATION TO BALANCE GENERALIZED ASSEMBLY LINES"** completed by **ŞEBNEM DEMİRKOL AKYOL** under supervision of **PROF. DR. ADİL BAYKASOĞLU** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy.

....
Prof.Dr. Adil BAYKASOĞLU

Supervisor

....
Prof.Dr. A. Nihat BADEM

Thesis Committee Member

....
Yrd.Doç.Dr. Yavuz ŞENOL

Thesis Committee Member

....
Doç.Dr. Metin DAĞDEVİREN

Examining Committee Member

....
Doç.Dr. A. Serdar TAŞAN

Examining Committee Member

Prof.Dr. Ayşe OKUR
Director
Graduate School of Natural and Applied Sciences

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ABSTRACT

The primary aim of this PhD study is to introduce a novel assembly line worker assignment and balancing problem (ALWABP) that considers ergonomic risk factors, ErgoALWABP. ErgoALWABP which is proposed in this PhD study is a special case of ALWABP that takes into account ergonomic conditions of the workplace. Since the proposed problem is NP-hard and multi-objective in nature, a rule based constructive randomized search heuristic is proposed to deal with it.

Within this perspective, first, the ALWABP benchmark data is solved by the proposed approach in order to test the performance of the heuristic. Computational experiments and computational results indicate that the proposed algorithm performs satisfactorily. Next, the proposed solution technique is used to solve the ErgoALWABP. Because the ErgoALWABP is multi-objective, a preemptive goal programming approach is introduced. Since ErgoALWABP is a novel problem, there is no set of benchmark instances for testing. Therefore, ergonomic conditions of the classic ALWABP is compared with ErgoALWABP in order to understand the improvement of ergonomic conditions of the assembly line.

At last, an industrial application at a company, which produces harness for automotive industry, is presented. Ergonomic risk of the working environment is assessed, and the assembly line is rebalanced. As a result, it is stated that the company operates with ergonomically poor conditions and some actions must be taken to improve workplace ergonomics.

Keywords: Assembly lines, assembly line balancing and worker assignment problem, ergonomic risk factors, OCRA index, multi-objective optimization, meta-heuristics

ÇOK AMAÇLI META-SEZGİSEL OPTİMİZASYON YAKLAŞIMI İLE GENELLEŞTİRİLMİŞ MONTAJ HATTI DENGELEME

ÖZ

Bu doktora çalışmasının temel amacı, ergonomik risk faktörlerini dikkate alan yeni bir montaj hattı dengeleme ve işgücü atama problemi (MHDİAP) çeşidi olan ErgoMHDİAP'ni tanıtmaktır. Bu doktora çalışmasında ortaya konan ErgoMHDİAP, MHDİAP'nin işyerindeki ergonomik risk faktörlerini göz önünde bulunduran özel bir durumudur. Önerilen problem doğası gereği NP-zor ve çok amaçlı olduğundan dolayı, bu karmaşık problemi çözmek amacıyla kural tabanlı çözüm kurucu rassallaştırılmış arama algoritması sunulmuştur.

Bu kapsamda, öncelikle, önerilen sezgiselin performansını test etmek amacıyla MHDİAP kıyaslama örnekleri seti önerilen yöntemle çözülmüştür. Deneysel çalışmalar ve sonuçlar algoritmanın tatmin edici performansa sahip olduğunu göstermiştir. Daha sonra, bu çözüm yöntemi kullanılarak ErgoMHDİAP çözülmüştür. ErgoMHDİAP çok amaçlı olduğu için öncelikli amaç programlama yaklaşımı geliştirilmiştir. ErgoMHDİAP yeni bir problem olduğundan test etmek için kıyaslama örnekleri seti yoktur. Bu nedenle, montaj hattının ergonomik koşularındaki iyileşmeyi anlayabilmek amacıyla, klasik MHDİAP ile ErgoMHDİAP'nin ergonomik koşulları kıyaslanmıştır.

Son olarak, otomotiv sektörü için kablo ağı üreten bir işletmede endüstriyel bir uygulama yapılmıştır. Çalışma ortamının ergonomik risk değerlendirmesi yapılarak, montaj hattı yeniden dengelenmiştir. Sonuç olarak, işletmenin ergonomik anlamda kötü koşullarda çalıştığı belirlenmiş ve işyeri ergonomisini iyileştirmek amacıyla bazı aksiyonlar alınması gerektiği bildirilmiştir.

Anahtar kelimeler: Montaj hatları, montaj hattı dengeleme ve işgücü atama problemi, ergonomik risk faktörleri, OCRA indeksi, çok amaçlı optimizasyon, meta-sezgiseller

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CHAPTER ONE
INTRODUCTION

1.1 Objectives and Motivations

Assembly lines are a special case of flow-line production systems that manufacture standardized commodities in large amounts. In an assembly process, subassemblies and components are put together on the semi-finished assembly which moves from station to station where the parts are added in sequence until the final assembly is produced. The tasks can be executed by workers, robots or both of them.

The assembly line concept in manufacturing is firstly introduced by Henry Ford. In 1913, Ford invented the first assembly line with a moving belt for mass production of an entire automobile. By using the assembly line, Ford produced Model-T cars at significantly lower prices. Since then, the assembly line concept has been present in various types of industries such as automobiles and other transportation vehicles, household appliances, electronic goods, computers, engines, and etc. In today's highly competitive market trends, companies need to meet the consumers' expectations in short time with minimum acceptable costs in order to be sustainable. This is why assembly line concept is so popular among all manufacturing systems. In such environment, an important decision problem, assembly line balancing problem (ALBP) arises.

ALBP is relevant for the allocation of the tasks, each having an operation processing time and a set of precedence relations, among workstations so that a given objective function is optimized and the precedence relations are satisfied. ALBP is NP-hard in nature. In classic ALBP, it is assumed that every task has a fixed operation time. However, in recent years the traditional ALBP has evolved and it is understood that the fixed operation time assumption is inconvenient for the real life manufacturing systems. Because every worker has unique characteristics such as skill, experience, ability, etc., especially in labor intensive assembly lines a task operation time differs depending on the worker who executes the task. In order to close this gap between the traditional ALBP and real life assembly line systems, a special case of ALBP which is called assembly line worker assignment and balancing problem (ALWABP) is introduced to the assembly line literature.

This problem arises when operation times of tasks vary due to the worker who executes the task, and some task-worker incompatibilities are occurred. Since task times are dependent on the worker, who operates the task, the concept of assigning tasks to workers is occurred in additional to the ALBP. In other words, ALWABP is a double assignment problem which includes assigning tasks to workers and workers to stations simultaneously. Even the traditional ALBP is NP-hard, the ALWABP is NP-hard and multi-objective in nature.

Since the ALWABP is a NP-hard hot research topic, many researchers have proposed various solution techniques to solve the problem. However, none of the proposed solution strategies is proven to be optimal for every benchmark test instance, and the problem is still attractive for researchers.

One of the main aims of this PhD study is to introduce an efficient solution approach for the ALWABP, which tries to minimize the cycle time of the line, in order to contribute satisfactory results to the literature.

In ALWABP literature, generally the primary objective is to minimize cycle time and the secondary objective is to distribute workload among stations as smooth as possible. The term workload is considered as computing the station times. It is assumed that, two workers executing different tasks on two different stations have the same workload if the station times are equal. However, even the operation times of two tasks are equal; the process that is required for executing two different tasks is not the same. In other words, two workers executing different tasks, make different operations. Thus, measuring workload in terms of station time is not appropriate for real life assembly lines. In order to distribute workload more correctly, control of the ergonomic risk factors at working environment is necessary. Although this is an important aspect, there is no research attempt studying ergonomic risk assessment in ALWABP literature.

From this point of view, one of the other important aims of this research study is to make ergonomic risk assessment in ALWABP. We call this new problem as ErgoALWABP. This newly introduced problem is our main contribution to the relevant literature. Furthermore, the solution procedure that is proposed for the ErgoALWABP, is implemented on an industrial case.

1.2 Research Methodology

ALWABP which is a special case of the traditional ALBP is a relatively new research topic. Since the problem is very popular in academic society, there have been many studies published in recent years. Also, the importance of the ergonomic conditions in the working environment becomes more of an issue nowadays. Especially in developed countries, the workplace ergonomics is controlled by legislation. In recent years, Directorate General for Occupational Health and Safety which works for Ministry of Labor and Social Security of the Republic of Turkey put some legal obligations, such as legislation numbered 6331, in order to control ergonomic risk factors in working environment. Although workplace ergonomics is an important aspect for governments and companies, it is barely considered in assembly line balancing literature. Moreover, none of the research studies incorporate ergonomic risk factors into ALWABP.

In this PhD study, we proposed a rule based constructive randomized search algorithm. At first, we applied the proposed solution technique to the classic ALWABP and we prove that our proposed approach works satisfactorily by comparing it with the relevant literature. Next, we introduce a new problem, ErgoALWABP to the literature by considering ergonomic risk factors in classic ALWABP. Then, we apply our proposed rule based heuristic to this new problem, and improve ergonomic conditions of the assembly lines.

1.3 Outline of the Thesis

This thesis is focused on worker assignment in assembly line balancing and ergonomic risk assessment. This study is organized as follows.

In Chapter 2, firstly main characteristics of the assembly line balancing problem are described in order to clarify assembly line worker assignment and balancing problem. Then, motivation behind the ALWABP, mathematical model of the problem and literature survey on ALWABP is given.

In Chapter 3, detailed information on one of the ergonomic risk assessment techniques, OCRA index and literature review on ergonomic risk factors in assembly line balancing is provided.

In Chapter 4, a rule based constructive randomized search algorithm for solving ALWABP and ErgoALWABP is proposed. The results of computational experiments are carried out.

In Chapter 5, a company that produces cable networks for automobile industry is introduced and implementation of the proposed solution method to the company is presented.

Finally in Chapter 6, the summary and the contributions of this thesis, and future research directions are discussed.

CHAPTER TWO
ASSEMBLY LINE WORKER ASSIGNMENT AND BALANCING PROBLEM

2.1 Introduction

The aim of this chapter is to provide an overview of the assembly line worker assignment and balancing problem. At first, the classic assembly line balancing concept is described in this chapter in order to explain assembly line worker assignment and balancing problem more explicitly. Then, main features of the assembly line worker assignment and balancing problem is presented. The rest of this chapter is organized as follows. In section 2.2, description of the assembly line balancing problem and its main concepts are given. In section 2.3, motivation behind the assembly line worker assignment and balancing problem and its characteristics are discussed. In section 2.4, literature survey on the assembly line worker assignment and balancing problem is stated.

2.2 Assembly Line Balancing Problem

Assembly line balancing problem (ALBP) is a decision problem arising when designing or redesigning an assembly line and it consists in finding the optimal assignment of tasks, each having an operation processing time and a set of precedence relations, among the workstations corresponding to some objectives. According to the objective function, the ALBP might be a single-objective or multi-objective problem. In single-objective optimization methods, the problem is described by only one objective function. In 1900s, assembly line manufacturers produced low variety of products in high volumes. Most of the companies considered only one objective such as maximizing throughput or minimizing costs, in those days. However, the assembly line concept has evolved during the decades. In today's highly competitive business environment, companies have the focus on customer needs and produce more customized products. Thus, companies have to cope with multiple objectives simultaneously. Some of the real life objectives can be listed as maximizing throughput, minimizing late delivery, minimizing setup times, minimizing inventory, minimizing cycle time, and etc. This is why we study multi-objective assembly line optimization in this study.

Depending on the objective function of the optimization problem, several versions of ALBP arise in the literature (Scholl, 1999). The most common problems used in the literature are Type–1 and Type–2 problems and each type of them belong to the NP-hard class of the combinatorial optimization problems (Karp, 1972). Type–1 problems try to minimize the number of workstations hence; the cycle time must be predetermined. In industrial life this type of balancing problems is generally occurred when the designing phase of a new assembly line. On the other hand, Type–2 problems try to minimize the cycle time for a fixed number of workstations. So, this type of balancing problems is more appropriate when redesigning an existing line. Moreover, Type–E problems try to maximize the line efficiency by simultaneously minimizing the cycle time and the number of workstations. Type–F problems seek for a feasible assembly line exists or not for predetermined cycle time and number of workstations. Also, Type–3, Type–4 and Type–5 problems try to maximize the workload smoothness, maximize the work relatedness and maximize multiple objectives with Type–3 and Type–4, respectively.

Assembly line balancing problems vary with regard to the number and variety of products, line control, variability of operation times, line layout, degree of automation in stations, type of stations, and etc and etc. (Scholl, 1999). The most important versions of the assembly lines are summarized in the following:

There are three fundamental types of ALBPs according to the product mix: single-model, multi-model and mixed-model. In single-model assembly lines, one homogenous product or several products with identical production process are manufactured on the same line. In multi-model lines, similar products are assembled in batches on the same line. In mixed-model lines, several versions of a basic product are manufactured on the same line simultaneously and continuously.

With regard to the line control procedures, assembly lines can be a paced line or an unpaced line. In paced lines a mechanical material handling equipment like conveyor belt, which has a constant speed, is present between workstations. In unpaced lines, there is no mechanical material handling equipment, so subassemblies are transferred by workers when the required operations are finished.

2.3 Assembly Line Worker Assignment and Balancing Problem (ALWABP)

The traditional ALBP and its main characteristics are summarized above. There is also one important assumption in traditional ALBP which is operation times of tasks are assumed to be fixed. By this assumption the problem is simplified and become easier to solve. However, ALBP with this assumption is unlikely to model the real life assembly lines, especially for labor intensive industries. Because every operator has his own skills, abilities, experience and working performance; a task's operation time is of course depend on the worker who executes the task. This is the reason for occurrence of Assembly Line Worker Assignment and Balancing Problem (ALWABP).

ALWABP is a new type of line balancing problem which appears in real assembly lines, but has recently been popular in academic area. This problem arises when the operation time for every task differs according to the worker. The problem is especially important for manually operated assembly lines with high labor turnover. Since the operation times of tasks vary due to the workers, the problem requires a simultaneous solution to the double assignment problem. Tasks must be assigned to workers and workers to stations, concurrently.

Since, even the traditional ALBP is NP-hard, the much more complex ALWABP is also NP-hard conclusively. In analogy with the traditional ALBP, ALWABP is also have the same types of problems such as; –1, –2, –E, and –F. In ALWABP–1 the number of workstations is tried to be minimized for a predetermined cycle time; and in ALWABP–2 the cycle time is tried to be minimized for a fixed number of workstations. In the relevant literature, single model of ALWABP –2 with paced line is the most common situation.

In order to define ALWABP more comprehensively, the main assumptions of the problem must be stated (Miralles et al., 2008):

- Operation times and precedence relations of tasks are known deterministically.
- A single product is assembled on the line.
- The assembly line is a serial paced line where buffers are not considered.
- Because operators have unique personal characteristics such as skills, abilities, capabilities, motivation, and etc., processing time of a task varies depend on the worker executing that particular task.
- There are not generically slow or speedy workers. Some workers can be very slow, or even incapable when executing some tasks, but very efficient when executing some others.
- Every worker is assigned to only one station.
- Every task is assigned to only one station, provided that the worker selected for that station is capable of performing the task, and that the precedence relations are satisfied.

2.3.1 Motivation of the ALWABP

Assembly line worker assignment and balancing problem (ALWABP) is firstly introduced by Miralles et al. (2007). One typical example of the ALWABP is sheltered work centers for the disabled (SWD). The idea behind the occurrence of the ALWABP is to employ disabled people. Since assembly lines carry out the division of work principle, operators perform specific tasks repeatedly and continuously. So, assembly lines are the most convenient manufacturing systems for disabled people to work.

According to the World Health Organization (WHO) there are about 386 million disabled people within the active labor age range (16-64). Although the unemployment rates of disabled people are relatively moderate in developed countries such as UK (13%), they are pretty high in many emerging countries (around 80%). This fact force many countries to facilitate the development of many SWDs in order to employ disabled people just like any other person. Turkey is one of the countries with higher unemployment rates and many active policies have been launched by national and regional governments to achieve a better labor integration of the disabled. An increasing number of companies are becoming concerned with this matter.

Miralles et al. (2007) summarized some features and constraints of a SWD:

- Operation times for each differ substantially according to the worker who executes the task.
- Some disabled workers cannot perform some specific tasks because of their physical characteristics; and some of them can perform a particular task in a huge amount of time.
- There are some task-worker assignments that should be considered a priori because of some specific reasons.
- Tasks which are executed by disabled workers have operations times with greater variability than tasks executed by normal workers. A disabled worker can execute a particular task very slowly while operating another one fastly. Because of this reason, it is not true to label a worker as slow or speedy. Each of them can be slow on some tasks and speedy on other particular tasks.
- Environmental factors affect disabled workers yield considerably. Thus, ergonomic risk factors of the workplace should be controlled carefully.
- There are some worker-station assignments that should be considered a priori because of some physical features of disabled workers.
- Because disabled workers have some health problems, absenteeism is also very common in this environment.
- Psychological aid must be provided to disabled workers periodically.
- The primary aim of a SWD is to integrate disabled workers to working environment such as a normal worker. Sometimes, disabled workers reach

their best yields in the SWD and leave it in order to work in a regular assembly line. In such cases, the SWD must be rebalanced by considering new disabled workers.

2.3.2 The Mathematical Model of the ALWABP–2

The notation used in this problem is given in Table 2.1.

Table 2.1 Notation used in ALWABP–2

i, j	Task
h	Worker
s	Workstation
N	Set of tasks
H	Set of available workers
S	Set of workstations
A	Set of assignments a priori (i, h) task–worker
I	Set of incompatible assignments task–worker (i, h)
Z	Set of assignments a priori (h, s) worker–station
c	Cycle time
m	Number of workstations
p_{hi}	Processing time for task i when worker h executes it
$lowp_i$	Lowest processing time for task i from all available actual workers
Dj	Set of tasks immediately preceding task j in the precedence network
x_{shi}	Binary variable equal to 1 only if task i is assigned to worker h in station s
y_{sh}	Binary variable equal to 1 only when worker h is assigned to station s

The mathematical programming model for the ALWABP–2 can be stated as follows (Miralles et al., 2007; Miralles et al., 2008):

$$\text{Min} \qquad c \tag{2.1}$$

subject to:

$$\sum_{h \in H} \sum_{s \in S} x_{shi} = 1 \qquad \forall i \in N, \tag{2.2}$$

$$\sum_{s \in S} y_{sh} \leq 1 \qquad \forall h \in H, \tag{2.3}$$

$$\sum_{h \in H} y_{sh} \leq 1 \qquad \forall s \in S, \tag{2.4}$$

$$\sum_{h \in H} \sum_{s \in S} s \cdot x_{shi} \leq \sum_{h \in H} \sum_{s \in S} s \cdot x_{shj} \qquad \forall i, j / i \in D_j, \tag{2.5}$$

$$\sum_{i \in N} p_{hi} \cdot x_{shi} \leq c \qquad \forall h \in H; \forall s \in S, \tag{2.6}$$

$$\sum_{i \in N} x_{shi} \leq M \cdot y_{sh} \qquad \forall h \in H; \forall s \in S \tag{2.7}$$

with

$$y_{sh} \in [0,1] \qquad \forall s \in S, h \in H$$

$$x_{shi} \in [0,1] \qquad \forall s \in S, h \in H, i \in N$$

$$M > \sum_{h \in H} \sum_{i \in N} p_{hi}$$

The objective function given in (2.1) minimizes the cycle time. The constraint given in (2.2) ensures that every task *i* is assigned to a single station *s* and worker *h*. Constraints sets given in (2.3) and (2.4) expresses that every worker can be assigned to only one station; and in every station there is only one worker, respectively. The constraint given in (2.5) states the precedence relations between tasks *i* and *j*, where *i* is predecessor of *j*. Constraints sets given in (2.6) and (2.7) ensures that every worker *h* assigned to station *s* can have more than one task, whenever given cycle time *c* is not achieved. As cycle time *c* and y_{sh} are both variables, (2.6) and (2.7) are defined separately in order to maintain the model linearity.

There are also some additional constraints for more specific SWD. Some specific features are expressed as following constraints:

$$\sum_{s \in S} x_{shi} = 1 \qquad \forall (i, h) \in A. \tag{2.8}$$

The constraint given in (2.8) expresses that some task-worker assignments must be considered a priori because of some specific reasons.

$$y_{sh} = 1 \qquad \forall (s, h) \in Z. \tag{2.9}$$

The constraint given in (2.9) ensures that some worker-station assignments must be considered a priori because of some physical features of disabled workers.

$$\sum_{i \in N} \sum_{s \in S} x_{shi} \geq 1 \qquad \forall h \in H. \tag{2.10}$$

The constraint given in (2.10) states that all workers must have at least one task assigned, even the slowest ones, because the philosophy of the SWD is to employ disabled people. This constraint is only feasible when the number of tasks exceeds the number of available workers.

2.4 Literature Review

Since the first article on the ALBP (Salveson, 1955), it has been a hot topic for researchers. Assembly line literature is mainly based on fixed operation times. Though many research studies on ALBP have been done for decades, ALWABP barely studied in the literature. The ALWABP concept is a relatively new type of ALBP.

The pioneer study on simultaneously operator assignment and line balancing is performed by Rubinovitz et al. (1993). They described a robotic assembly line configuration that has different robots with their own characteristics. Tasks operation times depend on robots and the objective is to assign the most efficient robot type for the task, to each workstation. By this assignment authors tried to balance the assembly line in such a way that the number of workstations is minimized. Hope et al. (2004) proposed a heuristic approach in order to minimize the cycle time in an assembly line which consists of workers with different skills.

Miralles et al. (2007) for the first time introduced the ALWABP to the assembly line literature. They proposed the SWD concept and presented a case study. They expressed that disabled workers can be changed with normal operators without any production loss by a logical assignment. Chaves et al. (2007) applied a clustering search approach and tested it on the generated ALWABP–2 data. Since then, the proposed benchmark data sets, which are composed of four families (Roszieg, Heskia, Tonge and Wee-Mag), have been used in every ALWABP–2 research study. One year later, Miralles et al. (2008) developed a branch-and-bound algorithm for the ALWABP, enabling the solution of small-sized instances. They randomly generate data based on the Jackson problem from the SALBP (Hoffmann, 1990) and solve the problem via branch and bound. Then, they integrate a heuristic approach to the branch and bound and apply the proposed method to an industrial case. Because of the problem complexity and the need to solve larger instances, the literature has since then shifted its efforts to heuristic methods.

Chaves et al. (2009) hybridized clustering search algorithm with the iterated local search in order to solve the ALWABP–2 benchmark data. They obtained good results in reasonable computation times. Moreira and Costa (2009) developed a minimalist tabu search algorithm that tries to be successful at simplicity, flexibility, accuracy and speed. Blum and Miralles (2011) proposed an iterated beam search algorithm for the ALWABP–2 and obtained the best results in the previous literature. Moreira et al. (2012) proposed a simple constructive heuristic approach that based on 16 task priority rules and 3 worker priority rules and hybridized it with the genetic algorithm. They obtained the fastest results found so far. Araujo et al. (2012) introduced two new versions of the classic ALWABP which are parallelization and collaboration between different workers. In order to solve the proposed problem, the authors developed an integer programming model and hybridized it with a constructed heuristic algorithm.

More recently, Mutlu et al. (2013) proposed an iterative genetic algorithm for the ALWABP–2 and obtained satisfactory solutions in short cpu times. Borba and Ritt (2014) developed an interval probabilistic beam search and hybridized it with the branch and bound procedure. Except the Wee-Mag family, they almost achieved the best results. Finally, Vila and Pereira (2014) published the last ALWABP-2 paper so far. They developed a branch and bound procedure with three different remember algorithms with a time constraint of 60 seconds, 600 seconds and with no time constraints. The time constraint of 600 seconds and no time constraint versions of their approaches acquired the best solutions in the relevant literature.

The literature review explained above in detail is given in Table 2.2.

Table 2.2 An overview of the approaches in ALWABP literature in chronological order

Year	**Researcher(s)**	**Line Configuration**	**Objective Function**	**Methodology**	**Test Problem**
1993	Rubinovitz, Bukchin & Lenz	Robotic straight line	Type-1	Heuristic, Branch and bound	Randomly generated
2004	Hopp, Tekin & Van Oyen	Straight line	Type-2	Heuristic	Randomly generated
2007	Chaves, Miralles & Lorena	Straight line	Type-2	Clustering search	Benchmark problems are generated for the first time
2007	Miralles, Garcia-Sabater, Andres & Cardos	Straight line	Type-2	Integer Programming	Randomly generated
2008	Miralles, Garcia-Sabater, Cardos & Andres	Straight line	Type-2	Heuristic, Branch and bound	Randomly generated
2009	Chaves, Lorena & Miralles	Straight line	Type-2	Iterated local search, clustering search	Benchmark problems
2009	Moreira & Costa	Straight line	Type-2	Tabu search	Benchmark problems
2011	Blum & Miralles	Straight line	Type-2	Iterated beam search	Benchmark problems
2012	Moreira, Ritt, Costa & Chaves	Straight line	Type-2	Hybrid genetic algorithm	Benchmark problems
2012	Araujo, Costa & Miralles	Straight line, Parallel stations	Type-2	Heuristic, Integer Programming	Benchmark problems
2013	Mutlu, Polat & Supçiller	Straight line	Type-2	Iterative genetic algorithm	Benchmark problems
2014	Borba & Ritt	Straight line	Type-2	Interval probabilistic beam search, Branch and bound	Benchmark problems
2014	Vila & Pereira	Straight line	Type-2	Branch and bound, Remember algorithm	Benchmark problems

It can be concluded from the above table that, there is no attempt to incorporate ergonomic risk factors to the assembly line worker assignment and balancing problem. Thus, in this PhD study we consider ergonomic factors for the ALWABP.

CHAPTER THREE
ERGONOMIC ASSEMBLY LINE BALANCING

3.1 Introduction

The aim of this chapter is to express ergonomic risk assessment in assembly line manufacturing environment. Although, there are many research attempts in assembly line balancing, ergonomic risk assessment in assembly lines is barely studied. Moreover, as it is denoted in previous chapter, none of these studies is about assembly line worker assignment problem. Therefore, we study ergonomic assembly line balancing in this PhD thesis. The rest of this chapter is organized as follows. In section 3.2, the effects of ergonomic conditions in manufacturing environment are expressed with statistical findings. In section 3.3, various techniques used in the literature to perform ergonomic risk assessment are described. In section 3.4, one of the most sophisticated ergonomic risk assessment techniques, OCRA index and its parameters are explained in detail. In section 3.5, a numeric example is given in order to explain how the OCRA index works, clearly. At last, in section 3.6 a literature survey on ergonomic assembly line balancing is presented.

3.2 Effects of Ergonomic Conditions in Manufacturing Environment

In assembly line balancing problems, tasks are distributed among workstations as smooth as possible in accordance with the precedence relations. However, smoothening just the total station time between stations is meaningless. In other words, two stations whose total station times are equal, contains different tasks. Consequently, their degrees of strain are different. This situation is underestimated in classical assembly line balancing, but it is an important aspect in reality. Especially in manual assembly lines, same type of work is done by the operator repetitively. As a result, there is a cumulative effect of repetitive work on worker. Assembly lines which are not well-designed ergonomically, cause not only lack of productivity, but also occupational diseases of workers.

An occupational disease is a chronic disease or disorder that occurs as a result of work or working conditions. Every year, 4–12 of 1,000 workers caught an occupational disease in world wide. According to this probability, the expected number of occupational diseases is between 40,000–80,000, in Turkey. However, the reported number of occupational diseases is in only 395 in the year 2012 (Berk et al., 2011; Fişek, 2013). This is because the majority of diseases are not diagnosed and recorded. Without diagnosing an occupational disease, it is impossible to prevent them. According to the specialists, occupational diseases are contagious because, if the required precautions are not taken, the same disease will occur on the other workers. Thus, it is very important to diagnose an occupational disease in order to take the required actions.

Another important aspect is that none of the 395 diseases is about the musculoskeletal system. However, in many developed countries, such as UK, the musculoskeletal diseases have a great portion in occupational diseases. It is predicted that about 40% of the total occupational diseases is related to the musculoskeletal diseases, in Turkey. Musculoskeletal diseases occur as a result of poor workplace ergonomics. This situation points out that ergonomic working conditions is disregarded, in Turkey. It is very important to know what damages can be caused by unfavorable working conditions, in order to prevent the damage. Within this perspective, in recent years, Ministry of Labor and Social Security of the Republic of Turkey, Directorate General for Occupational Health and Safety legislate in order to standardize the workplace ergonomics. Legislation numbered 6331, which is put in this context, is an important progress for our country.

Ergonomics is the scientific discipline concerned with the understanding of physical and psychological effects of workplace on worker. In other words, the terms ergonomics is basically the "fit" between the user/worker, equipment/machinery and their environments. Workplace ergonomics considers the capabilities and limitations of workers in order to enable fair working conditions.

The main aim of ergonomics is to protect occupational health and safety; by this way ergonomics also increases productivity, as well. Especially in manual assembly lines, because of the repetitive unfavorable working conditions, some occupational diseases such as, repetitive strain injury, carpal tunnel and joint elbow syndromes related with hand, wrist, elbow and shoulder, occur on operators. The cure of such occupational diseases takes a long time; and this causes workforce and productivity loss. In order to prevent these complications, the acceptable risk level for the workplace should be analyzed and ergonomic risk factors must be below this highest acceptable level.

3.3 Ergonomic Risk Assessment Techniques

There are many techniques used in the literature in order to determine the ergonomic risk factors of the working environment. Some of the most common ones can be listed as follows: Quick Exposure Check (QEC), National Institute for Occupational Safety and Health (NIOSH), Rapid Upper Limb Assessment (RULA), Rapid Entire Body Assessment (REBA), European Assembly WorkSheet (EAWS), OCcupational Repetitive Action (OCRA). All of the ergonomic risk assessment techniques have been studied and main features and areas of usage are determined throughout this PhD thesis.

Especially in manual assembly lines, workers perform the same type of work repetitively and continuously for long periods of time. In such cases, when analyzing ergonomic risks, it is very important to consider the cumulative effect caused by the repetitive work. Only two of the above mentioned ergonomic risk assessment techniques, OCRA and EAWS incorporate the repetitiveness and cumulative effect. When the rest of the techniques analyzes ergonomic risks of tasks one by one, OCRA and EAWS methods calculate fatigue occurred by the repetitive actions, cumulatively. Because the EAWS method has been introduced more recently (Schaub et al., 2010), the detailed procedures for calculations have not been published clearly yet.

OCRA method is firstly introduced by Occhipinti (1998) and there are many research attempts that study OCRA index through those years. Thus, OCRA method is the only technique that is suitable for assessing ergonomic risks in assembly lines. If there is more than one task in a workstation, OCRA index is calculated for the whole station (not task by task). By this way, the cumulative effect of the repetitive tasks can be considered. OCRA method is not appropriate for manufacturing systems that consist of many lifting and moving operations. It is convenient for the systems which have a mechanical material handling equipment such as conveyor belts. OCRA method analyzes the upper limbs of the body such as, hands, wrists, elbows and shoulders.

3.4 OCcupational Repetitive Actions (OCRA) Method

OCRA index is an ergonomic risk assessment method which is appropriate for ergonomic analysis of repetitive tasks at high frequency. OCRA index is especially used for analyzing upperlibs such as hand, wrist, elbow and shoulder. Also, it performs ergonomic analysis for each part of the body separately (left and right). OCRA index is calculated by as follows:

$$\text{OCRA index} = \text{Actual frequency} / \text{Recommended frequency} \tag{3.1}$$

In the relevant literature, repetitive tasks are tasks that are characterized by repeated work cycles. Technical actions are basic manual actions that have to be executed within the work cycle, such as holding, turning, pushing, cutting, moving, controlling, rotating, painting etc. Frequency of actions is the number of technical actions per minute. Frequency of actions and recommended frequency are calculated by as follows:

$$Actual\ frequency\ = \frac{Number\ of\ technical\ actions\ within\ a\ cycle}{Station\ time} * 60 \tag{3.2}$$

$$\text{Recommended frequency} = CF * PM * FM * RM * ARF * (RcM * DuM) \tag{3.3}$$

where *CF* is the constant of frequency of technical actions per minute, *PM* is the posture multiplier, *FM* is the force multiplier, *RM* is the repetitiveness multiplier, *ARF* is additional risk factors multiplier, *RcM* is the lack of recovery period multiplier, and *DuM* is the multiplier for the overall duration of repetitive tasks during a shift. *CF* is a constant value (European Committee for Standardization, 2007). All multipliers except *CF* are between 0–1. These parameters are equal to 1 for ideal conditions and decrease to 0 as the risk level increases.

3.4.1 OCRA Index Parameters

All parameters that used for calculating the OCRA index are explained in detail, in the following.

3.4.1.1 Constant of Frequency Multiplier

Frequency multiplier which is the first term of the required frequency is assumed to be 30 for ideal conditions. Ideal conditions illustrates a working environment that a shift takes 480 minutes at most, and there are at least 1 lunch break of 30 minutes and 2 coffee breaks of 10 minutes (1 must be before lunch break, and the other one must be after the lunch break.)

3.4.1.2 Posture Multiplier

Posture is the positions and movements of the upper limbs of an operator in order to execute a task. Four fundamental upper limbs are analyzed for the posture multiplier: hand, wrist, elbow and shoulder. The posture and movements of these upper limbs and their corresponding cycle time shares are considered when analyzing posture multiplier. The posture of every single operation is analyzed separately (task by task). Moreover, the posture of a task must be analyzed for both left and right part of the body. Some examples of awkward postures for shoulder, elbow, wrist and hand are illustrated in Figures 3.1, 3.2, 3.3 and 3.4, respectively.

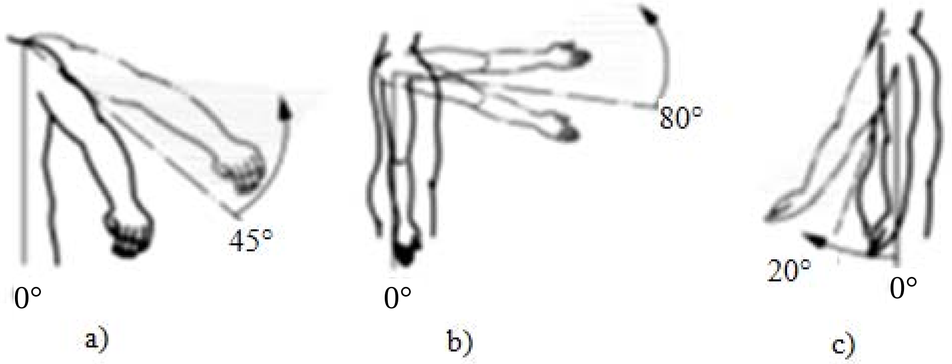


Figure 3.1 Examples for awkward postures of shoulder a) Lateral elevation abduction/adduction (awkward posture > 45º) b) Frontal elevation flexion (awkward posture > 80º) c) Extension (awkward posture > 20º) (European Committee for Standardization, 2007)

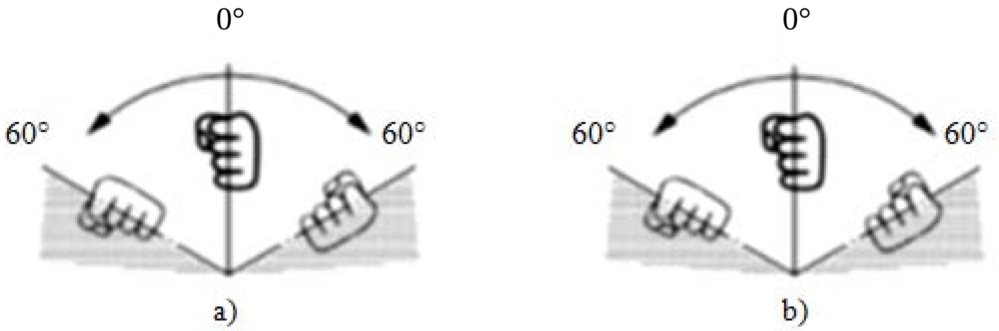


Figure 3.2 Examples for awkward postures of elbow a) Palmar flexion (awkward posture >45º) b) Dorsal extension (awkward posture >45º) (European Committee for Standardization, 2007)

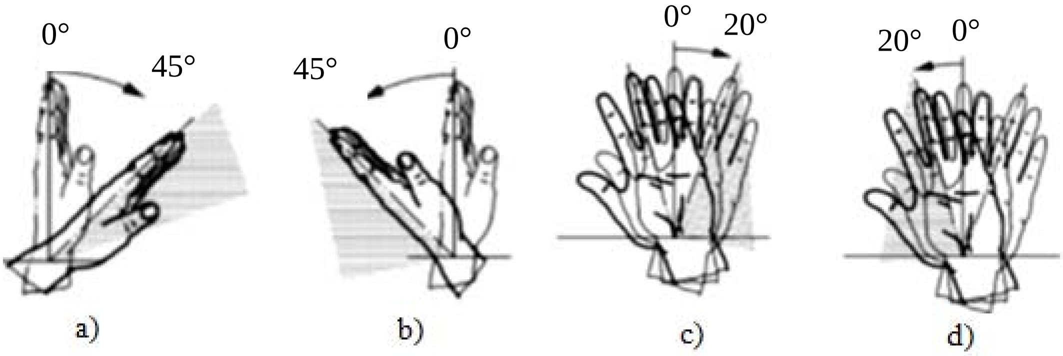


Figure 3.3 Examples for awkward postures of wrist a) Palmar flexion(awkward posture >45º) .b) Dorsal extension(awkward posture >45º) c) Ulnar deviation (awkward posture >20º) d) Radial deviation (awkpost>15º) (European Committee for Standardization, 2007)

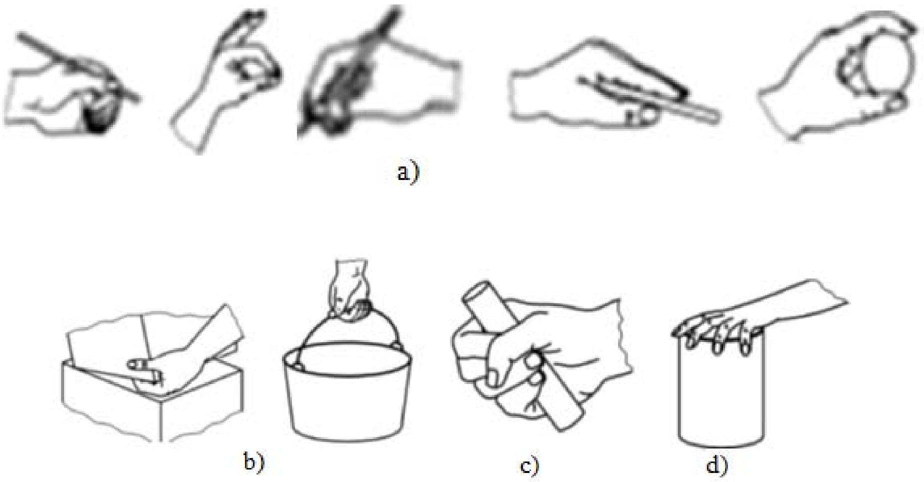


Figure 3.4 Examples for awkward postures of hand.a) Pinch b) Hook grip c) Power grip d) Palmar grip (European Committee for Standardization, 2007)

The duration of the exposure to the awkward postures illustrated in above figures are also very important for analyzing the posture. The higher the portion of the cycle time, the higher is the risk of posture (the lower is the posture multiplier value). Posture multiplier values related to awkward postures and their corresponding cycle time percents are given in Table 3.1.

Table 3.1 Posture multiplier related to awkward postures and their corresponding cycle time percents

Awkward Posture		**Cycle Time Percent**			
		%1 - %24	%25 - %50	%51 - %80	> %80
Severe	Elbow supination (≥60º) Wrist extension / flexion (≥45º) Hand pinch / hook grip / palmar grip (wide span)	1	0,7	0,6	0,5
Mild	Elbow pronation / flexion / extension (≥60º) Wrist radio / ulnar deviation (≥20º) Hand power grip with narrow span (≤2cm)	1	1	0,7	0,5

It can be seen from the above table that, there are two main kinds of posture; severe and mild. Some examples of severe and mild postures are given; and their corresponding posture multipliers according to the cycle time percent are reported. For instance, a worker executes a task with the awkward posture of elbow supination (≥60º). If the cycle time percent of the task operation time is smaller than 24%, then the posture multiplier will be equal to 1. On the other hand, if the cycle time percent of the task operation time is greater than 80%, then the posture multiplier will be equal to 0.5. As the exposure time of the awkward posture increases, the multiplier decreases in order to represent the risk. If there is a position with a greater angle than Table 3.1, it means that the posture is not awkward, and the posture multiplier value will be equal to 1.

Posture multiplier of every single task is analyzed by using Table 3.1. Then, the smallest posture multiplier value is set to be the station's overall posture multiplier value. By this way, the worst case scenario for that particular station is considered.

3.4.1.3 Repetitiveness Multiplier

Repetitiveness occurs due to executing repetitive tasks at high frequency. If the cycle time is greater than 15 seconds and/or the same technical actions of upper limbs are operated less than 50% of the cycle time, there occurs low repetitiveness and the repetitiveness multiplier will be equal to 1. Otherwise, there is high repetitiveness and the corresponding multiplier will be 0.7.

3.4.1.4 Force Multiplier

Force is the physical effort applied by the operator in order to execute technical actions. Operations that require serious force implementation constantly cause risks for musculoskeletal system. If there is no need to implement any force, the force multiplier will be equal to 1. Otherwise, force multiplier is a function of the average force level and represented in Table 3.2. The values listed in the following table are for one single task. The calculation of the overall force multiplier of the station is explained by a numeric example in section 3.5.

Table 3.2 Multiplier relative to the different use of force

Average Force Level (%)	5	10	20	30	40	≥50
Borg Value	0,5	1	2	3	4	≥5
Score	very, very week	very week	week	moderate	somewhat strong	strong / very strong
Force Multiplier (*FM*)	1	0,85	0,65	0,35	0,2	0,01

3.4.1.5 Additional Risk Factors Multiplier

Additional risk factors are other factors that apart the main risk factors (posture, repetitiveness, force, lack of recovery period and number of technical actions in a shift), occur due to the occupational nature. They are defined as additional, because they present temporarily. Some of these factors can be listed as follows:

- The use of vibrating tools,
- Precision of placement (1–2 mm tolerance in positioning an object),
- Implementing strong force or compressions on some local body structures,
- Exposure to cold or hot,
- Exposure to inconvenient lightening,
- Exposure to noise,
- The use of gloves,
- Requirement for sudden or fast movements,
- Objects handled have a slippery surface,
- The technical actions that requires a counter shock (such as hammering, using the hand as a tool etc.).

Additional risk factor multiplier is related to the above mentioned conditions and their corresponding exposure level in terms of cycle time portion. Share of cycle time and the corresponding additional risk multiplier values are as follows:

- ARF = 1, if exposure to the risk factor is ≤ 25% of the cycle time.
- ARF = 0.95, if exposure to the risk factor is between 26%–50% of the cycle time.
- ARF = 0.90, if exposure to the risk factor is between 51%–80% of the cycle time.
- ARF = 0.80, if exposure to the risk factor is ≥ 81% of the cycle time.

3.4.1.6 Lack of Recovery Period and Number of Duration of Repetitive Tasks within a Shift

Recovery period is the time for relaxing after operating technical actions. Lack of recovery period (*RcM*) and duration of repetitive tasks during a shift (*DuM*) multipliers do not change according to the tasks; they change according to the working environments. For a working environment *RcM* and *DuM* take constant values for all tasks. For the ideal conditions that is explained above (a shift taking 480 minutes at most, and at least 1 lunch break of 30 minutes and 2 coffee breaks of 10 minutes) *RcM* and *DuM* take the values 0.6 and 1, respectively.

3.4.2 Evaluation of the OCRA index

After the above mentioned OCRA index parameters are set, OCRA index is calculated by using the equation (3.1). Interpretation of the OCRA index is represented in Table 3.3.

Table 3.3 Interpreting the OCRA index

OCRA Index	**Zone**	**Interpretation of Risk**
≤ 2.2	Green	Acceptable
2.3–3.5	Yellow	Conditionally acceptable
> 3.5	Red	Not acceptable

If OCRA index is smaller than 2.2, it means the risk level is pretty low and the working environment satisfies ergonomic conditions. If the index is between 2.3 and 3.5, workplace ergonomics is conditionally acceptable. The ergonomist should reconsider the workplace in order to obtain an acceptable condition. Finally, if the index is greater than 3.5, the workplace is not acceptable to be an ergonomic environment; and the ergonomist should take some serious actions immediately.

3.5 Ergonomic Risk Assessment by Using OCRA Index: An Example

In order to clarify OCRA index implementation on assembly lines, we give a numeric example, in this section. We explain OCRA method on a traditional SALBP, because our aim is to represent the application of OCRA index on assembly lines, here. Later, in Chapter 4, we solve the ALWABP considering OCRA index.

Precedence relations of the assembly line are illustrated in Figure 3.5. The graph consists of 22 tasks which are represented in nodes. Operation times of tasks are indicated outside of the nodes, i.e. task 3 has an operation time of 51 seconds and in order to execute task 3, task 1 must be completed. Current cycle time of the line is 160 seconds, but it can be increased by 15% according to the company's policy.

OCRA parameters of the tasks are given in Table 3.4. Since *CF*, *RcM* and *DuM* multipliers do not change according to the task; they are not presented in the table. Remember that, for ideal conditions *CF* = 30, *RcM* = 0.6 and *DuM* = 1. Moreover, because the same technical actions of upper limbs are operated more than 50% of the cycle time for all tasks, the repetitiveness multiplier is 0.7 for all tasks, in this example problem.

The first column of Table 3.4 states the task numbers. In second and third columns, number of technical actions and operation times of the corresponding tasks are reported. Awkward postures are illustrated in fourth column. Average force applied to execute the corresponding task is given in column 5.

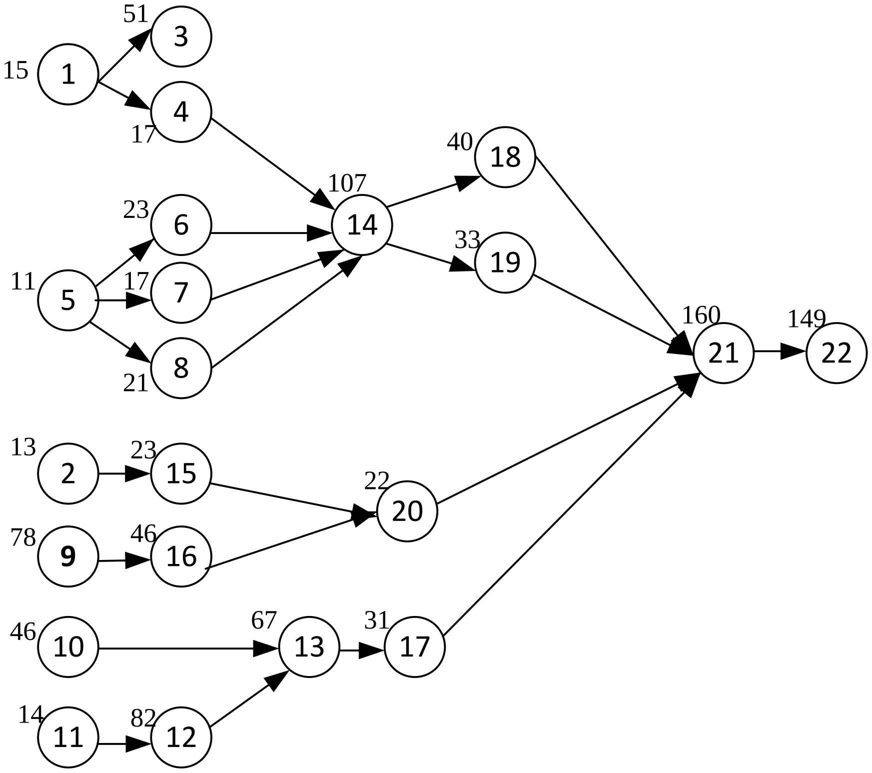


Figure 3.5 Precedence diagram of the numeric example

Finally, the addition risk factor multipliers are depicted in the last column. These values given in Table 3.4 are for the right part of the body. As it is stated previously, OCRA index must be calculated for right and left parts of the body separately. Then, the one with the higher OCRA index (represents worse ergonomic conditions), is selected for the station's OCRA index in order to represent the worst case. In this section, we calculate OCRA for the right hand in order to simplify the computation.

In the present situation of the assembly line, there are currently 7 workstations. Tasks 1, 3, 4, 5, 6, 7 and 8 are executed at station 1; tasks 2, 9, 10 and 11 are operated at station 2; tasks 14 and 18 are executed at station 3; tasks 12 and 13 are executed at station 4; tasks 15, 16, 17, 19 and 20 are operated at station 5; task 21 is operated at station 6; and finally task 22 is operated at station 7.

Table 3.4 OCRA parameters of the numeric example for the right upper limbs

Task no	**Number of Technical Actions**	**Operation Time**	**Posture**	**Average Force (%)**	***ARF***
1	14	15	Hand pinch	10	1
2	12	13	Elbow flexion (≥60º)	10	1
3	8	51	Palmar grip	5	1
4	12	17	Elbow supination (≥60º)	5	1
5	6	11	Elbow extension (≥60º)	20	0,95
6	11	23	Wrist radio deviation (≥20º)	5	1
7	11	17	Wrist extension (≥45º)	5	1
8	11	21	Hand pinch	5	0,95
9	14	78	Elbow flexion (≥60º)	15	0,95
10	11	46	Wrist flexion (≥45º)	10	0,95
11	12	14	Wrist ulnar deviation (≥20º)	10	1
12	25	82	Elbow extension (≥60º)	5	1
13	23	67	Wrist radio deviation (≥20º)	5	1
14	14	107	Palmar grip	5	1
15	26	23	Elbow flexion (≥60º)	5	1
16	26	46	Power grip with narrow span	5	1
17	14	31	Wrist flexion (≥45º)	5	1
18	16	40	Hand pinch	5	1
19	25	33	Power grip with narrow span	5	1
20	28	22	Elbow extension (≥60º)	5	1
21	38	160	Hook grip	5	1
22	33	149	Wrist radio deviation (≥20º)	5	1

In order to explain the application of the OCRA method, we calculate the OCRA index for the first station. Firstly, we must compute the actual frequency from equation (3.2):

Number of technical actions = 14 + 8 + 12 + 6 + 11 + 11 + 11 = 73
Station time = 15 + 51 + 17 + 11 + 23 + 17 + 21 = 155
Actual frequency = 73 * 60 / 155 = 28.26

We have to set the *CF*, *PM*, *RM*, *FM*, *ARF*, *RcM* and *DuM* multipliers in order to compute the recommended frequency. We previously set *CF*, *RM*, *RcM* and *DuM* equal to 30, 0.7, 0.6 and 1, respectively. We determine *PM*, *FM* and ARF from Table 3.4.

For determining *PM*, the type of the awkward posture and its corresponding cycle time share are required. It is read from Table 3.4 that, there is a hand pinch for Task 1. Since Task 1 is executed at Station 1, we compute the cycle time share as follows:

Task time / Station time * 100

For Task 1; cycle time percent is 15 / 155 * 100 = 8.6% where 155 is computed by the sum of operation times of tasks (tasks 1, 3, 4, 5, 6, 7 and 8) that are executed at Station 1 (15 + 51 + 17 + 11 + 23 + 17 + 21). So, *PM* is read from Table 3.1 as 1. For Task 3; the type of the awkward posture is palmar grip; and the cycle time percent is 51 / 155 * 100 = 33.1%. So, *PM* is read as 0.7 from Table 3.1. The rest of the postures of tasks are determined by the same way. For Station 1, *PM*s of the tasks are 1, 0.7, 1, 1, 1, 1, 1, respectively. Since the smallest *PM* value is 0.7, we take 0.7 as the station's *PM*.

In order to set the *FM* of Station 1, firstly we must compute the average force applied in such a way that:

(15/155)*10 + (51/155)*5 + (17/155)*5 + (11/155)*20 + (23/155)*5 + (17/155)*5 +(21/155)*5 ≅ 7

FM parameter is found as 0.94 (1 - (0.15/5)*2) by making interpolation from Table 3.2.

ARF multipliers of tasks are given in Table 3.4. The minimum *ARF* value belongs to tasks 5 and 8. So, Station 1's *ARF* multiplier is 0.95.

Now, we can compute the OCRA index for Station 1 from equations (3.1) and (3.3):

Recommended frequency = $CF * PM * FM * RM * ARF * (RcM * DuM)$

Recommended frequency = 30 * 0.7 * 0.94 * 0.7 * 0.95 * (0.6 * 1) = 7.88

OCRA index = Actual frequency / Recommended frequency = 28.26 / 7.88 = 3.6

Since the OCRA index is greater than 3.5, Station 1 is in red zone. We calculate the OCRA index of the rest of the stations in the same way. The results are summarized in Table 3.5. As it can be seen from the table that, there are two ergonomically red stations in the assembly line. This means that ergonomic conditions of the workplace is unacceptable. The ergonomist, must rebalance the line in order to reduce ergonomic risk factors of the workplace.

Table 3.5 The present situation of the assembly line

Station No	**Tasks**	**OCRA Index**	**Station Time**
1	1, 3, 4, 5, 6, 7,8	3.6 (Red)	155
2	2, 9, 10, 11	3.4 (Yellow)	151
3	14, 18	1.6 (Green)	147
4	12, 13	2.2 (Yellow)	149
5	15, 16, 17, 19, 20	3.7 (Red)	155
6	21	2.3 (Yellow)	160
7	22	2.1 (Yellow)	149

Since, in this section our aim is to explain the application of the OCRA index on assembly lines, we basically rebalance the line with COMSOAL (Computer Method for Sequencing Operations for Assembly Lines) procedure. According to the COMSOAL procedure, tasks that satisfy precedence relations and do not exceed the cycle time are set as assignable tasks; and one of these assignable tasks are selected and assigned to the current station randomly. The results obtained by rebalancing the example assembly line are presented in Table 3.6.

As it can be seen from Table 3.6 that red stations are eliminated, without increasing the total number of workstations. All stations are ergonomically acceptable in this new situation. As it represented in the numeric example, ergonomic conditions can be improved without increasing the total number of workstations.

Table 3.6 The situation after rebalancing the assembly line

Station No	Tasks	OCRA Index	Station Time
1	1, 5, 7,8	3.3 (Yellow)	115
2	2, 9, 10, 11	3.4 (Yellow)	151
3	4, 14, 18	2.0 (Yellow)	164
4	6, 12, 13	2.3 (Yellow)	172
5	15, 16, 17,19	3.3 (Yellow)	133
6	21	2.3 (Yellow)	160
7	20, 22	3.4 (Yellow)	171

3.6 Literature Review

Although considering ergonomic risk factors in assembly lines is crucial, this concept is barely studied in the literature. The limited work studied in the relevant literature is summarized here. Moreau M. (2003) developed an ergonomic risk assessment technique for design procedures at Peugeot-Citroën. He tried to reduce the ergonomic risks of critical stations in order to reduce the musculoskeletal diseases. He redesigned the workplace and he did not only improve the ergonomic conditions, but also decreased the cycle time- by 30%. Vieira and Kumar (2004) surveyed the literature on working postures. They stated that working postures are related to musculoskeletal health, directly. Authors claimed that, in order to prevent musculoskeletal diseases, information about working postures need to be collected and analyzed in a more systematic way. Battini et al. (2007) presented an industrial case application in order to state the relationship between ergonomics and assembly line design. They improved the productivity of the considered line by 15% and reduced the fatigue levels and injuries for the operators, by the proposed procedure. Longo and Mirabelli (2009) proposed a two-step approach to design an assembly line for heaters production with considering ergonomic factors. The authors designed the product and the assembly line by using simulation, in the first step. Then, in the second step, they balanced the line effectively and obtained a better case with better ergonomic conditions. More recently, Otto and Scholl (2011) claimed that by balancing an assembly line effectively, ergonomic risks of the workplace can be decreased substantially. They rebalanced an assembly line and showed that all stations lie under the critical acceptable ergonomic risk level without increasing the total number of workstations.

As it is mentioned above, there are a limited number of research studies on ergonomic assembly line balancing. Moreover, none of them considered worker assignment. Current literature only deals with the task assignment problem in assembly lines. However, as it is stated in Chapter 2, it is inconvenient to assume that all workers are identical. Also, motivation of the ALWABP is based on recruiting the disabled worker. Especially in assembly lines operated by disabled workers, a proper control of ergonomic risks is very important. Our primary aim in this PhD thesis is to make a contribution to the relevant literature by considering ergonomic risk factors in assembly line worker assignment and balancing problem.

CHAPTER FOUR
A RULE BASED CONSTRUCTIVE RANDOMIZED SEARCH ALGORITHM FOR SOLVING ALWABP AND ERGOALWABP

4.1 Introduction

Several solution techniques including exact and heuristic methods are applied to assembly line worker assignment problem (ALWABP), as it is stated previously. However, one optimum solution strategy has not been found so far. In this chapter, a rule based constructive randomized search algorithm is proposed for the ALWABP-2. At first, by using 39 different task priority rules, we sequence tasks and called it assignable tasks list. Then we apply 4 worker priority rules and select the most appropriate worker. After selecting the worker, we choose a subset of the assignable tasks lists by considering the cycle time limitation. It means the station is maximally loaded. At last, selected tasks and the relevant worker is assigned to the station. The proposed heuristic is tested on ALWABP benchmark data and satisfactory results are obtained. Moreover, ergonomic risk factors are added to the classic ALWABP and the proposed rule based heuristic is used to solve this unique problem.

The rest of this chapter is organized as follows. In section 4.2, the proposed rule based constructive randomized search heuristic is defined along with the necessary explanations and an illustrative example is depicted to clarify the understanding. In section 4.3, the proposed approach applied to the ALWABP-2 benchmark data. In section 4.4, ALWABP-2 benchmark problems with considering ergonomic risk factors are solved by using the proposed heuristic. Finally, in section 4.5 the context of this chapter is summarized.

4.2 The Proposed Rule Based Constructive Randomized Search Algorithm

In this chapter, we developed and tested a rule based constructive randomized search heuristic for the ALWABP-2. The heuristic prioritize tasks and sequentially assign tasks to the current station in order and then assign the best suitable worker to that station. This is called station-oriented assignment procedure in the relevant literature (Scholl & Voß, 1996).

The flowchart of the proposed algorithm is given in Figure 4.1. Initially, benchmark data is read and by using the data cycle time values (upper bound, lower bound, average and expected) are calculated. Assignable tasks are determined according to the precedence relations and then rule based search algorithm, which will be explained in detail in 4.2.1, is applied. After prioritizing tasks, a task is chosen randomly via roulette wheel selection. All assignable tasks are chosen one by one and are put in order sequentially. Then, worker selection rules are applied to the unassigned workers and one of them is selected.

After determining the worker, it must be checked that, is there any task which can be operated by only the selected worker, which is called *bottleneck task* in this work. If such a situation exists, it must be controlled that if the task is executed on the current station or not. If not, then solution is infeasible, because none of the remaining workers can operate the bottleneck task. If this is not the case then, the selected worker and tasks, which are a subset of the sequential task list, are assigned to the current station. While choosing tasks from the sequential list, two important points must be considered:

- If there is a task in the list that cannot be executed by the current worker, eliminate that one and go on from the sequential task list.
- Sum of operation times of the assigned tasks, namely *station time* cannot exceed the cycle time.

In the end, if a feasible solution is obtained, then the current cycle time is reduced and the whole process is applied again. By this way, at every feasible iteration cycle time is diminished and finally one feasible solution with the minimum cycle time is gathered when maximum iteration number is achieved. The idea of the proposed heuristic is summarized above. Now, task and worker selection mechanisms and cycle time update approaches (the shaded operations in Figure 4.1) are explained

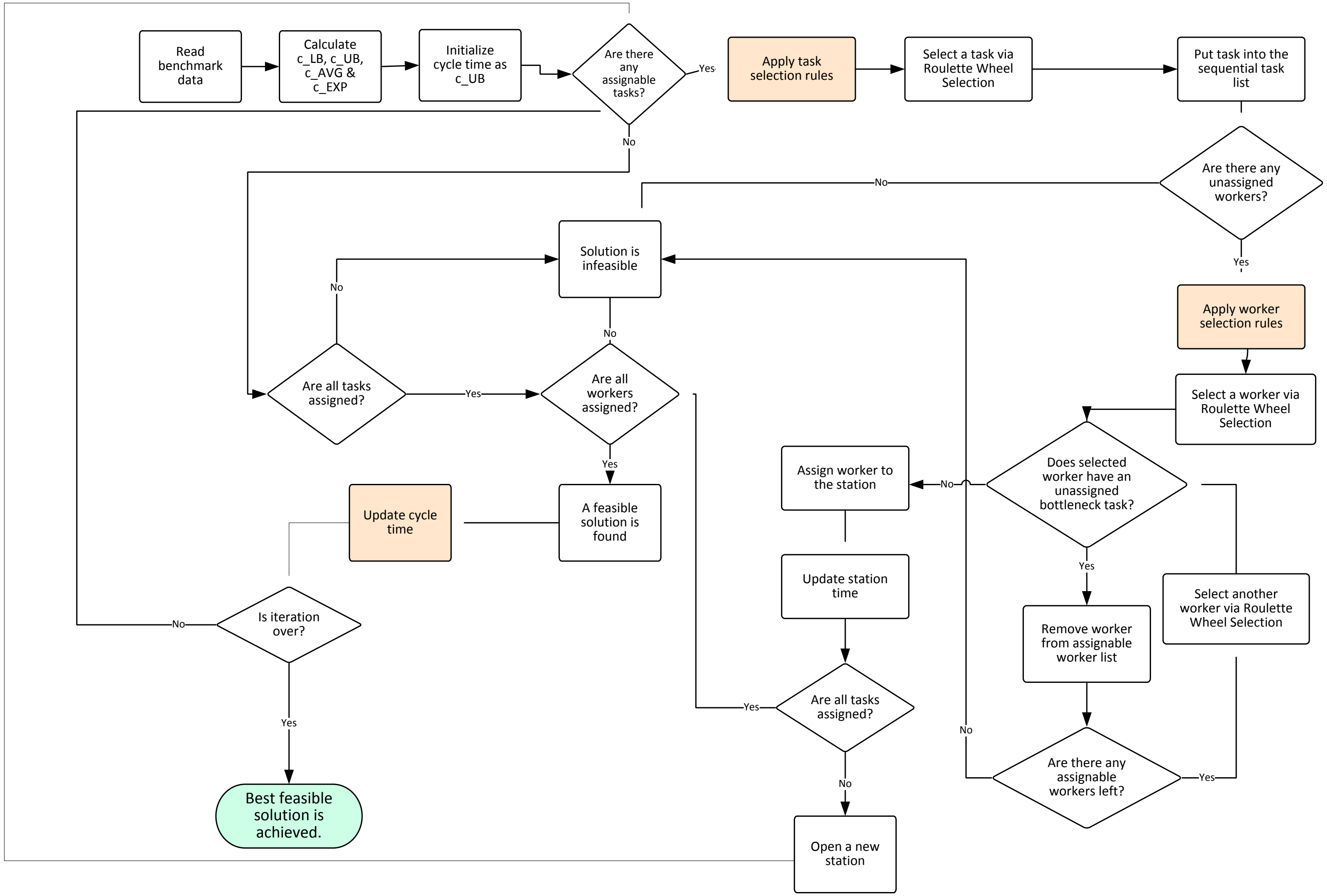


Figure 4.1 Flowchart of the proposed heuristic for the ALWABP-2

in detail in the next subsections. Also, an illustrative example is given in order to clarify the understanding.

4.2.1 Rule Based Task and Worker Selection Strategy

In this study, in order to select one task/worker among tasks/workers in an intelligent manner, we apply 39 rules to the tasks and 4 to the workers. Since, most of the priority rules based on the task execution times, which is a parameter that depends on the worker assigned to each workstation in our problem – ALWABP. So, to overcome this complication we consider tasks' minimum, average and maximum operation times. Moreover, some rules also based on the cycle time. Because of the same reason (varying operation times), we calculate the expected cycle time (c_{exp}) and use it instead of cycle time in the relevant rules.

$$c_{UB} = \max\left\{\sum \frac{maxt_{ij}}{W}, max\{t_{ij}\}\right\} \tag{4.1}$$

$$c_{LB} = \min\left\{\sum \frac{mint_{ij}}{W}, min\{t_{ij}\}\right\} \tag{4.2}$$

$$c_{avg} = \sum(avgt_{ij})/W \tag{4.3}$$

$$c_{exp} = \frac{1}{6} * (c_{LB} + 4 * c_{avg} + c_{UB}) \tag{4.4}$$

where max{ t_{ij}}, min{ t_{ij}}, avg{ t_{ij}} and W are the maximum, minimum and average values of the operation time of task i executed by worker j; and total number of workers, respectively.

4.2.1.1 Task Selection Rules

Task priority rules used in the proposed heuristic is listed in the following:

1. Maximum Longest Processing Time (LPT$_{\text{max}}$), t^i_{max}
2. Minimum Longest Processing Time (LPT$_{\text{min}}$), t^i_{min}
3. Average Longest Processing Time (LPT$_{\text{avg}}$), t^i_{avg}

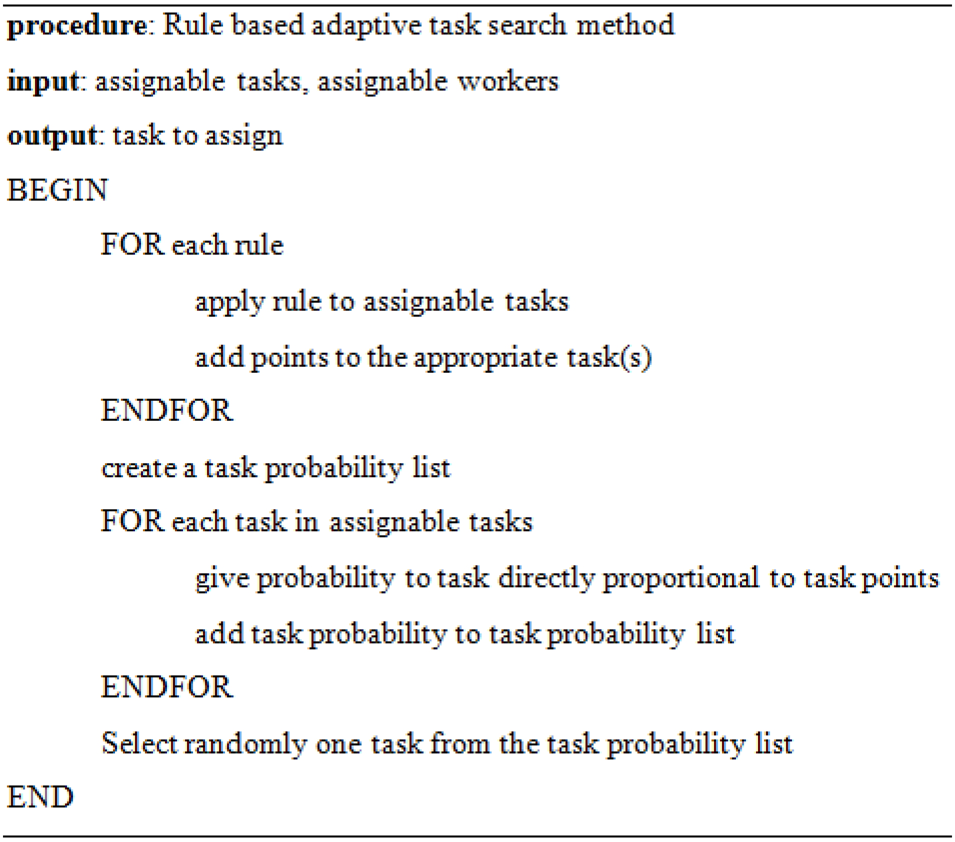
4. Maximum Shortest Processing Time (SPT$_{\max}$), t^{i}_{max}
5. Minimum Shortest Processing Time (SPT$_{\min}$), t^{i}_{min}
6. Average Shortest Processing Time (SPT$_{\text{avg}}$), t^{i}_{avg}
7. Greatest Number of Immediate Successors (GNIS), $|IS_i|$
8. Greatest Number of Successors (GNS), $|S_i|$
9. Greatest Number of Immediate Predecessors (GNIP), $|IP_i|$
10. Greatest Number of Predecessors (GNIP), $|P_i|$
11. Random priority (R)
12. Smallest Task Number (STN), i
13. Maximum Greatest Ranked Positional Weight (GRPW), $t_i^{\max} + \sum_{i \in s_i}^{i} t_j^{\max}$
14. Minimum Greatest Ranked Positional Weight (GRPW), $t_i^{\min} + \sum_{i \in s_i}^{i} t_j^{\min}$
15. Average Greatest Ranked Positional Weight (GRPW), $t_i^{avg} + \sum_{i \in s_i}^{i} t_j^{avg}$
16. Maximum Greatest Average Ranked Positional Weight (GARPW), $\left(t_i^{\max} + \sum_{j \in S_i} t_j^{\max} \right) / \left(|S_i| + 1 \right)$
17. Minimum Greatest Average Ranked Positional Weight (GARPW), $\left(t_i^{\min} + \sum_{j \in S_i} t_j^{\min} \right) / \left(|S_i| + 1 \right)$
18. Average Greatest Average Ranked Positional Weight (GARPW), $\left(t_i^{avg} + \sum_{j \in S_i} t_j^{avg} \right) / \left(|S_i| + 1 \right)$
19. Maximum Smallest Upper Bound (SUB), $N + 1 - \left[\left(t_i^{\max} + \sum_{j \in S_i} t_j^{\max} \right) / c_{\exp} \right]^{+}$
20. Minimum Smallest Upper Bound (SUB), $N + 1 - \left[\left(t_i^{\min} + \sum_{j \in S_i} t_j^{\min} \right) / c_{\exp} \right]^{+}$
21. Average Smallest Upper Bound (SUB), $N + 1 - \left[\left(t_i^{avg} + \sum_{j \in S_i} t_j^{avg} \right) / c_{\exp} \right]^{+}$

22. Maximum Smallest Upper Bound Divided by the Number of Successors (S_UB_NS), $UB_i^{\max} /(|S_i|+1)$
23. Minimum Smallest Upper Bound Divided by the Number of Successors (S_UB_NS), $UB_i^{\min} /(|S_i|+1)$
24. Average Smallest Upper Bound Divided by the Number of Successors (S_UB_NS), $UB_i^{avg} /(|S_i|+1)$
25. Maximum Greatest Processing Time Divided by the Upper Bound (G_PT_UB), $t_i^{\max} / UB_i^{\max}$
26. Minimum Greatest Processing Time Divided by the Upper Bound (G_PT_UB), $t_i^{\min} / UB_i^{\min}$
27. Average Greatest Processing Time Divided by the Upper Bound (G_PT_UB), t_i^{avg} / UB_i^{avg}
28. Maximum Smallest Lower Bound (SLB), $\left[\left(t_i^{\max} + \sum_{j \in P_i} t_j^{\max}\right) / c_{\exp}\right]^+$
29. Minimum Smallest Lower Bound (SLB), $\left[\left(t_i^{\min} + \sum_{j \in P_i} t_j^{\min}\right) / c_{\exp}\right]^+$
30. Average Smallest Lower Bound (SLB), $\left[\left(t_i^{avg} + \sum_{j \in P_i} t_j^{avg}\right) / c_{\exp}\right]^+$
31. Maximum Smallest Slack (SSLK), $UB_i^{\max} - LB_i^{\max}$
32. Minimum Smallest Slack (SSLK), $UB_i^{\min} - LB_i^{\min}$
33. Average Smallest Slack (SSLK), $UB_i^{avg} - LB_i^{avg}$
34. Maximum Smallest Number of Successors Divided by Task Slack (S_NS_SLK), $S_i /(UB_i^{\max} - LB_i^{\max})$
35. Minimum Smallest Number of Successors Divided by Task Slack (S_NS_SLK), $S_i /(UB_i^{\min} - LB_i^{\min})$
36. Average Smallest Number of Successors Divided by Task Slack (S_NS_SLK), $S_i /(UB_i^{avg} - LB_i^{avg})$

37. Maximum Greatest Task Time Divided by Task Slack (TT_SLK), $t_i^{\max} / \left(UB_i^{\max} - LB_i^{\max} \right)$
38. Minimum Greatest Task Time Divided by Task Slack (TT_SLK), $t_i^{\min} / \left(UB_i^{\min} - LB_i^{\min} \right)$
39. Average Greatest Task Time Divided by Task Slack (TT_SLK), $t_i^{avg} / \left(UB_i^{avg} - LB_i^{avg} \right)$

The idea of the first three rules is to select the task with the longest processing time. As it is stated previously, since task times depends on the worker, there are three situations: $t^i{}_{max}$, $t^i{}_{min}$ & $t^i{}_{avg}$ represent task i 's maximum, minimum and average operation time values. The second three rules are just the opposite of the first ones. They seek for the task with the shortest processing time. Rules number 7 & 8 choose a task with the maximum number of immediate successors and successors, respectively. On the contrary, rules number 9 & 10 choose a task with the maximum number of immediate predecessors and predecessors, respectively. 11th rule randomly prioritize a task. Rule number 12 prioritize a task with the minimum task number. Rules 13, 14 & 15 select a task with the maximum ranked positional weight. The rules use maximum, minimum and average task times, respectively. Similarly, rules 16, 17 & 18 find a task with the greatest average ranked positional weight. Rules 19, 20 & 21 seek for a task that has the smallest upper bound value. They use maximum, minimum and average operation time values while calculating the upper bound. 22nd, 23rd & 24th rules seek for a task that with the smallest upper bound value divided by the number of successors. Similarly, rules 25, 26 & 27 look for a task that has greatest processing time divided by the upper bound. Rules from 28 to 30 prioritize a task that has smallest lower bound. Rules 31, 32 & 33 select a task with the smallest slack value which is calculated by using upper and lower bounds. 34th, 35th & 36th rules seek for a task with the smallest number of successors divided by task slack. Finally, rules 37, 38 & 39 prioritize a task with the task time divided by task slack value.

Most of the above rules are inspired from Baykasoğlu (2006). By using these rules, assignable tasks are prioritized. Then, the task with the higher priority takes the higher selection probability. A task is randomly selected within assignable tasks. This strategy is called roulette wheel selection in the literature. The pseudo code of the proposed rule-based adaptive task search mechanism is illustrated in Figure 4.2.



```
procedure: Rule based adaptive task search method
input: assignable tasks, assignable workers
output: task to assign
BEGIN
    FOR each rule
        apply rule to assignable tasks
        add points to the appropriate task(s)
    ENDFOR
    create a task probability list
    FOR each task in assignable tasks
        give probability to task directly proportional to task points
        add task probability to task probability list
    ENDFOR
    Select randomly one task from the task probability list
END
```

Figure 4.2 Pseudo code of the proposed rule-based adaptive task search algorithm

4.2.1.2 Worker Selection Rules

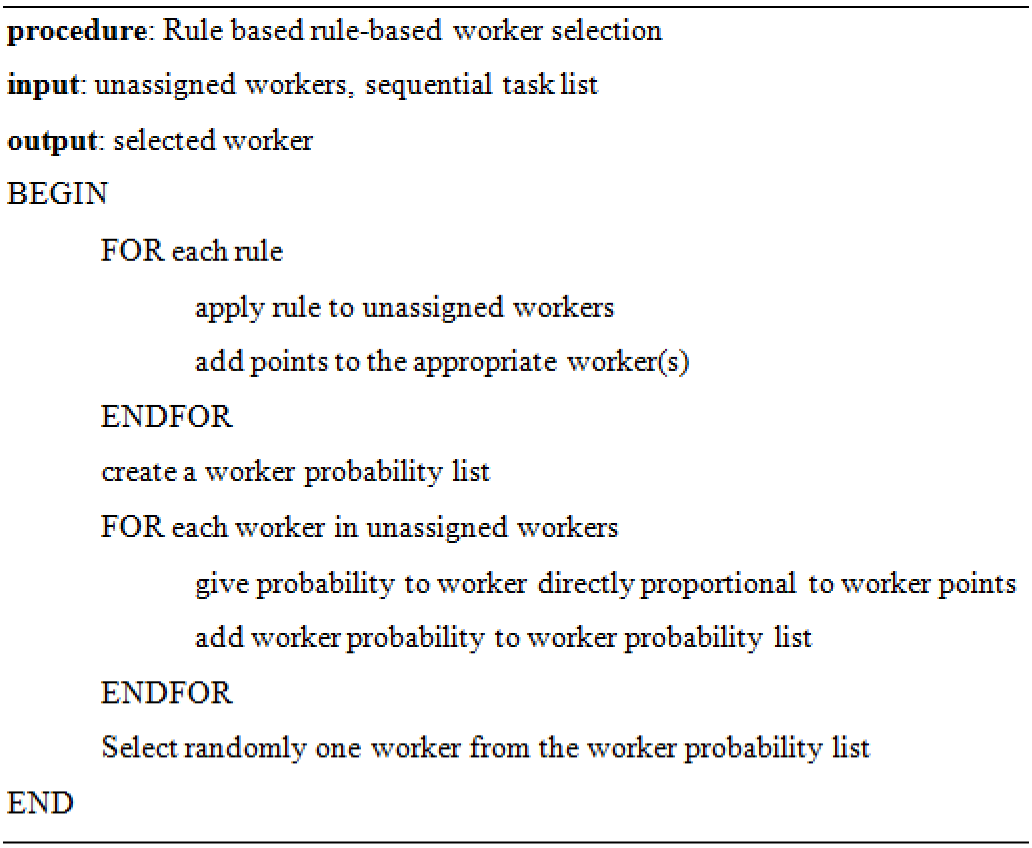
4 worker priority rules are applied in this study:

1. Greatest Number of Tasks can be Executed (GNTE), $\sum N_i$
2. Greatest Number of Tasks can be Executed in Minimum Time (GNTEMT), $\sum$ ti / $\sum N_i$
3. Maximum Utilization (MU)
4. Random priority (R)

The idea of the first rule is to select a worker that can execute as many tasks as possible. Second rule seeks for a worker which executes maximum tasks within minimum station time. Third rule looks for the maximum utilization. Bu this rule, stations are maximally loaded and station times are close to the cycle time. Lastly, the fourth rule just randomly selects a worker.

After applying these rules, every single worker has his own worker point. Then, just like the task selection mechanism, the worker with the higher priority takes the higher selection probability. At last, a worker is selected randomly.

The pseudo code of the proposed rule-based worker selection mechanism is given in Figure 4.3.



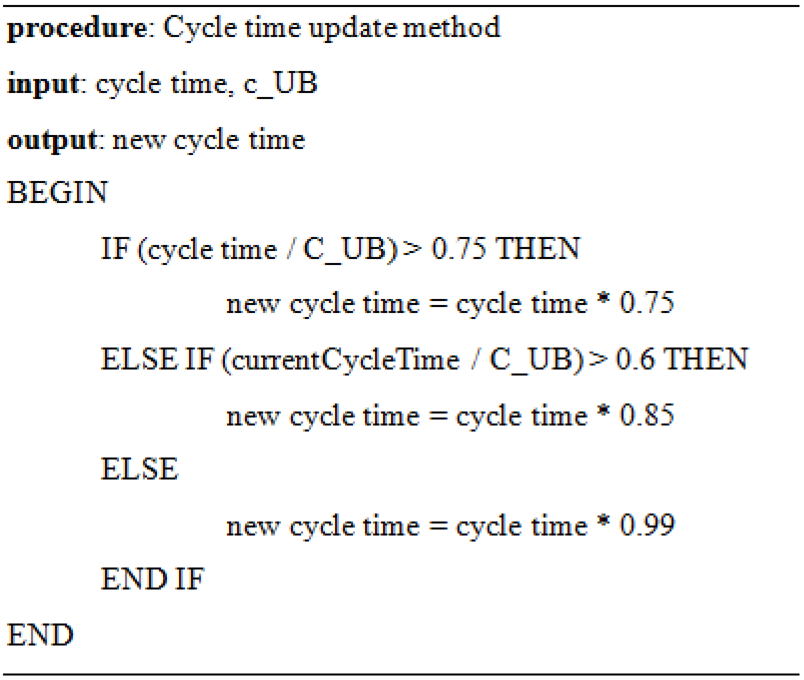
```
procedure: Rule based rule-based worker selection
input: unassigned workers, sequential task list
output: selected worker
BEGIN
    FOR each rule
        apply rule to unassigned workers
        add points to the appropriate worker(s)
    ENDFOR
    create a worker probability list
    FOR each worker in unassigned workers
        give probability to worker directly proportional to worker points
        add worker probability to worker probability list
    ENDFOR
    Select randomly one worker from the worker probability list
END
```

Figure 4.3 Pseudo code of the proposed rule-based worker selection algorithm

4.2.2 Cycle Time Update

The last shaded operation in flowchart of the proposed heuristic (Figure 4.1) is the cycle time update.

The pseudo code of the algorithm which is developed to update the cycle time properly is given in Figure 4.4.



```
procedure: Cycle time update method
input: cycle time, c_UB
output: new cycle time
BEGIN
        IF (cycle time / C_UB) > 0.75 THEN
                new cycle time = cycle time * 0.75
        ELSE IF (currentCycleTime / C_UB) > 0.6 THEN
                new cycle time = cycle time * 0.85
        ELSE
                new cycle time = cycle time * 0.99
        END IF
END
```

Figure 4.4 Pseudo code of the cycle time update algorithm

The idea of the above algorithm is to diminish cycle time by different coefficients. This is called inertia weight in the relevant literature which allows decreasing cycle time in a decreasing way. By decreasing cycle time dramatically, different locations of the search space are searched diversely at the beginning. But when the current cycle time is far away from the upper bound, it means that the best feasible solution (or may be the optimum solution) is near by the current solution. So, it is logical to decrease cycle time slightly to make and intensive search.

4.2.3 Illustrative Example

In order to explain the proposed approach more clearly, we give a simple numeric example. The task operation times per worker and precedence relations are given in Table 4.1 and Figure 4.5, respectively.

Table 4.1 Task execution times per worker

	Worker		
Task	1	2	3
1	8	6	10
2	-	20	22
3	10	-	30
4	-	20	15
5	8	6	-
6	22	32	42
7	25	20	30
8	30	25	15

As it can be seen from Table 4.1, there are some task-worker incompatibles, i.e., worker 1 cannot execute tasks 2 & 4, worker 2 is incompatible with task 3 and worker 3 cannot operate task 5. Also, numbers in the table are the operation times of tasks according to the corresponding worker, such as task 1 has an execution time of 8, 6 & 10 seconds when workers 1, 2 & 3 executes the task, respectively.

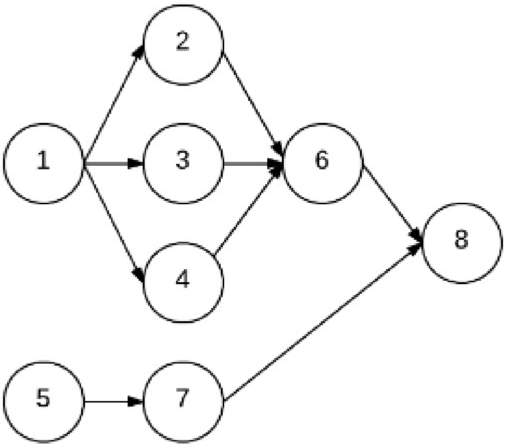


Figure 4.5 Precedence relations of the numeric example

The numbers inside nodes are the task numbers in Figure 4.5. According to the figure, task 1 has to be completed to execute tasks 2, 3 or 4. Also, task 6 cannot be started until tasks 2, 3 and 4 finished.

We calculate the cycle time values by the equations (4.1) – (4.4):

$$c_{UB} = \max\left\{\sum \frac{maxt_{ij}}{w}, max\{t_{ij}\}\right\} = \max\{64{,}42\} = 64$$

$$c_{LB} = \min\left\{\sum \frac{mint_{ij}}{w}, min\{t_{ij}\}\right\} = \max\{38{,}22\} = 38$$

$$c_{avg} = \sum \frac{(avgt_{ij})}{w} = 51.3$$

$$c_{exp} = \frac{1}{6} * (c_{LB} + 4 * c_{avg} + c_{UB}) = 51.2$$

For the first iteration we set cycle time equal to the upper bound (c_{UB} = 64sec.).

At the beginning, according to the precedence relations there are 2 assignable tasks {1, 5}. We apply task priority rules to the candidate tasks. The prioritized values of the two candidates are listed in Table 4.2.

The bold and shaded parts are the superior ones for the corresponding rule. Among the all 39 rules, task 1 is superior for the 34 rules and task 5 is better for 11 rules. So, there will be a selection with the probabilities:

- Task 1 → p_1 = 34/(34+11) = 0.76
- Task 5 → p_5 = 11/(34+11) = 0.24

We pick a random number between [0,1] that is 0,65 which corresponds to the task 1. We put task 1 to the *sequential task list* as the first element. All workers can execute task 1 and the operation times of the workers 1, 2 & 3 are 8, 6 & 10, respectively. Now, tasks 2, 3, 4 and 5 are assignable. We apply the priority rules again for the new tasks adaptively and then select one of them randomly with considering the probabilities.

Table 4.2 The prioritized values of the candidate tasks

	Tasks				Tasks	
Rules	1	5		Rules	1	5
1	**10**	8		21	**6**	8
2	**6**	**6**		22	**0.83**	2.67
3	**8**	7		23	**1.17**	2.67
4	10	**8**		24	**1.00**	2.67
5	**6**	**6**		25	**2**	1
6	8	**7**		26	**0.86**	0.75
7	**3**	1		27	**1.33**	1.17
8	**5**	2		28	**1**	**1**
9	**0**	**0**		29	**1**	**1**
10	**0**	**0**		30	**1**	**1**
11	*			31	**4**	7
12	**1**	5		32	**6**	7
13	**154**	38		33	**5**	7
14	**88**	26		34	1.25	**0.29**
15	**121.83**	32		35	0.71	**0.29**
16	**25.67**	12.67		36	0.83	**0.29**
17	**20.31**	10.67		37	**2.50**	1.14
18	**14.67**	8.67		38	**0.86**	0.86
19	**5**	8		39	**1.33**	1
20	**7**	8				

Let the newly selected task be task number 5. Then, the sequential task list becomes {1, 5}. Note that worker 3 cannot execute task 5. So, at the end of the iteration if worker 3 is assigned to the current station, task 5 should be eliminated and not assigned to the station.

Through the iteration, we continue to select tasks according to the rule based method and update the station time. At the end, we obtain the results as shown in Table 4.3.

Table 4.3 Task-worker assignment for the first station

Task	1	5	3	7	2	4	6	8
Worker 1 - station time	8	18	26	51	X	X	-	-
Worker 2 - station time	6	12	X	32	52	**72**	-	-
Worker 3 - station time	10	X	40	-	62	**77**	**119**	-
Station	1	1	1	1	1	1	1	1

Table 4.3 represents task and worker assignments to the first station. First low shows the sequence of tasks, namely sequential task list. Rows 2, 3 and 4 illustrates the station times if worker 1, 2 or 3 selected, respectively. The sign 'X' represents that the current worker cannot execute the corresponding task and the '-' sign means that the current worker cannot operate relevant task because of the precedence relations.

Moreover, the bold and shaded numbers illustrate that the cycle time is exceeded. For instance, worker 2 cannot operate task 3 and because of this, he also cannot operate tasks 6 and 8; hence task 3 must be finished in order to operate tasks 6 and 8 according to the precedence graph shown in Figure 4.5. As a result, if worker 2 is selected for the first station, tasks 1, 5, 7 & 2 can be assigned to the station because of the cycle time constraint. If task 4 is assigned to station 1, then the station time will be 72 seconds which is greater than the current cycle time (64 seconds).

After presenting the above table, now one of the workers must be selected according to the worker priority rules which are explained in 4.2.1.2. The prioritized values of the unassigned workers are presented in Table 4.4.

Table 4.4 The prioritized values of the candidate workers

	Workers		
Rules	1	2	3
1	6	**7**	**7**
2	17.17	18.43	**23.43**
3	0.8	0.81	**0.97**
4	*		

According to the table workers 1 and 2 are superior for one rule and worker 3 is superior for three rules. So, the probabilities of selection of the workers are 0.2, 0.2

and 0.6 for workers 1, 2 and 3, respectively. Let the random number be 0.11, then worker 1 is selected for the first station. Tasks 1, 5, 3 & 7 and worker 1 are assigned to the station 1, for the first iteration. After assigning the first station, the whole process is repeated for the remaining stations. At the end of the first iteration an initial solution is obtained. Table 4.5 illustrates the solution obtained by the end of the first iteration.

Table 4.5 Initial solution of the numeric example

Task	1	5	3	7	2	4	6	8
Worker	1	1	1	1	3	3	2	2
Station	1	1	1	1	2	2	3	3
Operation time	8	10	8	25	22	15	32	25
Station time	8	16	26	**51**	22	**37**	32	**57**

It can be understood from Table 4.5 that tasks 1, 5, 3 & 7 and worker 1 are assigned to station 1; tasks 2 & 4 and worker 3 are assigned to station 2 and lastly, tasks 6 & 8 and worker 2 are assigned to station 3. Station times of the stations 1, 2 and 3 are 51, 37 and 57 respectively. Now the cycle time will be diminished according to the algorithm 3 and a new solution will be gathered by using new cycle time. This process will be continued until maximum iteration number, which is 1000 in our case, is achieved.

4.3 Application of the Proposed Solution Method to ALWABP

To evaluate and assess the quality of the proposed heuristic, we solve the ALWABP benchmark problems which are given in the assembly line balancing website (http://alb.mansci.de/). The proposed heuristic is implemented in Microsoft Visual Studio Premium 2012 C# version 11.0.1. The tests were run on a Core 2 Duo i7 2.2 GHz processor and 6 GB main memory running the Windows 7 operating system.

4.3.1 Computational Experiments

Benchmark data is generated from the corresponding SALBP benchmark data set (Chaves et al., 2007). Test instances are derived by using five experimental factors at a low and a high level. These factors are the number of tasks, the number of workers, the order strength, the variability of the task execution time, and the number of infeasible task-worker pairs. The details of these characteristics are given in Tables 4.6 & 4.7. Operation times of a task have uniform distribution within the interval [1, t_i], where t_i is the operation time of the task as defined by the SALBP instance when there is low variability. If the variability is high, then the interval becomes [1, t_i]. Moreover, the number task-worker incompatibilities is 10% and 20% on the low and the high variability, respectively.

There are 320 test instances which are grouped into four families: Heskia, Roszieg, Tonge and Wee-Mag. Each one of the families contains 80 instances. The main characteristics of each group of instances, such as number of tasks, number of workers and the order strength are presented in Table 4.6. The order strength (*OS*) of the precedence network which is an indicator for complexity of problem instances, measures the relative number of precedence relations in the precedence graph is formulated as follows:

$$OS = \text{the number of precedence relations} / [N^*(N - 1)] \qquad (4.5)$$

Table 4.6 Test instance characteristics

Family	Number of Tasks (N)	Number of Workers (W)	Order Strength (%) (OS)
Roszieg	25 (low)	4 (groups 1–4) or 6 (groups 5–8)	71.67 (high)
Heskia	28 (low)	4 (groups 1–4) or 7 (groups 5–8)	22.49 (low)
Tonge	70 (high)	10 (groups 1–4) or 17 (groups 5–8)	59.42 (high)
Wee-Mag	75 (high)	11 (groups 1–4) or 19 (groups 5–8)	22.67 (low)

There are 32 task groups that each of them contains 10 test instances. Each task group is defined by the family name and a number between 1 and 8. The remaining characteristics, such as relation between tasks and operators, variability of operation times, and percentage of task-worker incompatibilities are listed in Table 4.7.

Table 4.7 Test groups characteristics

Factor	Low	High
Relation between tasks and operators	1, 2, 3, 4	5, 6, 7, 8
Variability of operation times	1, 2, 5, 6	3, 4, 7, 8
Percentage of task-worker incompatibilities	1, 3, 5, 7	2, 4, 6, 8

Because the proposed algorithm is a heuristic method, in order to obtain accurate results we run every single instance 10 times (10 replications) for 1000 iterations. It means that we run our program for 3200 times and every run has a maximum iteration number of 1000.

4.3.2 Computational Results and Interpretation

The performance of the proposed rule based constructive randomized search (RBCRS) algorithm is compared with the relevant literature. Table 4.8 reports the detailed results of the comparison of our proposed algorithm to the relevant literature. The first column represents the benchmark data family, while the second one represents the group number of that family. As it is stated previously, each family group consists of 10 instances, so the table shows the average results of 10 instances for each group of each family. The third column reports the optimum results found so far in the relevant literature under no running time constraints. The rest of the columns represent the referred papers and their solution techniques and results. Chaves et al. (2009) developed an iterated local search (ILS) algorithm and clustering search (CS) method. Moreira & Costa (2009) solved the ALWABP-2 problem via tabu search (TS) technique. Blum & Miralles (2011) used an iterated beam search (IBS) methodology. Moreira et al. (2012) and Mutlu et al. (2013) proposed a hybrid genetic algorithm (HGA) and an iterative genetic algorithm (IGA), respectively. Borba & Ritt (2014) compare two different techniques: interval probabilistic beam search (IPBS) and branch and bound (BB). Lastly, Vila & Pereira (2014) proposed a branch and bound and remember algorithm (BB&R)

Table 4.8 Comparison of the proposed RBCRS approach to the relevant literature

Family	Group	Opt.	Demirkol Akyol & Baykasoğlu		Chaves, Lorena & Miralles (2009)				Moreira & Costa (2009)		Blum & Miralles (2011)		Moreira, Ritt, Costa & Chaves (2012)		Mutlu, Polat & Supçiller (2013)		Borba & Ritt (2014)			Vila & Pereira (2014)		
			RBCRS		ILS		CS		TS		IBS		HGA		IGA		IPBS		BB	BB&R 60s	BB&R 600s	BB&R no time limit
			best	avg.	best	avg.	best	avg.	best	avg.	best	avg.	best	avg.	best	avg.	best	avg.	best	best	best	best
Roszieg	1	20.1	**16.1**	**16.1**	20.1	20.4	20.1	20.2	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1
	2	31.5	**16.8**	**16.8**	32.4	38.9	31.5	32.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5
	3	28.1	**24.5**	**24.5**	28.2	28.7	28.1	28.5	28.1	28.1	28.1	28.1	28.1	28.1	28.1	28.1	28.1	28.1	28.1	28.1	28.1	28.1
	4	28.0	**25.5**	**25.5**	28.0	28.1	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0	28.0
	5	9.7	**8.2**	**8.2**	10.3	11.8	9.7	10.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7
	6	11.0	**9.3**	**9.3**	11.5	14.3	11.0	12.1	11.0	11.0	11.0	11.0	11.1	11.1	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
	7	16.0	**13.4**	**13.4**	16.5	18.7	16.0	16.9	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
	8	15.1	**12.7**	**12.7**	15.3	17.7	15.1	15.6	15.1	15.2	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
	avg.	19.9	**15.8**	**15.8**	20.3	22.3	19.9	20.6	19.9	20.0	19.9	19.9	20.0	20.0	19.9	19.9	19.9	19.9	19.9	19.9	19.9	19.9
Heskiea	1	102.3	**99.4**	**99.4**	102.3	103.0	102.3	102.8	102.3	102.8	102.3	102.3	102.3	102.3	102.3	102.3	102.3	102.3	102.3	102.3	102.3	102.3
	2	122.6	**111.9**	**111.9**	122.7	124.2	122.6	123.8	122.6	122.8	122.6	122.6	122.7	122.7	122.6	122.6	122.6	122.6	122.6	122.6	122.6	122.6
	3	172.5	**172.5**	**172.5**	172.6	176.4	**172.5**	**175.5**	**172.5**	172.6	**172.5**	**172.5**	**172.5**	**172.5**	**172.5**	**172.5**	**172.5**	**172.5**	**172.5**	**172.5**	**172.5**	**172.5**
	4	171.2	**160.7**	**160.7**	171.3	171.8	171.2	171.7	171.2	171.8	171.2	171.2	171.2	171.7	171.2	171.3	171.2	171.3	171.2	171.2	171.2	171.2
	5	34.9	**34.5**	**34.5**	35.3	38.6	34.9	37.8	35.0	36.8	34.9	34.9	34.9	35.1	34.9	34.9	34.9	34.9	34.9	34.9	34.9	34.9
	6	42.6	**39.7**	**39.7**	43.6	45.7	42.6	44.7	43.1	44.6	42.6	42.6	42.6	42.8	42.6	42.6	42.7	42.8	42.7	42.7	42.7	42.7
	7	75.2	**74.2**	**74.2**	76.7	78.6	75.2	77.7	75.2	76.6	75.2	75.2	75.2	75.4	75.2	75.2	75.2	75.2	75.2	75.2	75.2	75.2
	8	67.2	**67.2**	**67.2**	68.1	72.4	67.2	70.7	67.3	68.4	67.2	67.2	67.2	67.6	67.2	67.2	67.2	67.2	67.2	67.2	67.2	67.2
	avg.	98.6	**95.0**	**95.0**	99.1	101.3	98.6	100.6	98.7	99.6	98.6	98.6	98.6	98.8	98.6	98.6	98.6	98.6	98.6	98.6	98.6	98.6

Table 4.8 Comparison of the proposed RBCRS approach to the relevant literature (Continue)

Family	Group	Opt.	Demirkol Akyol & Baykasoğlu		Chaves, Lorena & Miralles (2009)				Moreira & Costa (2009)		Blum & Miralles (2011)		Moreira, Ritt, Costa & Chaves (2012)		Mutlu, Polat & Supçiller (2013)		Borba & Ritt (2014)			Vila & Pereira (2014)		
			RBCRS		ILS		CS		TS		IBS		HGA		IGA		IPBS		BB	BB&R 60s	BB&R 600s	BB&R no time limit
			best	avg.	best	avg.	best	avg.	best	avg.	best	avg.	best	avg.	best	avg.	best	avg.	best	best	best	best
Tonge	1	90.6	**90.6**	**90.6**	120.0	135.3	96.7	116.6	100.1	108.3	94.9	96.7	92.8	95.9	93.0	94.1	91.3	92.2	**90.6**	**90.6**	**90.6**	**90.6**
	2	106.7	**106.7**	**106.7**	151.8	174.8	116.0	141.8	117.7	128.0	110.2	111.5	109.3	111.2	109.3	110.2	107.8	109.1	**106.7**	**106.7**	**106.7**	**106.7**
	3	159.3	**159.3**	**159.3**	214.6	236.5	167.7	199.4	171.5	187.4	165.0	168.0	162.2	166.3	162.4	165.2	160.8	161.7	**159.3**	160.3	**159.3**	**159.3**
	4	163.9	**160.7**	**160.7**	220.7	244.3	174.0	206.0	178.3	194.1	170.0	171.4	168.4	171.0	168.4	170.1	165.9	167.5	163.9	165.9	163.9	163.9
	5	31.6	**31.6**	**31.6**	64.2	71.1	41.3	51.3	41.7	47.6	33.1	34.2	34.1	35.2	33.1	33.1	32.2	32.5	**31.6**	31.8	31.7	31.7
	6	36.9	**36.9**	**36.9**	74.2	87.4	48.5	61.6	47.7	57.6	40.0	41.0	40.2	42.0	40.1	40.4	38.9	39.4	**36.9**	37.1	**36.9**	**36.9**
	7	63.2	**63.2**	**63.2**	113.7	129.3	77.8	93.0	75.5	82.1	66.4	67.9	66.6	69.6	66.4	66.4	64.5	64.9	63.4	63.9	63.2	63.2
	8	61.2	**61.2**	**61.2**	116.1	131.3	77.9	95.6	75.8	86.1	64.7	66.6	65.8	67.5	64.6	64.8	63.1	63.9	**61.2**	62.0	**61.2**	**61.2**
	avg.	89.2	**88.8**	**88.8**	134.4	151.3	100.0	120.7	101.0	111.4	93.0	94.7	92.4	94.8	92.2	93.0	90.6	91.4	89.2	89.8	89.2	89.2
Wee-Mag	1	26.1	43.0	43.0	31.2	35.5	29.0	32.7	35.3	38.4	28.7	29.7	26.7	27.8	26.7	27.4	27.1	27.6	26.8	26.6	**26.1**	**26.1**
	2	31.2	49.8	49.8	37.4	41.0	34.6	38.4	41.1	45.3	33.6	34.9	32.2	33.5	32.3	32.7	32.1	32.6	32.2	31.7	**31.2**	**31.2**
	3	45.8	78.6	78.6	54.3	61.3	50.8	56.7	58.4	64.8	50.1	51.6	47.6	49.9	47.6	48.2	47.5	48.4	47.5	46.6	46.1	45.8
	4	44.3	77.9	77.9	52.7	58.9	49.6	55.6	56.1	61.3	48.6	50.1	45.6	47.8	45.8	46.0	45.4	46.2	45.2	44.8	**44.3**	**44.3**
	5	9.6	15.0	15.0	16.7	45.4	13.1	20.9	19.9	23.8	10.3	10.7	10.5	11.1	10.3	10.4	9.9	10.0	9.9	9.8	**9.6**	**9.6**
	6	11.2	19.4	19.4	18.7	23.7	14.6	18.2	23.3	28.6	11.9	12.4	12.3	12.9	12.1	12.1	11.4	11.6	11.4	**11.2**	**11.2**	**11.2**
	7	17.1	26.9	26.9	25.1	31.1	21.2	27.1	32.6	39.2	18.2	19.0	18.6	19.7	18.2	18.5	17.7	17.9	17.6	17.4	17.2	17.2
	8	17.2	27.0	27.0	24.9	33.7	21.6	26.8	31.7	39.1	18.1	18.9	18.4	19.3	18.0	18.4	17.7	17.7	17.6	17.4	**17.2**	**17.2**
	avg.	25.3	42.2	42.2	32.6	41.3	29.3	34.6	37.3	42.6	27.4	28.4	26.5	27.8	26.4	26.7	26.1	26.5	26.0	25.7	25.4	25.3

with three cases: a time limit of 60 seconds, a time limit of 600 seconds, and without any time limit.

The results show that, our proposed RBCRS algorithm is superior to the all other techniques in general, but a detailed examination may indicate the following findings:

- We obtain the best results for the 75% of the 320 test instances for the ALWABP-2.

- For the Roszieg family, we report the best feasible solutions for all of the test instances. None of the referred papers have found results close to ours yet.

- For the Heskia family, we obtain the very best results for 87.5% of the 80 test instances. Except the group number 3, we report the minimum cycle time values; and for group 3 we found the best solution found so far in the relevant literature.

- For the Tonge family, we report the minimum cycle time value that have ever found for the group number 4; and for the rest of the family we obtain the best values found so far in the recent literature. As it can be seen from Table 4.8, only the last two references could have report the best values for some of the test groups. Except our algorithm, none of the above methods can get optimum solutions for all Tonge groups.

- We could not obtain the best results for the Wee-Mag family. This is only defect of our proposed algorithm.

4.4 Application of the Proposed Solution Method to ALWABP with Ergonomic Risk Factors

We solve ALWABP-2 benchmark data and show that our proposed RBCRS algorithm works very well, in the previous subsection. Now, we consider ergonomic risk factors in ALWABP-2. In the relevant literature there is no attempt to assess ergonomic risk factors and evaluate ergonomic conditions in ALWABP environment. We call this new problem as ErgoALWABP. Our proposed problem and solution technique is pioneer at this research area. So, this is our contribution to the literature.

We update our proposed solution method to evaluate ergonomic risk factors in the assembly line. The flowchart of this new version of our proposed heuristic is given in Figure 4.6. The figure looks like same as Figure 4.1 which illustrates the proposed heuristic without taking into account ergonomics, at the first glance. However, this new method is different at some points. First of all, Figure 4.6 states that, when a feasible solution is found, then OCRA indexes of all stations must be calculated (see section 3.4). Then, according to these OCRA indexes a preemptive goal programming approach, which is explained in 4.3.1 is applied. Because the problem is multi-objective, the preemptive goal programming gives us the best feasible solution by considering the predefined objectives.

4.4.1 Fitness Evaluation by Preemptive Goal Programming

There are many objectives in the proposed problem, ALWABP-2 with ergonomic risk factors, such as: minimizing cycle time, minimizing number of red stations, minimizing average red OCRA index, mean absolute deviation (mad) of all stations' OCRA indexes, average of all stations' OCRA indexes.

In this study, we solve classical ALWABP-2 with considering ergonomic risk factors. Since there is no relevant work in the literature that studying ergonomic conditions in ALWABP, we have no recent reference to compare our results.

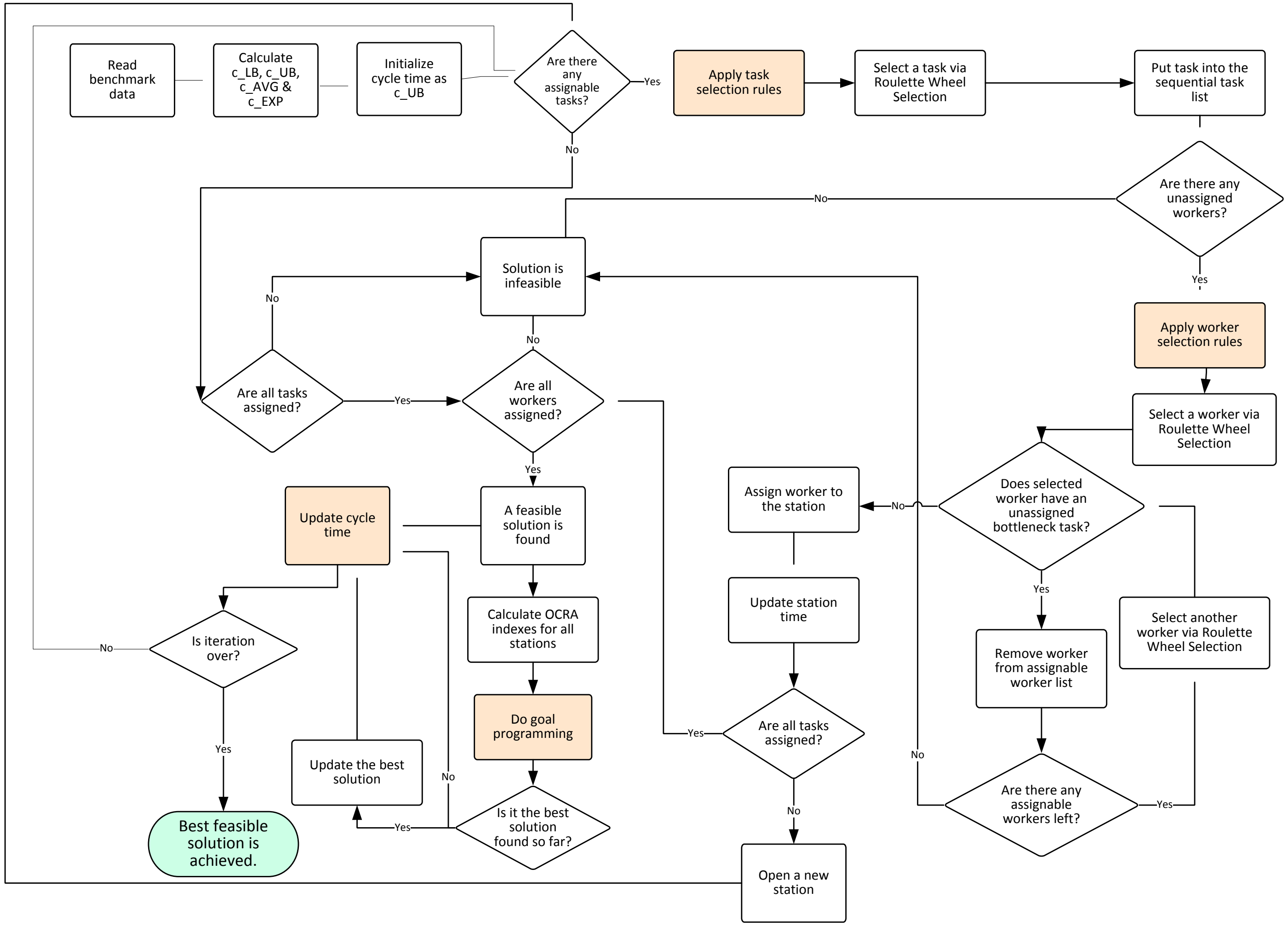


Figure 4.6 Flowchart of the proposed heuristic for the ALWABP-2 with considering ergonomic risk factors

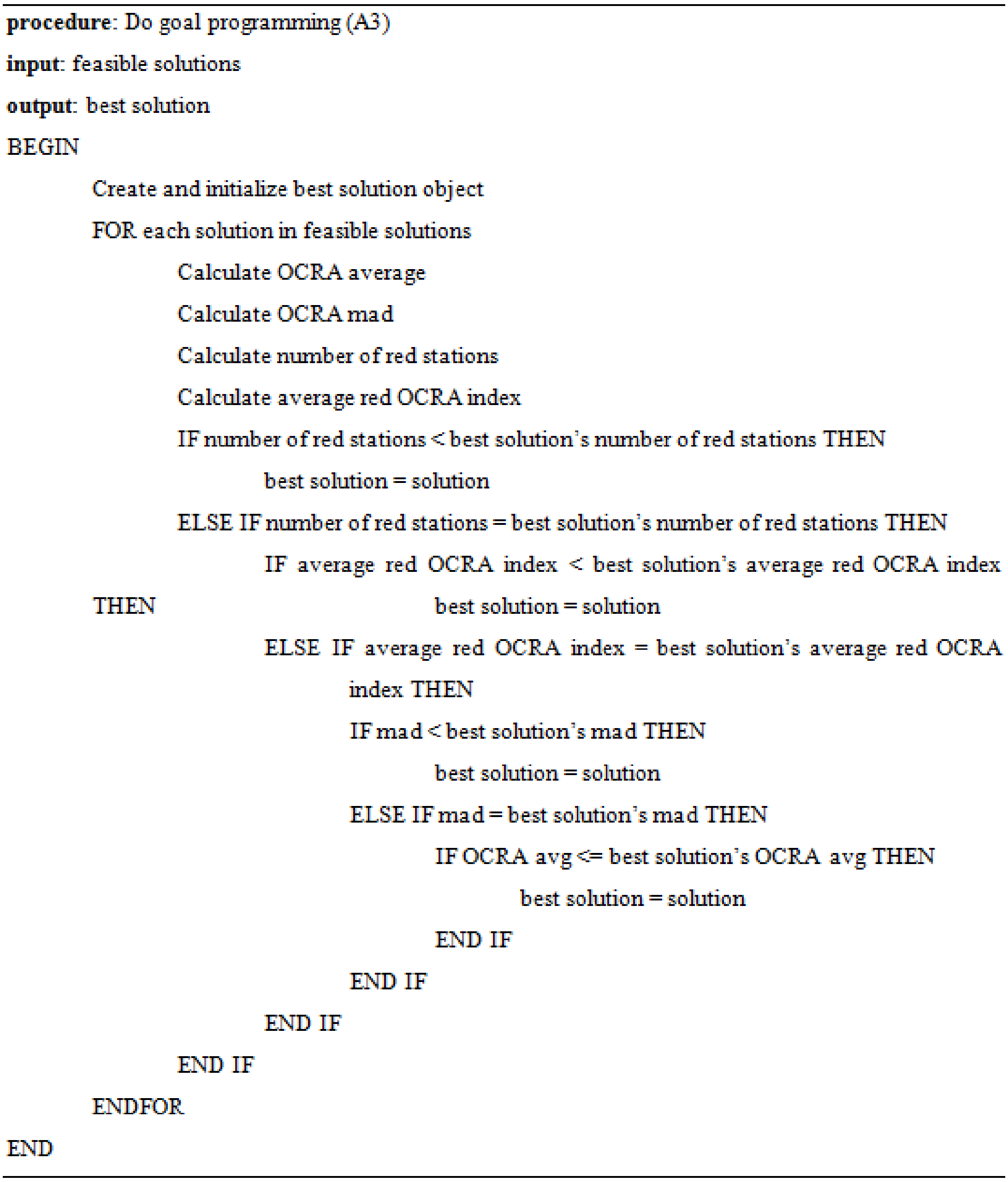
So, in order to make a meaningful comparison we develop a methodology. First, we solve the classical ALWABP-2 without taking into account any ergonomic conditions. Then, we solve the same test instance with considering ergonomic risk factors. We evaluate new solution via preemptive goal programming approach. We make preferences among above mentioned objectives and put them in order. By this order of objectives, we decide the current feasible solution is the best one or not. We inspired this methodology from Baykasoğlu (2005).

The pseudo code of the preemptive goal programming algorithm is given in Figure 4.7. Note that the primary objective is the number of red stations. If current solution has a smaller number of red stations than the best solution, then best solution is updated. In case of equality between two solutions, the secondary objectives are evaluated. The secondary objective is the average of red stations' OCRA indexes. If both of the primary and secondary objectives of the current solution are better than the best solution, or primary objectives are equal but current solution's secondary objective is better, then best solution is updated. Third and fourth objectives are mean absolute deviation (mad) of all stations' OCRA indexes ($\mathrm{OCRA}_{\mathrm{mad}}$) and average of all stations' OCRA indexes, respectively. The whole procedure is same as the process that is explained for the first two objectives.

Mean absolute deviation of all stations' OCRA indexes is calculated as follows:

$$\mathrm{OCRA}_{\mathrm{mad}} = \sqrt{\frac{\left(\mathrm{OCRA}_{\mathrm{avg}} - \mathrm{OCRA}_{\mathrm{station}}\right)^2}{K-1}} \tag{4.6}$$

where $\mathrm{OCRA}_{\mathrm{avg}}$ and $\mathrm{OCRA}_{\mathrm{station}}$ are the average of all stations' OCRA values and the OCRA value of the current station, respectively; and K refers to total number of workstations. The idea of setting $\mathrm{OCRA}_{\mathrm{mad}}$ as third objective is to smooth workload between workers in terms of ergonomic risks. In classical assembly line literature, one of the most important performance criteria is smoothing the workload among the work stations as equal as possible. However, in such studies, only the operation times of tasks is considered to calculate workload. In other words, the assignment of workload to the workstations is based purely on task times and the degree of difficulty of tasks for workers is ignored. But, in real life assembly systems, unfavorable working conditions are also important and the control of ergonomic risk factors among workstations is vital. To overcome this gap, we propose OCRA$_{mad}$ as third objective.



```
procedure: Do goal programming (A3)
input: feasible solutions
output: best solution
BEGIN
    Create and initialize best solution object
    FOR each solution in feasible solutions
        Calculate OCRA average
        Calculate OCRA mad
        Calculate number of red stations
        Calculate average red OCRA index
        IF number of red stations < best solution's number of red stations THEN
            best solution = solution
        ELSE IF number of red stations = best solution's number of red stations THEN
            IF average red OCRA index < best solution's average red OCRA index THEN
                    best solution = solution
            ELSE IF average red OCRA index = best solution's average red OCRA index THEN
                IF mad < best solution's mad THEN
                    best solution = solution
                ELSE IF mad = best solution's mad THEN
                    IF OCRA avg <= best solution's OCRA avg THEN
                        best solution = solution
                    END IF
                END IF
            END IF
        END IF
    ENDFOR
END
```

Figure 4.7 Pseudo code of the proposed preemptive goal programming algorithm

Some examples are given in the following to clarify this process.

Best feasible solution so far:		Current feasible solution:		Decision:
{7, 4.9, 1.4, 4.1}	→	{5, 5.2, 1.6, 3.9}	→	ACCEPT
{8, 5.9, 2.3, 5.1}	→	{7, 6.2, 2.4, 5.3}	→	ACCEPT
{3, 8.6, 3.4, 6.5}	→	{3, 5.9, 2.1, 5.2}	→	ACCEPT
{4, 3.9, 1.6, 2.9}	→	{4, 3.9, 1.6, 2.5}	→	ACCEPT
{6, 4.2, 2.3, 3.8}	→	{6, 4.9, 2.1, 4.1}	→	REJECT
{4, 3.8, 2.1, 3.2}	→	{4, 3.8, 2.1, 3.3}	→	REJECT

At first two examples, numbers of red stations are decreased in the current feasible solutions. So, there is no need to look into other objectives. We accept the current solution as the best solution. Example three illustrates that number of red stations are equal, but current solution's average of red stations' OCRA indexes value is smaller than the best. Then, current solution is accepted. At example four, only the last objective, average OCRA index value is smaller in current solution and the current solution is accepted. The last two examples are rejected. Example five illustrates the situation that the numbers of red OCRA stations are equal, but the current solution's average is greater. And in the last one, last objective value is higher in current solution. So, the best solution found so far is not updated in the last two examples.

4.4.2 Computational Experiments

In order to calculate OCRA index we use ergonomic parameters which are introduced by Otto & Scholl (2011). The benchmark ErgoALBP data is generated for SALBP-1 which are given in assembly line balancing website (Scholl, 1999).

For each SALBP-1 task in each instance, parameters such as frequency of actions, posture, force, repetitive actions and additional factors are generated. Moreover, in order to simplify the ergonomic analysis ErgoALBP data assume that all tasks imply symmetric operations for both hands. Hence, it is adequate to control OCRA index for only one of the upper limbs.

There are 27 replications of ergonomic parameters for every SALBP-1 benchmark data test instance in the literature. Since our proposed problem is ALWABP-2, we consider only Roszieg, Heskia, Tonge and Wee-Mag families. Also, because of the fact that each family has 80 test instances (320 instances totally), it is impossible to evaluate every ergonomic parameter set for each ALWABP test instances. As a remedy, we generate random data between [1, 27] and select three different ergonomic parameter set for each test instance. We run each problem for 1000 iterations and 10 replications. In total, we run our proposed RBCRS algorithm for 9600 (320*3*10) times.

4.4.3 Computational Results and Interpretation

Since our proposed ALWABP-2 considering ergonomic conditions is pioneer in the relevant literature, there is no any other study that we can compare with. In order to make a meaningful comparison, at first we solve pure ALWABP-2. Then, we take into account the ergonomic risk factors and we solve the same ALWABP-2 test instance for three different ErgoALBP data. By this way, we show that how much we can improve ergonomic conditions at the expense of increasing some amount of cycle time.

Table 4.9 reports the detailed results of the comparison of our RBCRS algorithm for the proposed problem, ErgoALWABP-2. The first column shows the benchmark ALWABP data family. The second column divides the results into two parts: better cycle time and better OCRA values. Better cycle time part illustrates the case without considering any ergonomic factors and just focusing on reducing the cycle time. In this case, we simply solve the ALWABP-2 test instance and then calculate and report the OCRA values.

Table 4.9 Comparison of the proposed RBCRS approach for the ErgoALWABP-2

Family			group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.
Roszieg	Better Cycle Time	Nr of green stations	1	0.82	2	1.56	3	1.51	4	2.00	5	1.39	6	1.63	7	1.73	8	1.89
Roszieg		Nr of yellow stations		1.61		1.35		1.78		1.67		1.58		1.55		2.12		1.91
Roszieg		Nr of red stations		1.56		1.10		0.72		0.33		3.03		2.82		2.15		2.20
Roszieg		Avg. red OCRA Index		4.72		4.36		3.74		2.60		5.06		5.04		4.63		4.79
Roszieg		OCRA mad		1.17		1.10		0.73		0.70		1.64		1.63		1.30		1.38
Roszieg		Avg. OCRA Index		3.39		2.78		2.61		2.39		3.62		3.49		3.14		3.13
Roszieg		Cycle time		16.10		16.80		24.50		25.50		8.20		9.30		12.70		13.09
Roszieg		Cpu time		1.31		1.30		1.57		1.16		2.01		2.62		3.02		2.85
Roszieg		*****************		****		****		****		****		****		****		****		****
Roszieg	Better OCRA values	Nr of green stations		0.77		1.53		1.41		1.77		1.31		1.61		1.77		1.69
Roszieg		Nr of yellow stations		2.48		2.22		2.37		2.14		2.70		2.49		3.28		3.18
Roszieg		Nr of red stations		0.74		0.25		0.22		0.09		1.99		1.90		0.95		1.12
Roszieg		Avg. red OCRA Index		3.88		2.05		1.97		0.92		5.21		5.43		4.34		4.53
Roszieg		OCRA mad		0.80		0.80		0.65		0.75		1.50		1.62		0.96		1.02
Roszieg		Avg. OCRA Index		2.94		2.42		2.46		2.31		3.36		3.28		2.76		2.83
Roszieg		Cycle time		20.71		23.45		32.68		33.22		11.13		12.32		17.87		17.12
Roszieg		Total cpu time		4.66		4.76		4.29		4.21		6.64		6.99		7.27		6.80
Family			group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.
Heskia	Better Cycle Time	Nr of green stations	1	0.91	2	0.81	3	0.71	4	0.95	5	3.30	6	3.60	7	3.40	8	3.30
Heskia		Nr of yellow stations		0.66		0.84		1.55		1.54		2.20		1.94		1.95		2.36
Heskia		Nr of red stations		2.44		2.36		1.74		1.51		1.50		1.46		1.65		1.34
Heskia		Avg. red OCRA Index		5.08		5.63		4.49		4.67		4.44		4.66		4.67		4.52
Heskia		OCRA mad		1.61		1.91		1.00		1.10		1.28		1.37		1.35		1.23
Heskia		Avg. OCRA Index		3.87		4.20		3.49		3.34		2.44		2.42		2.51		2.47
Heskia		Cycle time		99.40		111.90		172.50		160.70		34.50		39.70		74.20		67.20
Heskia		Cpu time		3.69		4.13		5.23		5.30		11.87		12.64		7.47		6.93

Table 4.9 Comparison of the proposed RBCRS approach for the ErgoALWABP-2 (Continue)

Heskia		*****************		****		****		****		****		****		****		****		****
Heskia		Nr of green stations		0.75		0.61		0.72		0.81		3.13		3.30		3.11		2.97
Heskia		Nr of yellow stations		1.66		1.71		2.28		2.24		3.11		2.96		3.11		3.41
Heskia		Nr of red stations		1.59		1.69		1.00		0.95		0.76		0.74		0.78		0.62
Heskia	Better OCRA values	Avg. red OCRA Index	1	5.64	2	5.62	3	4.10	4	4.17	5	4.35	6	4.33	7	4.57	8	4.54
Heskia		OCRA mad		1.61		1.58		0.96		0.95		1.07		1.05		1.05		0.98
Heskia		Avg. OCRA Index		3.69		3.81		3.26		3.15		2.35		2.30		2.37		2.42
Heskia		Cycle time		134.48		156.32		221.53		219.91		43.32		47.31		86.43		79.72
Heskia		Total cpu time		5.80		7.04		9.18		8.27		21.56		21.85		21.69		13.12
Family			group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.
Tonge		Nr of green stations		1.29		1.41		1.06		1.16		6.30		6.48		6.13		6.19
Tonge		Nr of yellow stations		1.68		1.54		2.11		2.38		4.99		4.95		5.15		5.13
Tonge		Nr of red stations		7.03		7.05		6.83		6.46		5.71		5.56		5.72		5.67
Tonge	Better Cycle Time	Avg. red OCRA Index		5.35		5.45		5.43		5.06		4.98		4.98		5.05		4.91
Tonge		OCRA mad		1.83		1.96		1.86		1.53		1.82		1.77		1.91		1.66
Tonge		Avg. OCRA Index		4.43		4.48		4.46		4.13		3.01		2.95		3.04		2.98
Tonge		Cycle time		90.60		106.70		159.30		160.70		31.60		36.90		63.20		61.20
Tonge		Cpu time		76.56		135.25		107.99		106.16		311.08		494.05		361.70		376.43
Tonge		*****************	1	****	2	****	3	****	4	****	5	****	6	****	7	****	8	****
Tonge		Nr of green stations		1.49		1.40		1.30		1.32		6.14		6.01		5.89		6.04
Tonge		Nr of yellow stations		2.83		2.86		3.09		3.51		6.56		6.83		6.82		6.83
Tonge		Nr of red stations		5.68		5.74		5.60		5.18		4.30		4.15		4.29		4.12
Tonge	Better OCRA values	Avg. red OCRA Index		5.75		5.66		5.70		5.38		5.14		5.02		5.01		4.96
Tonge		OCRA mad		2.02		1.95		1.93		1.74		1.70		1.61		1.59		1.47
Tonge		Avg. OCRA Index		4.29		4.29		4.29		4.00		2.87		2.87		2.90		2.86
Tonge		Cycle time		137.07		126.49		198.60		209.08		44.59		49.29		93.82		85.65
Tonge		Total cpu time		187.38		217.04		185.56		186.04		612.14		852.38		851.31		767.02

Table 4.9 Comparison of the proposed RBCRS approach for the ErgoALWABP-2 (Continue)

Family			group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.	group	Avg.
Wee-Mag	Better Cycle Time	Nr of green stations	1	0.17	2	0.16	3	0.26	4	0.11	5	2.05	6	1.60	7	1.61	8	1.20
Wee-Mag		Nr of yellow stations		0.15		0.44		0.48		0.69		1.56		2.33		1.79		2.30
Wee-Mag		Nr of red stations		10.68		10.39		10.26		10.20		15.39		15.06		15.60		15.47
Wee-Mag		Avg. red OCRA Index		8.65		8.48		6.89		6.39		6.96		6.52		6.20		6.30
Wee-Mag		OCRA mad		3.11		3.15		2.26		2.24		3.04		2.54		2.36		2.45
Wee-Mag		Avg. OCRA Index		8.45		8.15		6.64		6.13		6.01		5.60		5.48		5.56
Wee-Mag		Cycle time		43.00		49.80		78.60		77.90		15.00		19.40		26.90		27.00
Wee-Mag		Cpu time		71.91		136.70		34.70		28.72		276.01		299.03		320.73		248.62
Wee-Mag		*****************		****		****		****		****		****		****		****		****
Wee-Mag	Better OCRA values	Nr of green stations		0.61		0.74		0.71		0.69		2.00		1.94		1.90		2.20
Wee-Mag		Nr of yellow stations		1.16		1.19		1.98		2.38		3.30		3.98		4.11		3.99
Wee-Mag		Nr of red stations		9.23		9.07		8.31		7.94		13.70		13.08		13.00		12.82
Wee-Mag		Avg. red OCRA Index		9.03		8.88		6.79		6.78		6.77		6.69		6.68		6.76
Wee-Mag		OCRA mad		3.50		3.55		2.39		2.55		2.76		2.91		2.71		2.66
Wee-Mag		Avg. OCRA Index		7.95		7.69		5.81		5.63		5.53		5.37		5.33		5.34
Wee-Mag		Cycle time		46.50		67.83		87.55		88.08		24.83		25.50		34.78		32.19
Wee-Mag		Total cpu time		283.69		294.83		163.31		185.09		918.14		821.64		942.91		669.05

As it is stated in 4.3.2, each family group consists of 10 instances, so the values given in the table are the average results of 10 instances for each group of each family. Better OCRA values part is the case which we include ergonomic parameters at the beginning and we apply proposed preemptive goal programming approach to improve ergonomic objectives. Third column lists the ergonomic objectives, such as number of green stations, number of yellow stations, number of red stations, average OCRA index of red stations, mean absolute deviation of stations' OCRA indexes, average OCRA index of all stations, and cycle time and CPU time values. Rest of the columns, list groups 1-8 and give average values of the corresponding objective for each family.

In order to explain more clearly, Table 4.10 reports the average improvement of the above comparison. The first two columns represent the benchmark ALWABP data family and related group, respectively. Rest of the columns except the last one, illustrate the average ergonomic improvement at the assembly line by considering ergonomic factors, in terms of number of green stations, number of yellow stations, number of red stations, average OCRA index of red stations, mean absolute deviation of stations' OCRA indexes and average OCRA index of all stations, respectively. The term "improvement" means an increment for number of green and yellow stations; and a decrement for number of red stations, average OCRA index of red stations, mad of stations' OCRA indexes, average OCRA index of all stations. Finally, the last column shows the required amount of cycle time increase in order to improve ergonomic conditions.

Note that among all of the ergonomic goals, our primary goal is to decrease the number of red stations (see 4.4.1). Because total number of stations, in other words workers, is fixed, decreasing number of red stations means increasing number of green and yellow stations. For instance, for the fifth group of the Roszieg family, number of red stations decreased by 34.52% (see Table 4.10), and the average number of red stations decreased from 3.03 to 1.99 (see Table 4.9). This is a pretty well improvement.

Table 4.10 Average improvement of the comparison of the proposed RBCRS approach for the ErgoALWABP-2

Family	Group	Average improvement to initial ALWABP2 solution (%)						Cycle time increase
		Number of green stations	Number of yellow stations	Number of red stations	Avg. red OCRA index	OCRA mad	Average OCRA index	
Roszieg	1	5.39	54.17	52.54	17.79	31.50	13.02	28.62
	2	1.74	65.13	77.38	52.85	26.93	13.22	39.57
	3	6.41	33.47	69.66	47.36	11.54	5.71	33.38
	4	11.66	28.13	71.63	64.75	6.64	3.38	30.28
	5	5.51	71.34	34.52	3.07	8.97	7.19	35.72
	6	1.13	60.53	32.58	7.55	0.57	5.99	32.42
	7	2.49	54.60	55.94	6.38	26.25	12.08	40.70
	8	10.28	66.98	49.12	5.42	26.34	9.50	30.73
Heskiea	1	17.44	152.85	34.71	11.15	0.18	4.73	35.29
	2	24.67	103.57	28.44	0.32	17.06	9.07	39.69
	3	2.14	46.92	42.59	8.75	3.85	6.59	28.42
	4	15.09	45.02	36.73	10.74	13.78	5.65	36.84
	5	5.30	41.48	49.02	2.05	16.67	4.07	25.57
	6	8.39	52.56	49.46	7.08	23.58	4.77	19.17
	7	8.50	59.17	52.56	2.08	21.88	5.38	16.49
	8	10.06	44.80	53.95	0.43	20.14	2.23	18.64
Tonge	1	15.47	68.37	19.18	7.37	10.61	3.03	51.30
	2	0.74	86.28	18.64	3.87	0.38	4.12	18.55
	3	22.32	46.79	17.92	5.08	3.31	3.69	24.67
	4	13.03	47.44	19.83	6.44	13.18	3.30	30.11
	5	2.48	31.53	24.80	3.03	6.30	4.59	41.12
	6	7.21	37.90	25.35	0.81	9.14	2.91	33.56
	7	4.06	32.52	24.95	0.68	17.11	4.86	48.45
	8	2.41	33.10	27.33	0.94	11.25	4.13	39.95
WeeMag	1	260.78	678.65	13.57	4.31	12.54	5.90	8.14
	2	356.90	168.13	12.72	4.78	12.72	5.58	36.21
	3	173.49	310.95	19.02	1.48	5.90	12.51	11.38
	4	513.43	247.45	22.23	6.16	14.21	8.06	13.06
	5	2.28	111.55	10.99	2.79	9.27	8.13	65.51
	6	20.99	70.66	13.17	2.57	14.89	4.17	31.44
	7	17.74	129.40	16.68	7.71	14.46	2.70	29.28
	8	82.27	73.23	17.12	7.32	8.71	4.04	19.22

Since total number of workstations is 6 for this test group, number of the green or yellow coloured stations must be increased. It is read from Table 4.10 that number of yellow stations is increased by 71.34% (increased from 1.58 to 2.7) and number of green stations is decreased by 5.51% (decreased from 1.39 to 1.31) in order to fix total number of stations to six. Mark that in both cases total number of green, yellow and red stations is six.

The shaded values in Table 4.10 illustrate situations that there is no improvement. Let's continue on the same example. For the Roszieg family group 5, number of green stations and average red OCRA index values are shaded. For this particular test group, to decrease number of red stations, a little decrement on the number of green stations is necessary. This is not a bad case in terms of ergonomic conditions, because more critical stations (red and yellow) are improved very well. Also, average of red stations' OCRA index is increased slightly (3.07%). In fact, decreasing this value is our secondary objective. But, sometimes when number of red stations decrease, their average OCRA index can increase according to the work load. Here average red OCRA index increases from 5.06 to 5.21 which is not very important. Much important thing is to reduce number of red stations. Moreover, there is a 35.72% cycle time increment to make these ergonomic improvements for this test group. Additionally, in some test groups mean absolute deviation of OCRA indexes ($OCRA_{mad}$) are increased instead of a decrease. Actually, in order to control deviation of ergonomic risks among stations, we want to decrease $OCRA_{mad}$. This is why it is our third objective. However, in some cases when number of red stations is decreased, corresponding $OCRA_{mad}$ value can be increase a little bit depending on the work load. This can be ignored in terms of ergonomic conditions, since decreasing the number of red stations is the primary objective.

The results show that, by using the proposed preemptive goal programming approach we generate solutions with better ergonomic conditions. A detailed examination of Tables 4.9 and 4.10 may indicate the following findings:

- We decrease number of red stations and average value of all stations' OCRA indexes while increasing number of yellow stations, at every group of each family. This means that we improve the ergonomic environment of the assembly line drastically. Note that the motivation of the ALWABP is to employ disabled workers, this is very important. Ergonomic conditions of the working environment is important for human health, but it is vital essential for disabled workers.

- Although we decrease the number of red stations dramatically, we couldn't eliminate all of them. It may be required to hire one more worker and open a new station to get rid of all red stations.

- In order to improve ergonomic conditions, we have to increase cycle time a little bit. So, break-even analysis must be done and the decision of improving ergonomic conditions or not must be made by evaluating financial factors.

4.5 Chapter Summary

Assembly line worker assignment and balancing problem (ALWABP) is a new type of line balancing problem which appears in real assembly lines, but has recently been popular in academic area. This problem occurs when operation times of tasks differs according to the operator. Although the operation time of a task is assumed to be fixed in classical ALBP, it depends on the operator who executes the task in ALWABP. Although ALWABP is a relatively new problem, it has attracted the scientists' interest. Many research studies have been made to solve ALWABP in recent years, but one optimum solution method cannot be found so far. Minimizing the cycle time is commonly used as a primary objective in ALWABP literature (ALWABP-2). Even traditional ALBP is NP-hard, this much more complex ALWABP-2 is NP-hard, of course. Because of the complex problem nature, optimum seeking methods are not capable of solving it. So, we proposed a rule based constructive randomized search (RBCRS) algorithm to solve ALWABP-2. In the proposed RBCRS heuristic, 39 task priority rules and 4 worker priority rules were used to sequence tasks and select workers. We tested our proposed method on ALWABP-2 benchmark data which consists of four families, each having 80 test instances, in order to evaluate the performance. We ran every test instance for 10 replications, and in total we execute our proposed heuristic for 3200 times. The results showed that our proposed algorithm outperforms all others in the relevant literature.

Though minimizing cycle time is the primary objective for ALWABP-2, it is not the only objective. In ALBP literature, secondary objective is generally to balance the workload between workstations smoothly, and only task times are taken into consideration when smoothing workload. However, the degree of difficulty of tasks is also very important. Two workers executing two different stations with the same station time are assumed to be equally loaded according to the traditional perception. In fact, even they have the same station time; their workloads are different because of the different tasks they execute, in real life assembly line configurations. In order to close this gap between the real life and the literature, we proposed an ALWABP problem with considering ergonomic risk factors (ErgoALWABP) and balance work stations in an ergonomic manner by making ergonomic risk assessment. We used OCRA index to calculate the ergonomic risk factors of the stations. By this way, the assignment of tasks to workers and workers to stations is performed by considering ergonomic risk factors. Since our proposed problem and solution technique is the first study in this research area, this is our contribution to the assembly line literature. Because there is no other study in this research area, we could not compare our results with other works. As a remedy, at first we solved pure ALWABP-2, then we considered ergonomic parameters and solved the same ALWABP-2 test instance for three different ErgoALBP data. We ran every test instance for 10 replications, and in total we execute our proposed RBCRS algorithm for 9600 (320*3*10) times. The results showed that by increasing cycle time slightly, we obtain significant improvement in ergonomic conditions.

CHAPTER FIVE
THE INDUSTRIAL APPLICATION

5.1 Introduction

The aim of this chapter is to apply the proposed rule based constructive randomized search algorithm in order to solve an industrial case. This study is supported by Ministry of Science, Industry and Technology of Turkey Republic for the research project numbered 1512.STZ.2012-2. The industrial case is presented at a harness production company which manufactures cable networks for automotive sector. The proposed problem is an over-constrained problem, so our rule based heuristic obtained satisfactory results for the company. The rest of this chapter is organized as follows. In section 5.2, the products and manufacturing environment of the company are presented. In section 5.3, the generalized assembly line problem occurred at the company is defined in detail. In section 5.4, the proposed heuristic is applied to solve the well defined problem. Finally, in section 5.5 the context of this chapter is summarized.

5.2 Presentation of the Company

The company studied in this chapter is established in 1997, in İzmir. It is a multi-national company, whose origin is USA, with a production volume of 10,687,235 hours/year. The company produces harness, namely cable network for automotive industry. In other words, the company under consideration is a supplier industry enterprise for automotive sector.

Harness is an integrated number of cables that transmits electricity from one point to another in order to enable some functions such as heating, air conditioning, listening to radio, security, etc. A cable network (harness) that is produced at the mentioned company is illustrated in Figure 5.1.

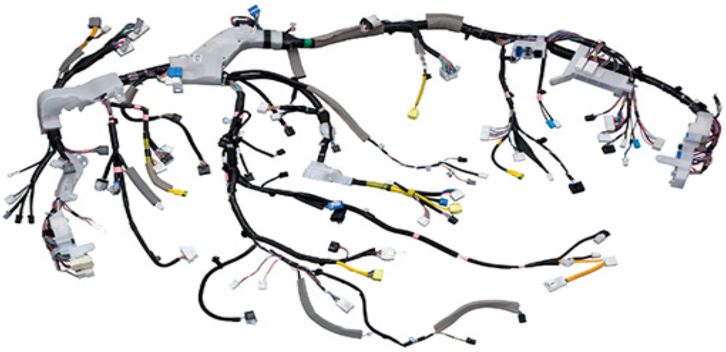


Figure 5.1 Cable network (Baykasoğlu et al., 2013)

Figure 5.2 represents the cable network of an automobile. The cable networks of the automobile looks like blood vessels of human body. Just like blood vessels transferring blood, harnesses also transmit electricity for automobiles.

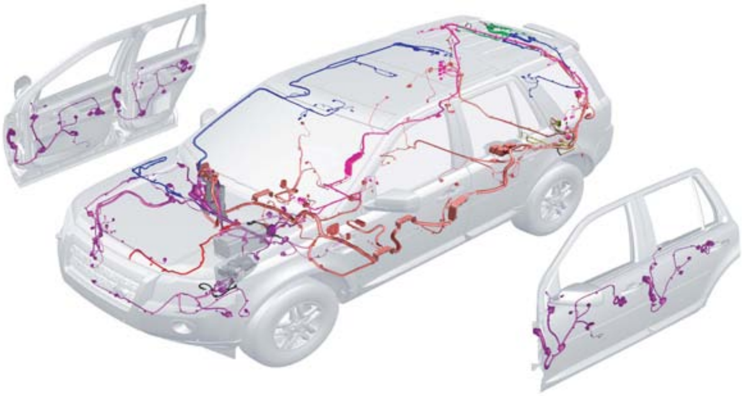


Figure 5.2 Cable network of an automobile (Baykasoğlu et al., 2013)

5.2.1 Literature Review on Harness Production

Harness production is one of the most complicated, difficult and time consuming assembly lines. Since it is quite hard to model a harness production system, there have not been many research studies presented about harness assembly lines. Moreover, many of the proposed studies are related to the design phase of a harness; they are not related to the production concept. The limited number of work that is discussed in literature is reviewed in this section.

Aguirre and Raucent (1994) compared the economic performances of different harness assembly techniques in order to enable the designer to make the right choice. They benchmarked the costs of manual method, semi-automatic method and robotized method with single and multiple robots; and concluded that it is appropriate to prefer manual method for low production volume and semi-automatic method for medium production. Simmons et al. (1998) applied virtual reality to harness production. They used a computer program in order to automate cable layout design. Jiang et al. (2010) proposed to use robots in harness production instead of workers. Since harness manufacturing operations are quiet complicated, it is difficult to replace them by robots. But, the authors implemented automatic assembly successfully with the prototype robot system.

As it can be understood from the above review, there isn't any research study to analyze assembly line manufacturing harness. The harness production in assembly line is only mentioned as a title such as, ‘n-sided’ assembly line, in a PhD study by Simaria (2006). The author only described the problem and did not make any analysis.

Therefore, the proposed industrial application is very important for the harness literature. Our study is the only one that balances a harness assembly line with considering ergonomic factors.

5.3 Definition of the Present Problem

The harness production company has two main production areas; cable cutting area and final assembly area. In cable cutting area, cables are cut according to defined length using general assignment which is independent from customer or product. After cutting operation, cut leads are distributed to related final assembly area to produce harness.

Assembly area contains sub assembly, assembly, post prep and test area. During manufacturing system design, operator assignment should be done by taking care of eliminating cross movements by station lay out and operational ergonomic constraints. Operational ergonomic constraints are defined. Operator assignment to stations is done according to upper and lower level groups in accordance with defined constraints. As a consequence, during operator assignment to stations assigning similar work elements to station will provide assigning correct operator to the correct station.

Start up of new products, product design change or customer demand change, drives new manufacturing system design or revision of present serial manufacturing design necessity. There is need for assign works to stations to assure productivity target by considering work priority alternatives, ergonomic factors and quality expectations in assembly area that has various models and variable demand. In present situation, this process is done manually by methods engineers, by considering all constraints and targets. Although all constraint and targets are considered, it is difficult to find an optimum result as all constraints and targets effect each other in different way.

In light of the foregoing, we analyze the problem occurred at the company separately. The problem is divided into three main problems which have to be solved simultaneously:

- Subassembly line balancing
- Main assembly line balancing
- Layout problem of stations of the two assembly lines in order to minimize transactions between two lines.

The layout of the subassembly and main assembly lines are illustrated in Figure 5.3. The straight line is the subassembly line that feeds the main assembly process. Subassemblies that are manufactured in Figure 5.3 are transported to the main line in order to form the final product.

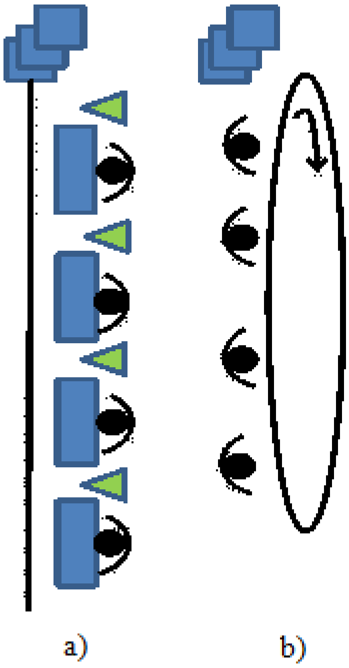


Figure 5.3 Layout of the subassembly and main assembly lines a) Subassembly line b) Main assembly line

It is decided to manufacture a task at the subassembly or main assembly lines, in production planning phase. After assigning tasks to the lines, both of the lines are balanced. Note that, since the subassembly line feeds the main line both lines have the same cycle time values which is 165.3 for this industrial case.

5.3.1 Balancing the Subassembly Line

There are some problem specific constraints additional to traditional ALBP constraints, such as:

- Positive / negative zoning constraints: There are some zoning constraints due to the problem nature. When some of the tasks have to be operated on the same station, some of them have to be executed in separate stations because of worker and/or requirements.

- Operator height constraint: According to the company's policy, there are three categories for operator height, A, B and C such that; A is the operators whose height is between 1.5 and 1.6 meters, B is the operators whose height is between 1.6 and 1.7 meters, C is the operators whose height is greater than 1.7 meters.

- Transactions between subassembly stations: Although the main concept of the subassembly line is to feed the main line, there are some transactions within subassembly lines which cannot be avoided due to the problem nature. But, company management requests to minimize these transactions in order to eliminate cross movements.

- Ergonomic constraint: Depending on long working hours and repetitive tasks with awkward postures, many operators suffer from musculoskeletal diseases especially at their hands and wrists. In order to prevent these diseases and their consequences, the ergonomic risk level of the workplace must be control properly.

5.3.2 Balancing the Main Assembly Line

All additional constraints of the main line is similar to the constraints of the subassembly line. But, there is one more constraint in this case as follows:

- Positive / negative zoning constraints
- Operator height constraint
- Transactions between subassembly stations
- Ergonomic constraint
- Assignment of the subassembly line tasks constraint: As it is illustrated in Figure 5.3, only one side of the main assembly line faces with the subassembly line. Thus, tasks that are transmitted from subassembly line must be operated at main assembly stations which are located on this side.

5.3.3 Layout Problem

This problem occurs due to the aim of minimizing total transactions between subassembly and main assembly lines and also within subassembly stations.

Layout problem is represented as Quadratic Assignment Problem (QAP) (Koopmans & Beckman, 1957), in the relevant literature. QAP basically assigns facilities to locations in order to minimize total transportation costs.

5.4 Proposed Solution Method

Since the defined problem is very complex and over constrained, we separate the problem into three parts above. Thus, we solve the ALBP and layout problem separately in the following.

5.4.1 Solution Procedure for Subassembly and Main Assembly Lines

There is not a situation that requires worker assignment in the proposed problem, because the only variable for workers is the operator height. The company management is assumed that task operation times are fixed and do not depend on the worker executing it.

Moreover, the concept of the problem is to design an assembly line for a new product model. This means that we have to balance the line from the beginning. There is no fixed number of workstations, and we know the cycle time of the line due to customer orders. Also, one homogeneous product is assembled in the line.

As it is defined in section 2.2, this is a typical SALBP–1. The notation used in SALBP–1 is given in Table 5.1.

Table 5.1 Notation used in ALWABP–2

i, r, s	Task
j	Workstation
C	Cycle time
$m_{\max}$	Maximum number of stations
n	Number of tasks
t_i	Operation time of task i
S	Set of precedence relations
x_{ij}	Binary variable equal to 1 only if task i is assigned to station j
z_j	Binary variable equal to 1 only if station j is opened

The mathematical programming model for the SALBP–1 can be stated as follows (Scholl, 1999):

Minimize $$\sum_{j=1}^{m_{\max}} z_j \tag{5.1}$$

Subject to

$$\sum_{j=1}^{m_{\max}} x_{ij} = 1 \qquad \forall i \tag{5.2}$$

$$\sum_{i=1}^{n} t_j \cdot x_{ij} \le C \cdot z_j \qquad \forall j \tag{5.3}$$

$$\sum_{j=1}^{m_{\max}} j\left(x_{rj} - x_{sj}\right) \le 0 \qquad \forall (r,s) \in S \tag{5.4}$$

$$x_{ij}, z_j \in \{0,1\} \tag{5.5}$$

The objective function given in (5.1) minimizes the number of workstations. The constraint given in (5.2) ensures that every task *i* is assigned to a single station *j*. The constraint given in (5.3) guarantees that each workstation’s station time cannot exceed the cycle time. The constraint given in (5.4) states the precedence relations between tasks *r* and *s*, where *r* is predecessor of *s*. The constraint given in (5.5) represents that decision variable *x* and *z* are binary variables.

Moreover, zoning constraints can be added as in the following, where ZP_{ij} and ZN_{ij} are positive and negative zoning relations, respectively. The constraint given in (5.6) states that tasks that have positive zoning have to be operated at the same workstation. The constraint given in (5.7) avoids executing incompatible tasks at the same station.

$$x_{ij} + M * \left(1 - \left(x_{ij} * ZP_{ij}\right)\right) \geq 1 \tag{5.6}$$

$$x_{ij} - M * \left(1 - \left(x_{ij} * ZN_{ij}\right)\right) \leq 0 \tag{5.7}$$

Also, ergonomic constraint must be added to the traditional SALBP–1 in order to represent the proposed problem. Since the problem addressed above is a labor intensive manual assembly line, and movement at the line is provided by a conveyor system; OCRA index is suitable to assess ergonomic risks of the workplace. One more constraint can be added to the model such as:

$$OCRA_i + d_i^- + d_i^+ = OCRA_{average} \tag{5.8}$$

Because the above mentioned problem is very complex and over constrained, it is not possible to solve it via mathematical programming. So, we use our proposed rule based constructive randomized search algorithm in order to solve this problem. Flowchart of the proposed heuristic is illustrated in Figure 5.4. Since the industrial application is a version of SALBP–1, there are a few changes with regard to the Figure 4.3 in Chapter 4, such as updating the number of workstations at every iteration. Additional to the Figure 4.3, zoning constraints are considered in this flowchart. Also, there are not any worker selection rules because all workers are assumed to be identical in terms of working performance. But, the operator height is a variable that should be considered. When assigning a worker to a station, it is checked that if the operator height is appropriate for the tasks assigned to that station or not. In Figure 5.4 the shaded operations represent algorithms which are explained in previous chapter.

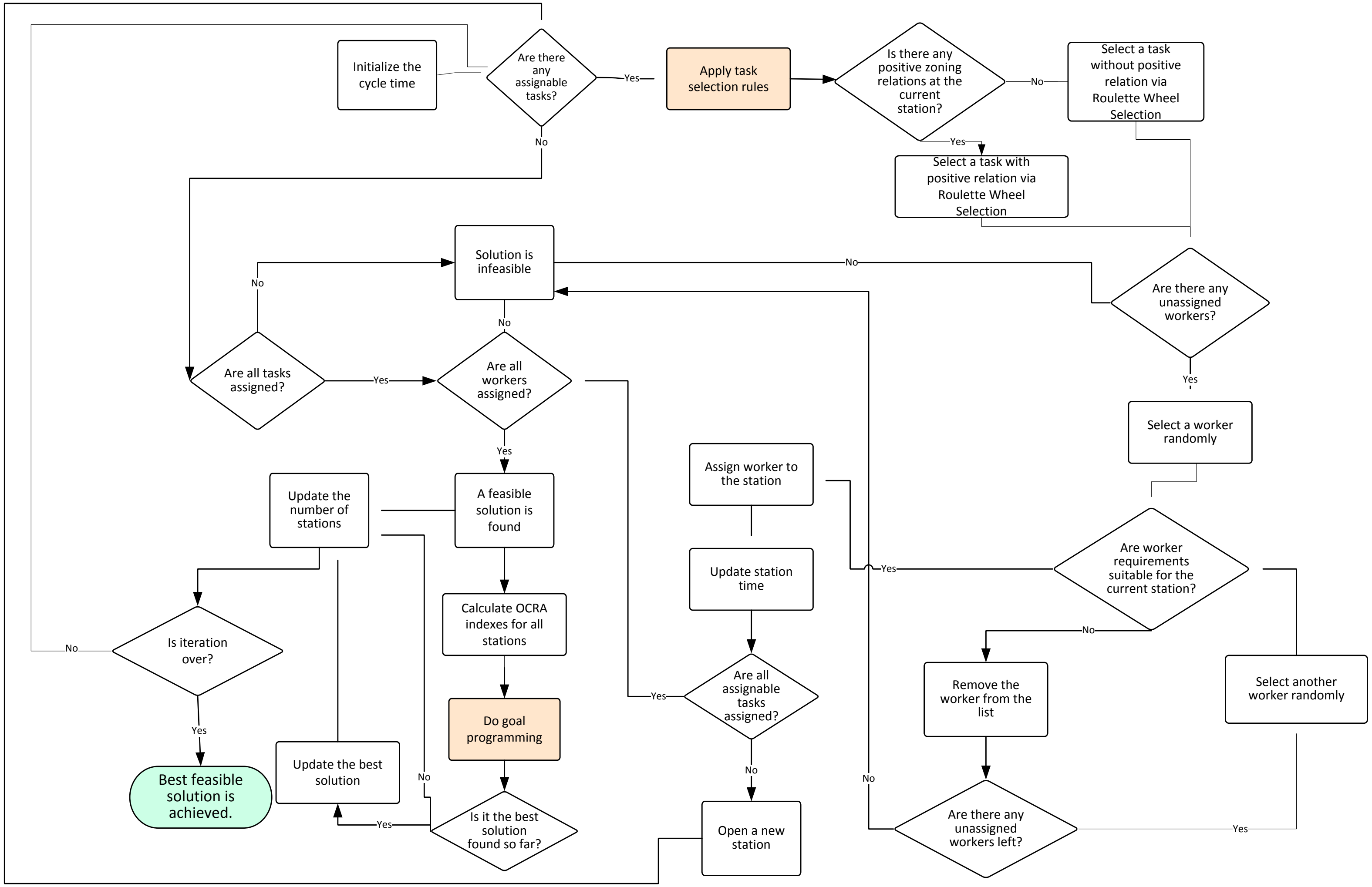


Figure 5.4 Flowchart of the proposed heuristic for the industrial application

The characteristics of the rule based task selection and goal programming algorithms are explained in detail in chapter 4. Thus, we do not repeat the same rules. Note that, there is also worker assignment in chapter 4. But, in this case, there is no such thing and the task operation times are fixed. So, some rules must be updated according to fixed task times, i.e., in chapter 4 there are three different longest processing time rules (LPT_{max}, LPT_{min} & LPT_{avg}) due to the varying task times. However, in this case, there is only a fixed operation time for each task. Hence, there occurs only one LPT rule.

Precedence graph of the proposed problem is given in Figure 5.5. As it can be seen from the graph, the problem is very complicated. Nodes denote tasks and arcs represent the relations. Since the graph is very complex, we do not write the task IDs for simplification. Red and blue dotted areas imply those tasks belong to the sub and main assembly lines, respectively. A different type of operation is executed on each task. In order to simplify the process, we offer the company to label each task as its operation type. For this process, we use the following abbreviations as listed in Table 5.2.

Table 5.2 Abbreviation of manufacturing operations

Assembly / plugging operations	A
Taping operation	TAP
Conduit operation	C
Tube operation	TP
Grommet operation	GR
Therostat operation	TR
Routing operation	ROT
Splice operation	SPL
Rolling operation	ROL
Kit hanging operation	HNG
Zuh operation	Z
Test operation	T

After assigning tasks and workers to the stations according to the proposed rule based constructive randomized search heuristic, the OCRA indexes of workstations must be computed to analyze the ergonomic risk level.

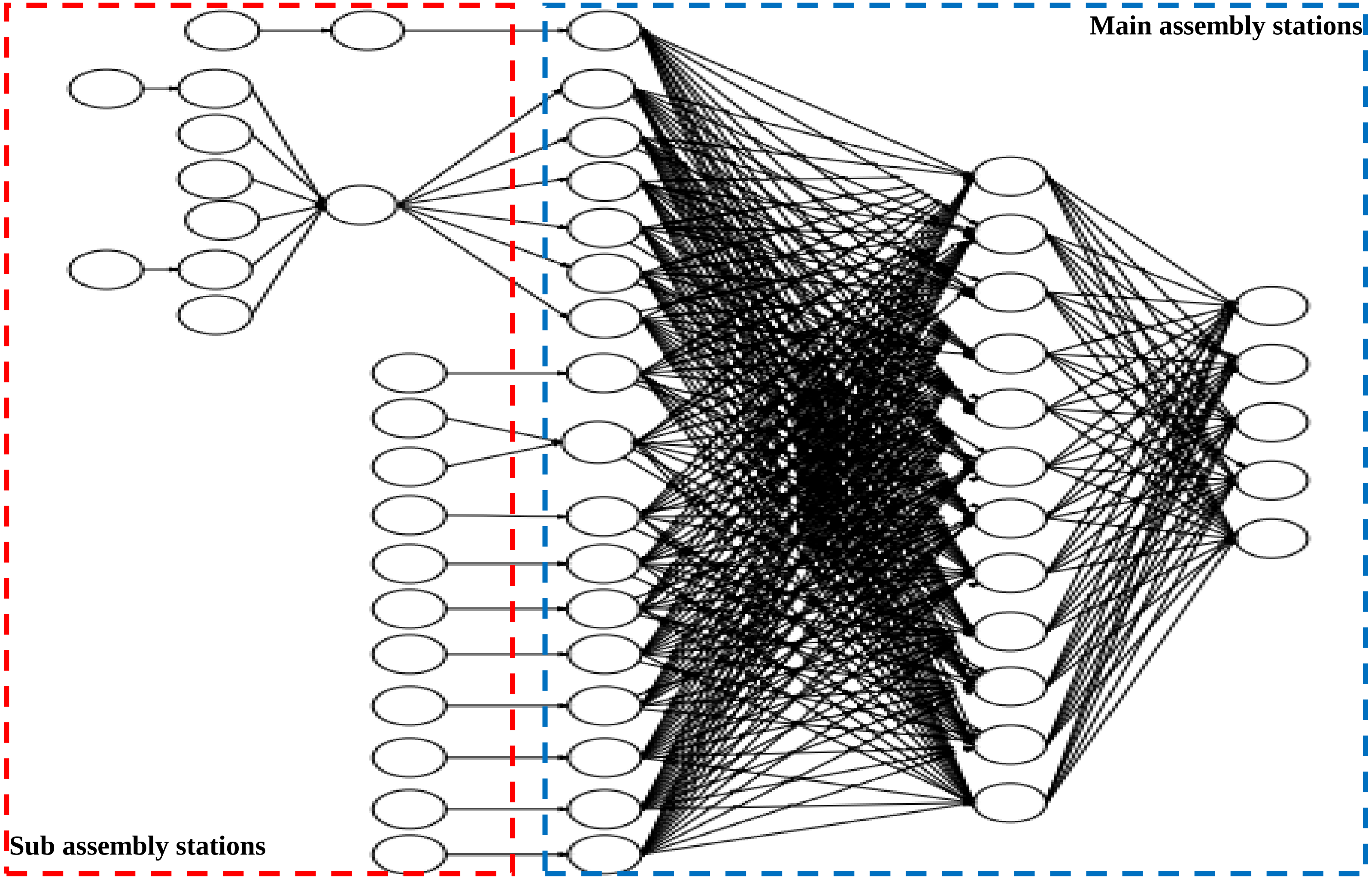


Figure 5.5 Precedence relations of the proposed problem

The computation of OCRA index is explained in detail in Chapter 3. We have to compute actual and recommended frequencies in order to calculate OCRA index. Table 5.3 represents determination techniques of technical actions.

Table 5.3 Determination of technical actions

Operation	**Type of the Operation**	**Number of Technical Actions**
Assembly / plugging operations	Subassembly	3*number of assembled parts
	Main assembly	2*number of assembled parts
PVC taping operation	Discrete	3 + taping distance/(tape width + 2cm)
	Continuous	3 + taping distance/tape width
	Point	4*number of point tapes
Tenacious taping operation	Discrete	4 + taping distance/(tape width + 2cm)
	Continuous	4 + taping distance/tape width
	Point	5*number of point tapes
Sponge taping operation	Continuous	5 + taping distance/sponge width
	Flag	5 + sponge length/80
Linen taping operation	Point	3*number of point tapes
Branch taping operation	Point	6*number of point tapes
Conduit operation	Conduit	3 + conduit length/80
Tube operation	Cut	2 + tube length/80
	Uncut	7*number of tubes
	Uncut manual	3 + tube length/80
Grommet operation	Device	6 + 2*number of cables
	Manual	3 + 2*number of cables
Therostat operation	Therostat	6*number of therostats
Routing operation	Connector routing	2*number of connectors
	Cable routing	2*number of cables
Splice operation	With taping	10 + number of cables
	With heating	11 + number of cables
	At the line	12 + number of cables
Rolling operation	Long cable (>3m)	6
	Medium cable (1.5-3m)	4
	Short cable (<1.5m)	3
Kit hanging operation	Kit	4
Zuh operation	Zuh	6*number of zuhs
Test operation	Test	6

By using the above calculations we compute the number of technical actions and consequently, we find the actual frequency.

We must set OCRA parameters, *CF*, *PM*, *FM*, *RM*, *ARF*, *RcM* and *DuM* to calculate recommended frequency as it is stated in equation (3.3). Since *CF*, *RcM* and *DuM* are fixed multipliers, we have to determine *PM*, *FM*, *RM* and *ARF*.

Awkward postures of operations are listed in Table 5.4.

Table 5.4 Awkward postures of operations

Operation	**Awkward Posture**	**Severe**	**Mild**
Assembly / plugging operations	Hand pinch	X	
Taping operation	Wrist extension (≥45º)	X	
Conduit operation	Elbow supination (≥60º)	X	
Tube operation	Elbow supination (≥60º)	X	
Grommet operation	Wrist flexion (≥45º)	X	
Therostat operation	Power grip		X
Routing operation	Elbow supination (≥60º)	X	
Splice operation	Power grip		X
Rolling operation	Elbow supination (≥60º)	X	
Kit hanging operation	Hook grip	X	
Zuh operation	Hand pinch	X	
Test operation	Hand pinch	X	

According to the cycle time percent of the operation, the posture multiplier (*PM*) is set from Table 3.1

As it is explained in section 3.4.1.3, repetitiveness multiplier (*RM*) of an operation is determined as high or low repetitiveness in accordance with the task time.

Strain levels of operations are given in Table 5.5 for indicating the force multiplier (*FM*). Average force level of the station is calculated by using Table 5.5 and operation times. Then, by making interpolation from Table 3.2, *FM* parameter is found just as explained in numeric example in section 3.5.

Table 5.5 Strain levels of operations

Operation	**Very, very week**	**Very week**	**Week**	**Moderate**	**Somewhat strong**	**Strong /very strong**
Assembly/plugging	X					
Taping	X					
Conduit		X				
Tube		X				
Grommet			X			
Therostat	X					
Routing	X					
Splice	X					
Rolling		X				
Kit hanging		X				
Zuh		X				
Test		X				

Additional risk factors are depicted in Table 5.6. By using the following table and cycle time shares of operations *ARF* multiplier is determined.

Table 5.6 Additional risk factors of operations

Operation	**Additional risk factors**
Assembly / plugging operations	Using protective equipment - gloves
Taping operation	Using sharp equipment - scissors
Conduit operation	Using protective equipment - gloves
Tube operation	Using protective equipment - gloves
Grommet operation	Using sharp equipment - cutter
Therostat operation	Exposure to chemicals
Routing operation	Requirement for absolute accuracy
Splice operation	Using protective equipment - gloves
Rolling operation	-
Kit hanging operation	-
Zuh operation	Using dangerous equipment
Test operation	-

After stating all parameters of OCRA index with partners from the company, the risk levels of stations are computed by the proposed computer program.

5.4.2 Solution Procedure for Layout Problem

The mathematical model of the NP-hard QAP is stated in the following (Burkard et al., 1998). At first, notation used in QAP is given in Table 5.7.

Table 5.7 Notation used in QAP

p, r	Facilities
q, s	Locations
N	Set of facilities
c	Cost of assigning facilities p & r to locations q & s
x_{pq}	Binary variable equal to 1 only if facility p is assigned to location q

Minimize
$$\sum_{p=1}^{N}\sum_{q=1}^{N}\sum_{\substack{r=1\\r\neq p}}^{N}\sum_{\substack{s=1\\s\neq q}}^{N} c_{prqs}\cdot x_{pq}\cdot x_{rs} \tag{5.9}$$

Subject to

$$\sum_{p=1}^{N} x_{pq} = 1 \qquad q = 1,\dots, N \tag{5.10}$$

$$\sum_{q=1}^{N} x_{pq} = 1 \qquad p = 1,\dots, N \tag{5.11}$$

$$x_{pq} \in \{0,1\} \tag{5.12}$$

The objective function given in (5.9) minimizes total transportation costs. The constraint sets given in (5.10) and (5.11) express that each location must be placed by a single facility; and each facility must be assigned to only one location, respectively. The constraint given in (5.12) represents that decision variable x is binary.

5.4.2.1 Solution Method for Layout Problem: An Example

Due to the nature of the industrial case, we have to solve the layout problem also. But, the layout problem is beyond the scope of this thesis. So, we shortly explain our basic QAP solution technique with a numeric example. The considered assembly line configuration is illustrated in Figure 5.6

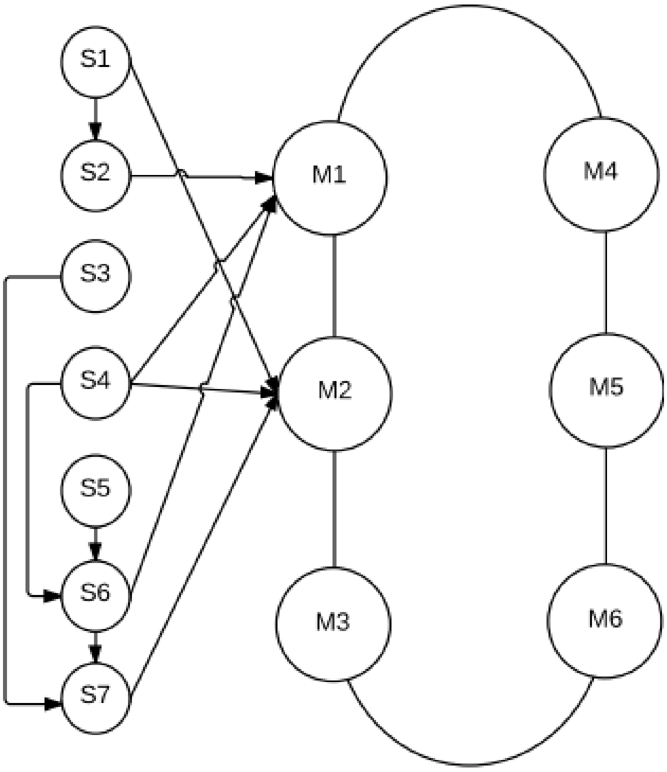


Figure 5.6 Transportation flow within subassembly line and between sub & main assembly lines

The nodes that are labeled as S1, S2, …, S7, are workstations of the subassembly line and the remaining ones (M1, M2, …, M6) are stations of the main line. Arcs represent one unit of transportation between corresponding nodes. Distance matrixes within subassembly stations and between sub and main assembly stations are presented in Tables 5.8 and 5.9, respectively.

Table 5.8 Distance matrix within subassembly stations

Stations	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	—	1	2	3	4	5	6
2	1	—	1	2	3	4	5
3	2	1	—	1	2	3	4
4	3	2	1	—	1	2	3
5	4	3	2	1	—	1	2
6	5	4	3	2	1	—	1
7	6	5	4	3	2	1	—

Table 5.9 Distance matrix between sub and main assembly stations

Sub / Main Assembly	**1**	**2**	**3**
1	1	2	3
2	2	1	2
3	2	1	1
4	4	3	2
5	5	4	3
6	6	5	4
7	7	6	5

All distances and flows are 1 unit for this problem. Now, we can basically compute the total transportation cost for the present situation as in the following Tables 5.10 and 5.11.

Table 5.10 Transportation within subassembly stations for the present situation

From	**To**	**Flow**
S_1	S_2	1
S_3	S_7	4
S_4	S_6	2
S_5	S_6	1
S_6	S_7	1
Total	**-**	**9**

Table 5.11 Transportation between sub and main assembly stations for the present situation

From	**To**	**Flow**
S_1	A_2	2
S_2	A_1	1
S_4	A_1	2
S_4	A_2	1
S_6	A_1	3
S_7	A_2	2
Total	**-**	**11**

Total number of transportations for the present situation is 20 units (9+11).

In seeking for a better solution, we apply local search. We use various neighborhood structures such as swap, insert and switch. Note that in main assembly line there is a moving conveyor between workstations. This means, it is not possible to replace main assembly stations. So, we fixed the locations of main assembly stations, and change the places of subassembly stations by using neighborhood structures. We apply one neighborhood structure at every iteration. By this way, we obtain a new solution and compute new total number of transportations. We keep the solution with the minimum total number of transportations as best solution and continue the local search. At the end, we have an assembly line layout with minimum moves.

For example, we apply a swap move between stations 3 & 4 as in Figure 5.7. New transportation costs within subassembly stations and between sub and main assembly stations are depicted in Tables 5.12 and 5.13, respectively.

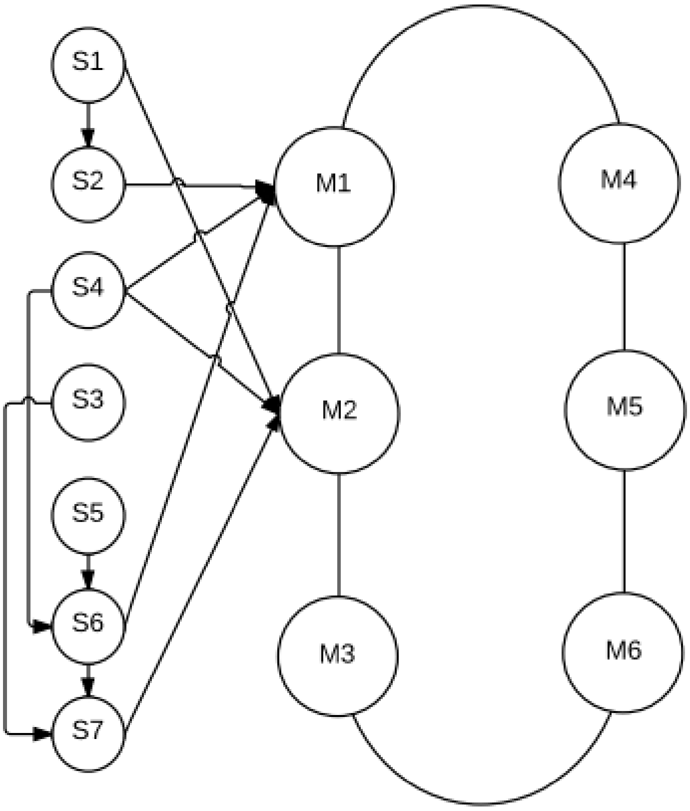


Figure 5.7 Transportation flow after swap between S_3 & S_4

Table 5.12 Transportation within subassembly stations after the swap move

From	**To**	**Flow**
S_1	S_2	1
S_3	S_7	3
S_4	S_6	3
S_5	S_6	1
S_6	S_7	1
Total	**-**	**9**

Table 5.13 Transportation between sub and main assembly stations after the swap move

From	**To**	**Flow**
S_1	A_2	2
S_2	A_1	1
S_4	A_1	1
S_4	A_2	1
S_6	A_1	3
S_7	A_2	2
Total	**-**	**10**

Total number of transportations after the swap move is 19 units (9+10). Since this solution is better than the first one we keep this solution is the best solution found so far and continue the local search for predetermined number of iterations.

5.5 Results of the Industrial Case Implementation

Firstly, we analyze the present situation of the manufacturing area in order to compare with our results obtained by the solution procedure that is proposed in section 5.4. We evaluate the ergonomic risk levels by using OCRA index, and compute total number of transportations for the present situation. Findings are illustrated in Figure 5.8. All characteristics of a station are represented in Figure 5.8. There are 8 subassembly and 7 main assembly stations. Station numbers are written at the top of the each station such as S1, S2… and so on. Tasks that are executed on the station and height of the assigned operator are noted inside the stations. Finally, station times and OCRA indexes are stated at the bottom of each station. All of the main assembly stations are in the red zone whereas 6 of the subassembly stations are in the red zone. The remaining subassembly stations are in green and yellow zones. Also, total number of transportations for the present layout is 62 units.

Then, we apply the proposed heuristic. As it is stated in section 4.4.1, we have 4 goals to be optimized:

- minimizing number of red stations,
- minimizing average red OCRA index,
- mean absolute deviation (mad) of all stations' OCRA indexes and
- average of all stations' OCRA indexes.

In order to analyze all goals, we change the ranking of the goals and solve the problem. Since there are 4 goals, we obtain 24 (4!) different solutions with different goal sequences. The results are reported in Table 5.14.

First column represents the problem; subassembly line balancing, main assembly line balancing, and transportation problem. Second and third columns states the number of solution and goal sequence, respectively. At first, analysis of the present situation is reported, and then obtained solutions are listed. G1, G2, G3 and G4 imply the goals: minimizing number of red stations; minimizing average red OCRA index; mean absolute deviation (mad) of all stations' OCRA indexes and average of all stations' OCRA indexes, respectively. For the first solution minimizing number of red stations is the primary goal; minimizing average red OCRA index is secondary goal, and so on…

Rest of the columns denotes different things according to the problem type. For the sub and main assembly line balancing problems, total number of stations, cycle time, CPU time, number of green stations, number of yellow stations, number of red stations, average OCRA index of red stations, mean absolute deviation, average OCRA index of all stations, and mean absolute deviation of OCRA indexes are given.

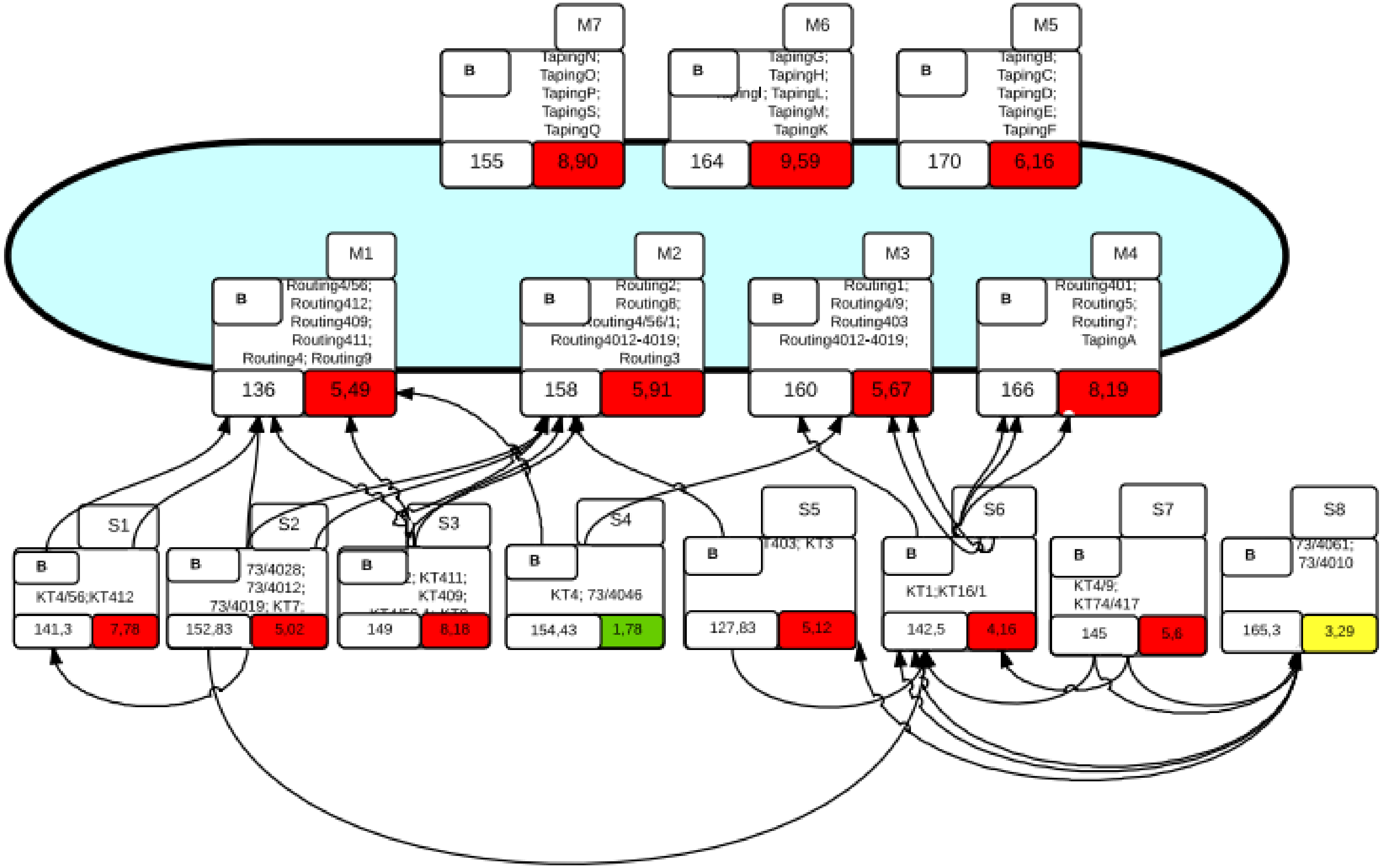


Figure 5.8 Present situation of the working environment

Table 5.14 Results of the industrial application

			Nr of stations	Cycle time (sec)	CPU time (sec)	Nr of green stations	Nr of yellow stations	Nr of red stations	Red Station Avg OCRA Index	MAD	OCRA Avg	OCRA MAD
Sub assembly	Present situation		8	165.30		1	1	6	5.98	23.79	5.12	2.14
	1	G1, G2, G3, G4	8	159.10	2.29	1	0	7	5.70	23.75	5.21	2.30
	2	G1, G2, G4, G3	8	161.77	0.47	1	0	7	5.69	23.79	5.22	2.29
	3	G1, G3, G2, G4	8	163.47	4.70	1	1	6	6.13	23.88	5.24	2.29
	4	G1, G3, G4, G2	8	166.17	2.03	1	1	6	6.79	17.13	6.79	1.62
	5	G1, G4, G2, G3	8	165.43	0.58	0	0	8	4.87	23.38	4.87	1.49
	6	G1, G4, G3, G2	8	161.00	3.43	0	0	8	4.86	26.29	4.86	1.51
	7	G2, G1, G3, G4	8	162.60	0.87	1	0	7	5.71	23.82	5.22	2.31
	8	G2, G1, G4, G3	8	162.83	0.88	1	0	7	5.69	23.83	5.20	2.32
	9	G2, G3, G1, G4	8	164.20	6.24	1	0	7	5.51	23.74	5.09	2.20
	10	G2, G3, G4, G1	8	166.77	4.82	1	0	7	5.12	23.76	5.09	2.19
	11	G2, G4, G1, G3	8	166.77	4.67	1	0	7	5.55	23.89	5.08	2.38
	12	G2, G4, G3, G1	8	165.60	0.98	1	0	7	5.51	23.74	5.09	2.20
	13	G3, G1, G2, G4	8	162.60	2.07	1	1	6	6.21	23.91	5.25	2.37
	14	G3, G1, G4, G2	8	165.30	2.45	0	2	6	5.48	33.24	4.89	1.57
	15	G3, G2, G1, G4	8	163.80	1.94	1	1	6	6.15	23.90	5.25	2.31
	16	G3, G2, G4, G1	8	163.00	4.16	1	1	6	6.04	23.93	5.13	2.32
	17	G3, G4, G1, G2	8	165.30	3.93	0	2	6	5.52	26.24	4.86	2.27
	18	G3, G4, G2, G1	8	166.77	0.45	1	1	6	5.53	25.93	4.81	2.40
	19	G4, G1, G2, G3	8	163.80	1.24	0	0	8	4.87	25.33	4.87	1.49
	20	G4, G1, G3, G2	8	165.43	6.05	0	0	8	4.88	26.44	4.88	1.50
	21	G4, G2, G1, G3	8	165.60	1.87	0	0	8	4.87	26.40	4.87	1.48
	22	G4, G2, G3, G1	8	164.60	5.99	0	0	8	4.87	26.31	4.87	1.49
	23	G4, G3, G1, G2	8	164.00	0.42	0	0	8	4.87	26.30	4.87	1.51
	24	G4, G3, G3, G1	8	166.76	5.11	0	0	8	4.86	26.29	4.86	1.51

Table 5.14 Results of the industrial application (Continue)

			Nr of stations	**Cycle time (sec)**	**CPU time (sec)**	**Nr of green stations**	**Nr of yellow stations**	**Nr of red stations**	**Red Station Avg OCRA Index**	**MAD**	**OCRA Avg**	**OCRA MAD**
Main assembly	Present situation		7	165.30		0	0	7	7.13	14.46	7.13	1.71
	1	G1, G2, G3, G4	7	159.10	5.41	0	0	7	7.17	10.07	7.17	2.20
	2	G1, G2, G4, G3	7	161.77	4.54	0	0	7	7.17	10.25	7.17	2.28
	3	G1, G3, G2, G4	7	163.47	5.71	0	1	6	7.80	16.72	7.17	2.13
	4	G1, G3, G4, G2	7	166.17	4.84	0	0	7	6.79	17.13	6.79	1.62
	5	G1, G4, G2, G3	7	165.43	2.34	0	0	7	6.97	14.12	6.97	2.53
	6	G1, G4, G3, G2	7	161.00	4.43	0	0	7	6.93	17.09	6.93	2.15
	7	G2, G1, G3, G4	7	162.60	2.46	0	0	7	7.13	10.28	7.13	1.90
	8	G2, G1, G4, G3	7	162.83	2.62	0	0	7	7.16	9.78	7.16	1.84
	9	G2, G3, G1, G4	7	164.20	3.14	0	0	7	7.15	9.80	7.15	1.44
	10	G2, G3, G4, G1	7	166.77	2.69	0	0	7	7.15	9.92	7.15	1.20
	11	G2, G4, G1, G3	7	166.77	3.53	0	0	7	7.17	10.03	7.17	2.48
	12	G2, G4, G3, G1	7	165.60	3.62	0	0	7	7.17	9.97	7.17	2.66
	13	G3, G1, G2, G4	7	162.60	2.92	0	0	7	7.16	9.88	7.16	1.47
	14	G3, G1, G4, G2	7	165.30	1.32	0	0	7	6.97	13.67	6.97	1.61
	15	G3, G2, G1, G4	7	163.80	0.53	0	0	7	7.18	9.76	7.18	2.04
	16	G3, G2, G4, G1	7	163.00	4.09	0	0	7	7.01	10.20	7.01	2.18
	17	G3, G4, G1, G2	7	165.30	2.62	0	1	6	7.79	11.79	7.17	2.15
	18	G3, G4, G2, G1	7	166.77	0.96	0	1	6	7.65	12.49	7.05	2.32
	19	G4, G1, G2, G3	8	163.80	0.85	0	0	8	6.71	49.61	6.71	2.22
	20	G4, G1, G3, G2	8	165.43	1.94	0	0	8	6.81	49.14	6.81	2.20
	21	G4, G2, G1, G3	8	165.60	2.21	0	0	8	6.75	49.00	6.75	2.69
	22	G4, G2, G3, G1	8	164.60	4.16	0	0	8	6.66	49.00	6.66	2.72
	23	G4, G3, G1, G2	7	164.00	1.90	0	0	7	6.90	17.12	6.90	2.55
	24	G4, G3, G3, G1	8	166.76	1.30	0	0	8	6.69	49.24	6.69	2.48

Table 5.14 Results of the industrial application (Continue)

			S1			S2			S3			S4			S5			S6			S7			S8			Total		
			T1	**T2**	**T**	**T1**	**T2**	**T**	**T1**	**T2**	**T**	**T1**	**T2**	**T**	**T1**	**T2**	**T**	**T1**	**T2**	**T**	**T1**	**T2**	**T**	**T1**	**T2**	**T**	**T1**	**T2**	**T**
Transportation		Present situation	0	2	2	5	4	9	0	12	12	1	4	5	1	4	5	0	21	21	2	0	2	6	0	6	15	47	**62**
	1	G1, G2, G3, G4	0	11	11	3	0	3	2	3	5	9	5	14	1	6	7	0	1	1	1	2	3	0	14	14	16	42	**58**
	2	G1, G2, G4, G3	0	11	11	4	10	14	5	0	5	1	5	6	0	4	4	11	0	11	0	1	1	0	13	13	21	44	**65**
	3	G1, G3, G2, G4	0	23	23	11	0	11	1	4	5	8	0	8	8	20	28	0	2	2	1	6	7	0	16	16	29	71	**100**
	4	G1, G3, G4, G2	4	26	30	4	14	18	1	1	2	4	3	7	1	7	8	0	3	3	3	0	3	0	16	16	17	70	**87**
	5	G1, G4, G2, G3	3	33	36	2	16	18	21	4	25	3	5	8	6	0	6	8	6	14	0	12	12	0	1	1	43	77	**120**
	6	G1, G4, G3, G2	1	14	15	8	11	19	6	15	21	14	0	14	6	0	6	2	7	9	0	13	13	0	1	1	37	61	**98**
	7	G2, G1, G3, G4	0	10	10	3	8	11	7	0	7	2	5	7	7	0	7	0	10	10	0	8	8	0	1	1	19	42	**61**
	8	G2, G1, G4, G3	0	11	11	7	0	7	4	0	4	0	1	1	6	5	11	1	4	5	3	3	6	0	10	10	21	34	**55**
	9	G2, G3, G1, G4	2	24	26	4	4	8	6	1	7	2	4	6	2	7	9	0	3	3	3	8	11	0	17	17	19	68	**87**
	10	G2, G3, G4, G1	4	9	13	4	6	10	12	2	14	5	5	10	2	5	7	3	2	5	0	38	38	0	4	4	30	71	**101**
	11	G2, G4, G1, G3	5	32	37	12	2	14	5	2	7	5	2	7	2	5	7	3	12	15	0	16	16	0	1	1	32	72	**104**
	12	G2, G4, G3, G1	5	38	43	3	1	4	8	4	12	2	5	7	6	2	8	5	6	11	0	16	16	0	3	3	29	75	**104**
	13	G3, G1, G2, G4	0	11	11	7	0	7	13	3	16	0	2	2	1	2	3	2	5	7	0	6	6	0	12	12	23	41	**64**
	14	G3, G1, G4, G2	4	2	6	7	3	10	2	10	12	3	7	10	0	11	11	4	0	4	0	5	5	0	14	14	20	52	**72**
	15	G3, G2, G1, G4	0	11	11	6	0	6	1	5	6	4	6	10	8	6	14	0	2	2	3	2	5	0	11	11	22	43	**65**
	16	G3, G2, G4, G1	1	32	33	0	8	8	3	4	7	11	1	12	2	4	6	2	1	3	0	38	38	0	2	2	19	90	**109**
	17	G3, G4, G1, G2	4	10	14	1	7	8	3	0	3	3	14	17	2	0	2	1	1	2	0	15	15	0	3	3	14	50	**64**
	18	G3, G4, G2, G1	3	44	47	5	6	11	2	12	14	4	0	4	2	5	7	2	1	3	0	13	13	0	2	2	18	83	**101**
	19	G4, G1, G2, G3	10	8	18	3	12	15	1	38	39	4	0	4	2	6	8	10	0	10	0	21	21	0	1	1	30	86	**116**
	20	G4, G1, G3, G2	5	5	10	1	6	7	1	9	10	0	5	5	4	0	4	6	1	7	2	7	9	0	14	14	19	47	**66**
	21	G4, G2, G1, G3	2	10	12	3	9	12	8	4	12	8	2	10	1	0	1	0	5	5	3	6	9	0	14	14	25	50	**75**
	22	G4, G2, G3, G1	1	4	5	2	9	11	8	0	8	1	0	1	7	8	15	3	6	9	0	1	1	0	11	11	22	39	**61**
	23	G4, G3, G1, G2	4	7	11	3	8	11	3	0	3	5	0	5	0	3	3	4	9	13	1	1	2	0	15	15	20	43	**63**
	24	G4, G3, G3, G1	2	10	12	4	9	13	1	38	39	5	6	11	10	0	10	1	0	1	0	13	13	0	1	1	23	77	**100**

For the transportation problem, columns represent the number of transportations from subassembly station 1 (S1) to other subassembly stations (T1) and main assembly stations (T2). T1 and T2 are the number of moves within subassembly stations and between sub and main assembly stations, respectively. T is the total number of transportation (T1+T2) for the corresponding station.

For the first solution, by summing up the moves from stations S1, S2,…, S8, we obtain total number of transportations within subassembly stations, between sub and main assembly stations as 16 and 42, respectively. Consequently total number of transportations for the first solution is 58 (16+42). This is better than present situation because total number of transportations is 62 for present case.

We make brainstorming sessions with company authorities and select the first solution as the best solution of 24 solutions. The main reason is that first solution is the one with the minimum number of transportations among all solutions. According to the company policy, the main priority is reducing transportations. Our partners from the company claim that ergonomic conditions for all solutions are poor. So, some actions must be taken seriously and immediately in order to reduce the risk level. None of the 24 solutions is superior in terms of ergonomics. However, the first solution is outperforms in terms of transportation. Thus, solution number 1 is selected to be implemented at the manufacturing plant. The implemented solution is illustrated in Figure 5.9.

In present situation the proposed problem is handled by industrial engineers manually. The engineer has to analyze the problem and consider various constraints simultaneously. This process takes about 8 weeks to be completed. Also, the ergonomic risk assessment is not included to the process. As it can be read from Table 5.14, total CPU time for the first solution is 7.80 (2.29+5.41) seconds, including the ergonomic risk assessment. This is a pretty huge improvement. In the context of this Santez project, we developed the proposed heuristic and it is implemented successfully by the company.

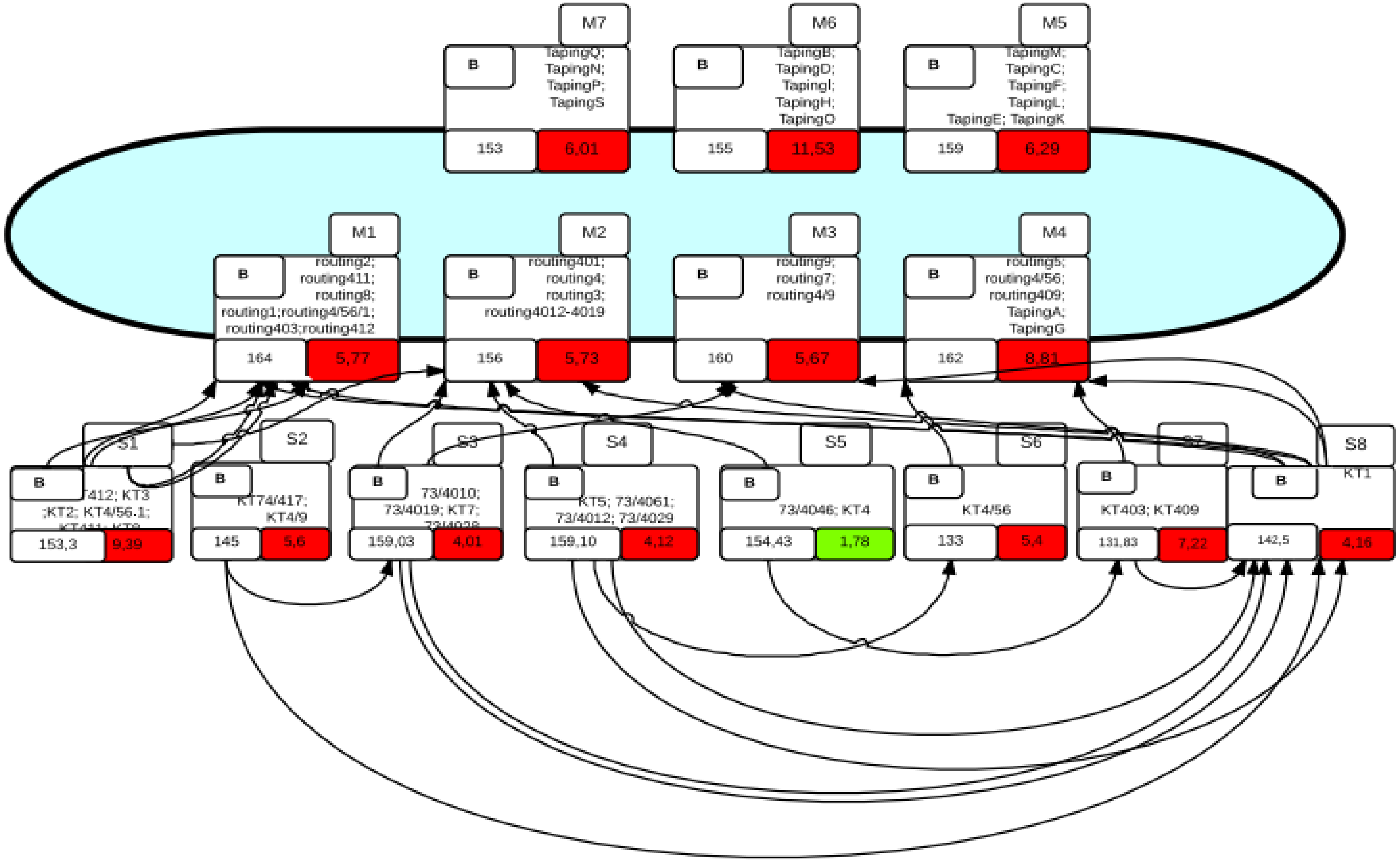


Figure 5.9 The implementation of solution number 1

5.6 Chapter Summary

In this chapter, we presented a harness production company that is located in Izmir. We explained the cable network manufacturing process and stated the difficulties. Then, we defined the present problem that occurs at the manufacturing plant. In order to develop a satisfactory solution, we analyze the present problem and divide into three problems, such as subassembly line balancing, main assembly line balancing and layout problem. We used the rule based constructive randomized search heuristic, which is proposed in Chapter 4, to sub and main assembly line balancing problems. Also, we applied OCRA method for ergonomic risk assessment. For solving the layout problem, we performed a basic quadratic assignment procedure. Although the layout problem is beyond the scope of this dissertation, we basically explained the solution procedure. Finally, we applied the proposed computer program and find out 24 different solutions with regard to different sequences of goals. One of the 24 solutions is selected to be implemented at manufacturing area. Results showed that although total number of transportations is decreased by the proposed solution, serious actions must be taken immediately due to the poor ergonomic conditions of the workplace.

CHAPTER SIX
CONCLUSION

6.1 Summary and Concluding Remarks

Human factors play an important role in labor intensive assembly lines. Since every worker has his own characteristics, such as skill, ability, morale, experience, etc., it is inappropriate to consider workers as unique. However, in classical assembly line balancing literature, this aspect is disregarded and all workers are assumed to be unique. Consequently, task operation times are assumed to be fixed and do not depend on the workers. But this assumption does not represent the real life assembly systems. In order to relax fix operation times assumption, assembly line worker assignment and balancing problem (ALWABP) is introduced, recently.

ALWABP is a decision problem that occurs when operation times of tasks vary due to the worker who executes the task. ALWABP is much more complex and complicated than the traditional ALBP, since ALWABP involves simultaneous double assignment (tasks to workers and workers to stations). Thus, ALWABP is multi-objective and NP-hard in nature.

In this PhD study, to deal with the ALWABP rule based constructive randomized search heuristic is proposed. The proposed heuristic is proven to be successful as a result of computational experiments on benchmark data.

Moreover, in ALWABP literature horizontal balance of the line is an important aspect. In classical approach, when assigning tasks equally among workstations, only tasks operation times are considered. Two stations that have the same station times are assumed to be equal. However, the strain levels of the workstations cannot be equal because of varying tasks. Within this context, a novel ALWABP that considers ergonomic risks, ErgoALWABP is introduced in this dissertation. OCRA index is used for ergonomic risk assessment. In order to deal with the multi-objective nature of the proposed problem, a preemptive goal programming approach is developed.

Furthermore, the proposed heuristic method is applied on a manufacturing plant that produces harness.

6.2 Contributions

The contributions of this PhD thesis can be summarized as follows:

- A new constructive heuristic is developed to solve ALWABP. After doing a set of computational experiments, it is proven that the proposed approach outperforms all current solution techniques suggested so far.

- A novel type of ALWABP that includes ergonomic risk assessment is introduced to the assembly line literature. Unlike the current literature, ergonomic risk level of workplace is computed for the ALWABP. In order to solve this over constraint problem the proposed rule based constructive randomized search heuristic is used. Besides, in order to cope with the multi-objectivity a preemptive goal programming approach is developed.

- The proposed heuristic approach is applied to a harness production company. By using the proposed solution procedure, the company management is informed about ergonomic risks of the working environment and it is decided to take actions in order to reduce risk. Also, undesired cross movements are diminished. Additionally, the required time for the line balancing is decreased from 8 weeks to 7 seconds.

6.3 Future Research Directions

The future research directions for both the problem and the solution method can be stated as follows:

- In order to analyze ergonomic risk factors on ALWABP, the ergo data that is introduced for SALBP is modified, in this thesis. In a future study, ergo data that is divided into two parts such denoting high risk and low risk can be generated for the ALWABP.

- In this PhD thesis, ergonomic factors are considered as a constraint of the problem. It can be modified to study as a part of objective function.

- 39 task selection and 4 worker selection rules are developed for the proposed rule based constructive randomized search heuristic. Some other rules may be added in the future.

- The proposed heuristic can be extended to solve different assembly line balancing problems with different line configurations.

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