DOKUZ EYLÜL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

COLLABORATIVE ASSEMBLY LINE BALANCING WITH WORKER AND COBOT ASSIGNMENT

by

Perihan BEKDEMİR

July, 2022

İZMİR

COLLABORATIVE ASSEMBLY LINE BALANCING WITH WORKER AND COBOT ASSIGNMENT

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"COLLABORATIVE ASSEMBLY LINE BALANCING WITH WORKER AND COBOT ASSIGNMENT"** completed by **PERİHAN BEKDEMİR** under the supervision of **ASSIST. PROF. DR. SEREN ÖZMEHMET TAŞAN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Assist. Prof. Dr. Seren ÖZMEHMET TAŞAN

Supervisor

Assoc. Prof. Dr. Derya EREN AKYOL

(Jury Member)

Assist. Prof. Dr. Ilgın POYRAZ ACAR

(Jury Member)

Prof. Dr. Okan FISTIKOĞLU

Director

Graduate School of Natural and Applied Sciences

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COLLABORATIVE ASSEMBLY LINE BALANCING WITH WORKER AND COBOT ASSIGNMENT

ABSTRACT

For many years, the assembly line balancing problem has been handled with different solution approaches in the literature. Recently, the use of collaborative robots (cobots) on the assembly line has become very popular. Cobots have many advantages, especially in production systems where repetitive movements and/or lifting heavy loads are required while assisting workers. Cobots can work with workers to replicate human movements in the system and also minimize ergonomic risks because they are capable of doing hundreds of times more work than ordinary workers this does not apply to humans. Ergonomic risks also need to be evaluated and reduced in the working environment. For workers who are exposed to heavy working conditions from time to time, it is necessary to take a break according to the degree of difficulty of their work in order to minimize these ergonomic risks. While a break time is not required for cobots, they are known to work slower than workers. In this study, a linear integer programming model is proposed for the cost-based worker-cobot collaborative assembly line balancing problem in which energy expenditure problems are also addressed from ergonomics perspective. To evaluate the effectiveness of the cobots in assembly lines, a total of four different scenarios; i.e. assembly line only with the manual workforce, the collaborative assembly line with the cobots where the ergonomics perspective is ignored, collaborative assembly line with the cobots where the ergonomics perspective is ignored with different parameters in objective function, and collaborative assembly line with the cobots where the ergonomics perspective is addressed-change in energy expenditures were considered and their results were compared. and their results were compared.

Keywords: Cobot, collaborative assembly line, ergonomic risks, integer programming

İŞÇİ VE KOBOT ATAMA İLE İŞBİRLİKÇİ MONTAJ HATTININ DENGELENMESİ

ÖZ

Uzun yıllar boyunca montaj hattı dengeleme problemi literatürde farkli çözüm yaklaşımlarıyla ele alınmıştır. Son zamanlarda montaj hattında işbirlikçi robot (kobot) kullanımı oldukça popüler hale gelmiştir. Kobotlar, özellikle işçilere yardımcı olurken tekrarlayan hareketlerin ve/veya ağır yüklerin kaldırılmasının gerekli olduğu üretim sistemlerinde birçok avantaja sahiptir. Kobotlar işçiler ile birlikte çalışıp sistemdeki insan hareketlerinin aynısını gerçekleştirebilmekte ve ayrıca sıradan bir işçiden yüzlerce kat daha fazla iş yapabilme yeteneğine sahip olduğu için ergonomik riskleri en aza indirmektedir. Fakat bu durum insanlar için geçerli değildir. Çalıştığı ortamda ergonomik risklerin de değerlendirilmesi ve azaltılmasına ihtiyacı vardır. Zaman zaman ağır çalışma şartlarına maruz kalan işçiler için bu ergonomik risklerin en aza indirilmesi adına yaptığı işin zorluk derecesine göre mola vermesi gerekmektedir. Kobotlar için bir mola süresi gerekli olmasa da işçilerden daha yavaş çalıştığı bilinmektedir. Bu çalışmada, enerji harcama problemlerinin de ergonomi perspektifinden ele alındığı, maliyet tabanlı işçi-kobot işbirlikçi montaj hattı dengeleme problemi için doğrusal bir tamsayılı programlama modeli önerilmiştir. Kobotların montaj hatlarındaki etkinliğini değerlendirmek için sadece manuel işgücünün olduğu montaj hattı, ergonomi perspektifinin göz ardı edildiği kobotlarla işbirlikçi montaj hattı, ergonomi perspektifinin göz ardı edildiği farklı parametrelerin amaç fonksiyonuna etkisi ile birlikte kobotlarla işbirlikçi montaj hattı ve ergonomi perspektifinin ele alındığı enerji tüketiminin değişiminin değerlendirildiği kobotlarla işbirlikçi montaj hattının ele alındığı toplam dört farklı senaryo kullanılmış ve sonuçları karşılaştırılmıştır.

Anahtar kelimeler: Kobot, işbirlikçi montaj hattı, ergonomik riskler, tamsayılı programlama

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ABBREVIATIONS

ACO	: Ant Colony Optimization
AL	: Assembly Line
ALB	: Assembly Line Balancing
ALS	: Assembly Line Sequencing
AWL	: Working Level
B&B	: Branch and Bound
CP	: Constraint Programming
DP	: Dynamic Programming
EA	: Evolutionary Algorithm
GA	: Genetic Algorithm
IBS	: Iterative Beam Search
IP	: Integer Programming
LIP	: Linear Integer Programming
LP	: Linear Programming
MILP	: Mixed Integer Linear Programming
MIP	: Mixed Integer Programming
MMALB	: Mixed Model Assembly Line Balancing
MMALB/S	: Mixed Model Assembly Line Balancing and Sequencing
MMULB/S	: Mixed Model U Line Balancing and Sequencing
MWR	: Average Work Rate
RA	: Relaxation Allowance
RALB	: Robotic Assembly Line Balancing

RR : Relaxation Rate

SA : Simulated Annealing

SALBP : Simple Assembly Line Balancing Problem

TALBP : Two Sided Assembly Line Balancing Problem

UALBP : U Type Assembly Line Balancing Problem

CHAPTER 1

INTRODUCTION

The role of automation (work-sharing between workers and machines) in the manufacturing sector is becoming more and more effective day by day. However, no matter how effective it becomes, automation cannot be achieved at the desired rate. The reason for this is that workers still do most of the work intensively and have a very active role in adding value to it. In order to prevent this, a different method has emerged, although not fully automated. This method consists of worker-robot collaboration where worker and robot work together. The general name of this method is known as collaborative robot (cobot). Cobots, which have increased in value in recent years, have many advantages both in service and especially in production. Cobots, which are preferred in many areas to lower the operational costs, are used in automatic or manual production by working with workers. Cobots have much more job skills than a regular worker. Among the important reasons for its popularity, it is economical, and the role of energy-saving is quite high. Its usage will become more common in the future as it has more physical dexterity than robots. It is estimated that this cooperation will be an effective initiative and will continue to increase and maintain its effectiveness in the future.

Cobots are well suited for collaborative use with workers on an assembly line (AL). Cobots have many advantages, especially in AL systems where repetitive movements and/or lifting heavy loads are required while assisting workers. Cobots can work with workers to replicate human movements in the system and also minimize ergonomic risks because they are capable of doing hundreds of times more work than ordinary workers this does not apply to humans. While designing a collaborative AL, many different features, such as costs, ergonomics, and collaboration levels, should be considered. However, these features complicate balancing, and sequencing aspect of the design problems. Furthermore, the assignments of workers and cobots should also be considered while balancing the collaborative AL. This thesis study started based on these points of view.

The main objective of this thesis study is to solve the cost-based collaborative assembly line balancing (ALB) problem in which energy expenditure problems are also addressed from ergonomics perspective. Unlike the assignment of workers that a normal ALB problem deals with, in this thesis study there is the assignment of workers and cobots. Therefore, the cost of assigning workers and cobots to the station is different. Therefore, the aim is to minimize the resulting cost. Since the cycle time is known, a problem that tries to minimize the number of opened stations (the ALB type 1 problem) is considered. To solve this problem, a two-step solution methodology based on mixed integer programming (MIP) has been proposed. In the first step, preliminary calculations are done to aid the mathematical model used for MIP in step two. The MIP model evaluates how workers and cobots with different characteristics will share tasks, both ergonomically and economically. The proposed equations regarding the energy expenditure of the worker at the workplace are considered, and if necessary, a relaxation allowance is assigned to the workers. To evaluate the effectiveness of the cobots, a total of four different scenarios; i.e. AL only with the manual workforce, the collaborative AL with the cobots where the ergonomics perspective is ignored, collaborative AL with the cobots where the ergonomics perspective is ignored with different parameters in objective function, and collaborative AL with the cobots where the ergonomics perspective is addressed-change in energy expenditures were considered and their results were compared. The structure of this thesis study is summarized in Figure 1.1, which also constitutes of seven chapter.

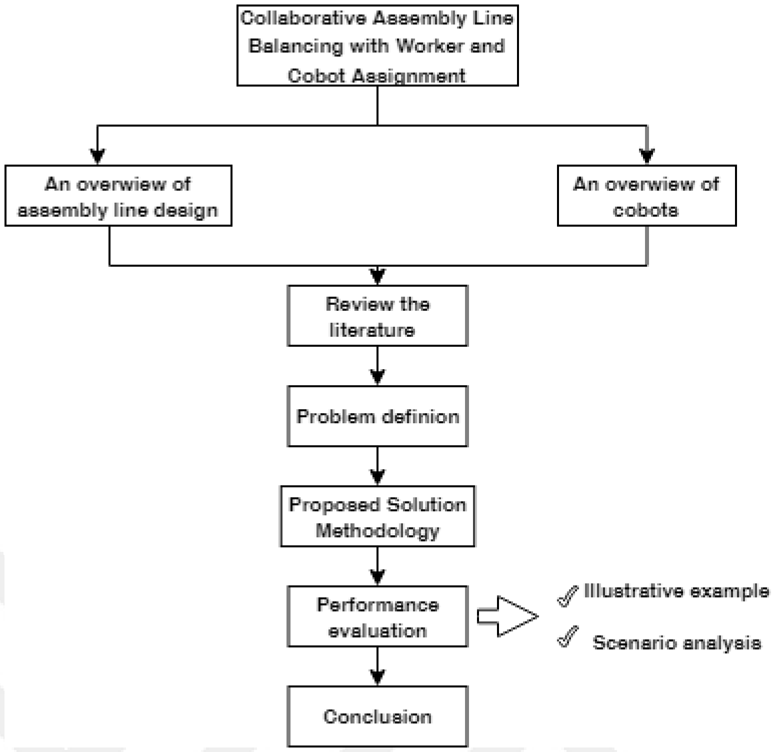

Figure 1.1 Flow of the research process of the study

Following the first chapter, AL design problems are defined and general information on these problems and cobots are given in chapter two in order to provide background overview on the important subjects of this thesis. The second chapter, which includes cobots and also describes components of the AL design problem generally refers to how many different structures it consists of. Then, chapter three includes the recent review of the literature on the important subjects. Next, chapter four consists of the problem definition together with the necessary equations. Additionally, the formulation of the MIP model for the defined problem is given in this chapter. Later, chapter five, the proposed two-step solution methodology is explained in detail. In chapter six, first a illustrative example is solved to show the applicability of the proposed solution methodology and then scenario analysis is performed to evaluate the effectiveness of cobot usage in ALs. Finally, chapter seven contains the concluding remarks and outputs of this thesis study and the possible research directions that need to be performed in future studies.

CHAPTER 2

ASSEMBLY LINE DESIGN AND COBOTS

As the main purpose of the AL is to increase efficiency and reduce costs at the same time, AL design is a problem of industrial importance. Some jobs on assembly lines have been handled by robots for a very long time. Recently, the use of cobots has also become very popular since they not only handle repetitive movements and/or lifting heavy loads but also, they assist workers in a collaborative way, while minimizing the jobs ergonomic risk impact on the worker.

2.1 Assembly Line Design

ALs are classified according to the layout, the number of models, the control structure of the line, the processing time of jobs, and automation level. According to the layout, it is divided into four as straight lines, U-type lines, parallel lines, and different angled lines. According to the number of models, they are divided into single-model, multi-model and mixed-model lines. According to the control structure of the line, there are delayed and non-delayed lines (gecikmeli ve gecikmesiz). According to the processing time, there are deterministic and stochastic lines. According to the level of automation, there are manual and automatic lines. This classification should be thougt about as design prerequisites for the AL balancing and sequencing problem.

2.1.1 Assembly Line Balancing

ALB is the primary problem of the AL. It is a significant formation of mass production. One of the problem that arise when designing an AL is the priority relationship of tasks. Tasks should be assigned in order of priority. When assigning tasks, the cycle time should not be exceeded. It is desired that the smoothness index is small and the efficiency of the line is high. In fact, it is the most appropriate and desired situation for the line to be 100% efficient (Kucukkoc & Zhang, 2014). While balancing the AL, some targets are set such as maintaining a regular flow of material, using resources efficiently, and reducing production costs.

Here are some concepts that should be considered while investigating AL systems.

- The task cannot be divided. It is the smallest indivisible part of the work.
- The task time is the time required to perform each task on the AL.
- The station is the place where tasks are assigned to fulfill their tasks, considering the priority relations between them.
- The station time is the total duration of each task assigned to the station.
- The cycle time is the time allocated for the sum of the times of the tasks in a station. There is one thing to be careful about the cycle time. The rule that applies to each opened station is that the sum duration of the jobs assigned to the opened station must be less than or equal to the cycle time.
- Station idle time is defined as the dissimilarity between the total time of the jobs assigned to the station and the cycle time.
- There are precedence relationships between the tasks in the AL. Because every task has a specific predecessor and successor. The diagram showing these relationships is the precedence diagram. In Figure 2.1 is the precedence diagram. For task number five to start, tasks two and three must be completed first. In this case, tasks two and three are predecessors to task number five. Task number five is expressed as successors of tasks two and three.

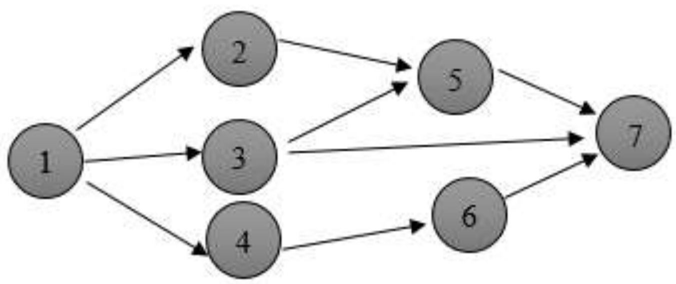

Figure 2.1 Precedence diagrams

Different types of ALs can be used when designing an AL. The classification presented will be based on these three elements: precedence graph characteristics; station and line characteristics; objectives (Boysen, Fliedner, & Scholl, 2007). Table

2.1 shows the classification methods and their explanations addressed in ALB schematically. The aim, optimization, station and line characteristic, and precedence graph characteristic of ALB are used as criteria for the classification purposes. In this table, the second column represents the type of the problem and the third column represent the detailed explanations of the four criteria.

Table 2.1 Classification of ALB (Boysen et al., 2007)

	The aims of ALB can be classified as …	
Type	*Type F*	Objective dependent problem, The applicability of the ALB for a endowed cycle time and number of stations.
	Type 1	Aims to minimize the number of stations when the cycle time is known.
	Type 2	Aims to minimize the cycle time when the number of workstations is known.
	Type E	Minimizing the number of stations and cycle time to best determine the efficiency of the line
	The optimizations of ALs can be classified as ...	
Type	*m*	Minimize the number of stations m
	c	Minimize the cycle time c
	E	Maximize the line efficiency E
	Co	Minimizing the cost
	Pr.	Maximize profit
	SSL^{λ}	The station times should be smoothed
	score	Minimizing or maximizing some composite points
	o	Just searching for feasible solutions
	Station and line characteristics can be classified as …	
Type	*β1*	Movement of workpieces
	β2	Line layout
	β3	Parallelization
	β4	Resource assignment
	β5	Station-dependent time increments
	β6	Additional aspects of line configuration
	Precedence graph characteristics can be classified as …	
Type	*α1*	Product-specific precedence graphs
	α2	Structure of the precedence graph
	α3	Processing times
	α4	Sequence-dependent task time increments
	α5	Assignment restrictions
	α6	Processing alternatives

2.1.2 Assembly Line Sequencing

While it does not require sequencing during the assembly of single-model products, multiple product lines (mixed/batch production) on assembly line sequencing (ALS) considers scheduling products and ALB together. With the increasing need for product diversity and the development of the industry, AL problems can no longer be addressed only as a balancing problem. Therefore; balancing problem is now considered as a part of this study in order to better solve the problems that arise due to limited time and resources. There are two main purposes encountered in a single model AL. These;

- Finding the smallest value of stations opened for jobs under a certain cycle time
- Finding the smallest value of cycle time for a certain number of powered workstations

In multi-model ALs, products or models often require a similar sequence of operations. Since different models are produced, people, tools, and necessary materials are rearranged while passing from one model to another. Since it is desired to minimize the lost time during this arrangement, a certain sequence is required. There are two main problems encountered here:

- How can the line balance be achieved for each of the different products?
- How should sequencing be created to minimize lost time?

A mixed model assembly line balancing (MMALB) deals with dissimilar models of a product or models of multiple similar products as opposed to a simple model AL where a single product is produced. In this line, separate workpieces; uneven workflow, idle station times, and stocks of half-assembled products. The main problems of multi-model lines are;

- How should the line be balanced when different products have different business content?
- What should be the optimum sequencing?

Mixed model scheduling, car scheduling, and level scheduling approach are used to minimize work overload and leveling part usage. Minimizing the sequence-dependent work overload (but in an explicit manner) is called the ***mixed model***

sequencig problem. Holding the load of the workstations of the line (but in an implicit manner), as stable as possible is called the ***car sequencing*** problem. Keeping the usage rate of the parts as constant as possible is called the ***level sequencing*** problem. ***Hybrid sequencing*** approaches have been developed to optimize both objectives (Wu, Ding, & Shi, 2021).

2.1.3 Worker Assignment

In ALB problems, workers are assumed to have equal characteristics. Therefore, only job assignments are made to the stations. However, this may not be possible in real life. Workers often have different characteristics. Therefore, the time it takes for workers to complete their duties differs. For this reason, wages paid to workers also differ.

People have different characteristics and abilities. Therefore, the duration of the tasks assigned to him will of course be different. Sometimes the worker may not even have the skills to do the job. Workers are appointed in order to complete the tasks assigned to them as soon as possible and to carry out the works with the least cost. Both work and workers are assigned to stations. Worker assignments are made for workers with disabilities or inexperienced workers.

2.2 Robots in Assembly Lines

Industrial robots are used in many wide applications such as material handling, welding, and robotic assembly. They are preferred for use in repetitive work as they do not get tired and do not make mistakes. They can quickly adapt to different product lines while offering financial advantages. There are two main problems when balancing a robotic assembly line. Robotic ALB (RALB)-I problem is to reach the optimal balance for a given number of stations or cycle time. RALB-II problem is to assign the most suitable robot required to the station.

There may be ALs with only robots or ALs where workers and robots take part in together. To design human-robot task sharing in lines where workers and robots work together, production tasks must be distributed effectively, and cell layouts must be correct. Today, these hybrid systems where human and robot work together, which manufacturing companies use to gain strength, benefit from the efficiency of the robot and the flexibility of the human at the same time.

2.3 Collaborative Work Environment with Cobots

With the valuation of automation on a sectoral basis, the lack of automation to the required extent attracts the attention of manufacturers. In automation, the fact that workers are more active than machines and the manual labor of the workers causes a low level of automation. In terms of supporting workers, worker-robot collaboration is an important step to create a more flexible production workspace. Cobots, which are very advantageous in terms of both financial and flexible production, adapt to the line without the use of extra safety devices (Weckenborg & Spengler, 2019).

One of the advantages of cobots, which have started to play an important and active role both in the service and especially in the production sector, is the ability of a normal worker to do many times more work. It gets ready to work quickly at any time and can always work. It is very efficient in terms of economy and low energy consumption. They are of great benefit to workers in providing a flexible production and working environment, and they are also very adept at doing heavy and monotonous work that workers have difficulty with (Proente, 2020).

While Industry 4.0 aims to increase mass production, the product produced in Industry 5.0, which will take place from now on, will be more suitable for people's personal needs and contain more complicated details. Therefore, manual labor is more necessary in production, and cobots working with workers will undertake monotonous and heavy loads. The Industry 5.0 summit, which focuses on personalized product, will benefit from the interaction of workers and cobots in many sectors such as health, education, supply chain, logistics, and natural disasters (earthquake, fire, disease, etc.) (Maddikunta et al., 2021).

2.3.1 Human-Cobot Systems Interaction Ways

Different communication ways can be chosen between the worker and the cobot, depending on the task to be accomplished. (Hashemi-Petroodi, Thevenin, Kovalev, & Dolgui, 2020).

- Coexistence/Independent: Although there is no communication between them, worker and cobot take on different tasks, not working in different places
- Synchronized/Sequential: A situation where the worker and the cobot do not work at the same time, but work in the same place. They alternately perform two tasks in the same item.
- Cooperation/Simultaneous: Robots and workers take joint work together. But their duties are different.
- Collaboration/Supportive: Both fulfill a common task; a hybrid mission on a single item jointly

2.3.2 Human-Cobot Communication

Possible modes of communication between workers and robots (Hashemi-Petroodi et al., 2020) are. The possible modes of communication between humans and cobots can be seen in several ways. Communication mode types and their definitions are intended to be made and defined in this section.

• Direct physical interaction:	There may be body contact with a cobot.
• Remote contactless interaction	Interfaces such as motion recognition software are used to communicate between worker and cobot.
• Teleoperation	Thanks to an interface, people can drive a cobot
• Message exchange	Knowledge is interchanged thanks to digital signals transmitted via tangible buttons.

It is known that cobots assisting workers actually have more dexterity than robots. Collaboration between humans and robots high-impact initiative. Collaboration between humans and cobots has a significant economic impact on the industry (Ajoudani et al., 2018). When humans and robots interact, it is troublesome to maintain a certain level of stability. Both of them are stable within themselves and may be unstable in the system they work with. For example, a fast-running robot and a human trying to adapt to that robot. On the other hand, one of the features that need to be addressed is the transparency of the robot during work. The robot should not oppose the human, and even act according to the human. Transparency is often achieved by force feedback control. Transparency also requires stability.

CHAPTER 3

LITERATURE REVIEW

Since the assembly line design problem occupies a very important place in the industry, there have been many studies in this field for studies on ALB, studies on ALS , simultaneous studies on ALB and sequencing, and studies on recently popular cobots are examined separately. These studies are also grouped within themselves and you can see this grouping in Figure 3.1. The meanings of the abbreviations used in the tables created in each literature review are shown in Figure 3.1.

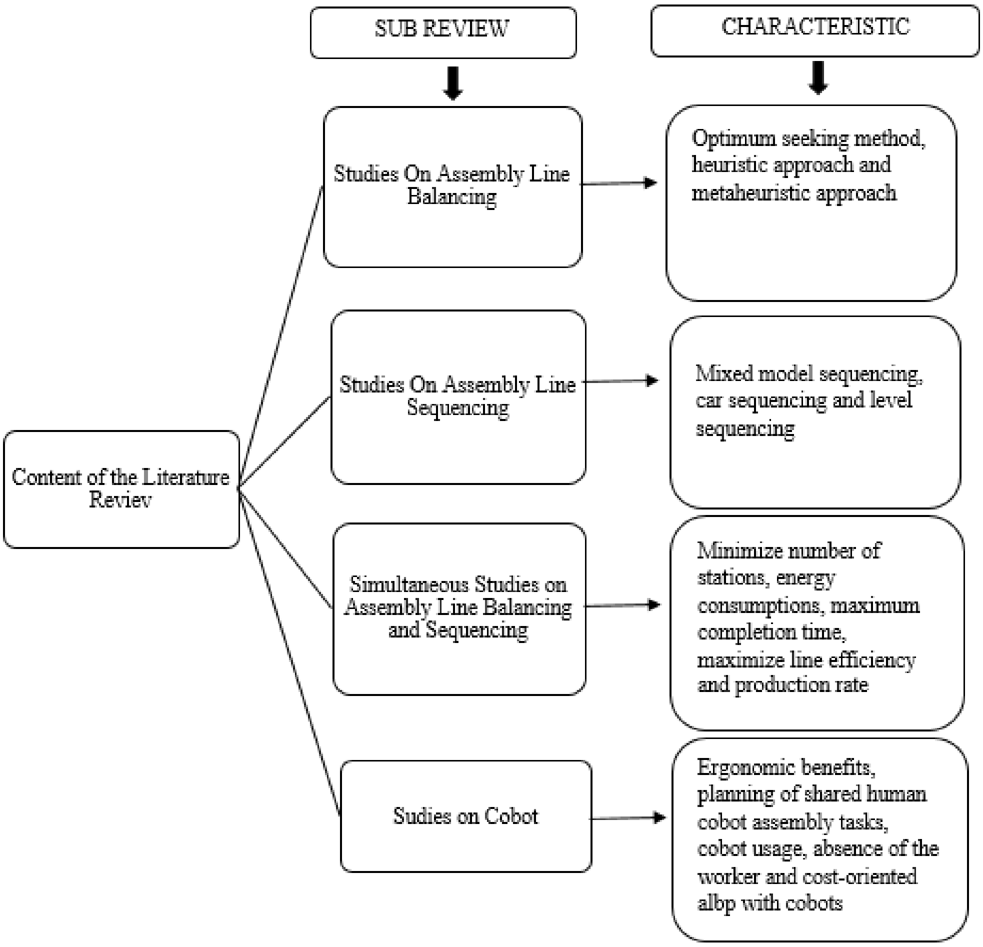

Figure 3.1 Important issues addressed in the literature review

3.1 Studies on Assembly Line Balancing

Bryton (1954) first came up with the idea of balancing ALs. The ALB problem was examined in three groups those who proposing an optimum seeking method, those who proposing a heuristic approach, and those who proposing a metaheuristic approach.

First of all, studies that propose optimum seeking methods are examined. Salveson (1955) first created his mathematical model. Mete and Ağpak (2013) presented a resource-constrained mathematical model for two-sided assembly line problem (TALBP) lines for large-sized products. Atahan, Kapuağası, Koç, Gençosman, and İnkaya (2018) developed an integer programming (IP) method for the MMALB problem on the elimination of bottlenecks in production and determining the standard time. Michels, Lopes, Sikora, & Magatão (2019) proposed mixed integer linear programming (MILP) with new symmetry-breaking constraints for the multi-man ALB problem. They aimed to find the smallest value of the workers and the stations opened. Shadkam & Ghavidel (2021) proposed a linear integer programming (LIP) model for the increasingly popular hybrid model ALB problem. This model has three purposes: to minimize cycle and idle time of the line, and to raise the line's efficiency's.

Secondly, the studies applying the heuristic method are examined. Helgeson and Birnie (1961) developed a position-weighted position balancing technique that weighted each work item according to the excess of the total time of the work items that follow it. Kilbridge and Wester (1961) developed an intuitive line balancing method by addressing the problems of ordering the models by applying the grouping method around certain rules because the both workstation and cycle time were variable. Moddie and Young (1964) developed a two-stage heuristic solution in that the process times could be utilized as fixed and variable, in which assignments were made according to certain rules in the first stage, and then the optimum line balance was tried to be found with small changes in the cycle time. Arcus (1965) first developed a technique called COMSOAL, which selected the alternative with the least loss of balance after assigning jobs that were suitable to be assigned not exceeding the cycle time and creating various solutions as a result of these appropriate jobs. Dar-El (1973) developed the heuristic solution algorithm called the "West Ratio" of the number of tasks per station, which suggested the idea that the completion time of any job has a normal distribution. Raouf, Tsui, and El-Sayed (1980) improved the "CPM - Critical Path Method", which balanced each station not to exceed the reliability; and wanted to reach the smallest value of workstations. Baybars (1986) developed a five-step heuristic method targeted at reducing the problem size. Shin (1990) suggested a heuristic method that was non-deterministic task time, predicting that the total cost be minimized after they have minimized the cycle time in the workstation. Boctor (1995) has worked on a four-rule heuristic method for ALB aimed at finding smallest value of workstations, and has also solved other ALB problems in the literature with this method and achieved 85% success. Kayar and Akalın (2014) first made a method analysis, the effect of the method analysis on the efficiency of the AL and the production volume was examined, and they performed ALB work with the position weight method.

Finally, studies using the metaheuristic method for ALB problems are examined. Martinez-Contreras (2015) heuristic method used to clarify the balancing problem in the flat AL were adapted for the U-type assembly line and proposed two genetic algorith (GA), which were coded directly and indirectly. Roshani & Nezami (2017) proposed MIP and simulated annealing (SA) methods to clarify the mixed model multi-man ALB. They wanted to minimize the number of workers and the number of stations opened. Küçükkoç (2018) proposed a new ant colony optimization (ACO) method that minimizes the cycle time and the number of stations on the MMALB and TALBP containing incompatible workstations. Foroughi & Gökçen (2018) considered a cost-oriented ALB problem for stochastic tenures. Since there is no test problem to evaluate the efficiency of the GA used to solve the problem, a new test problem has been proposed. B. Zhang & Xu (2020) proposed the ga to solve the type 2 U-shaped assembly line problem. To find the smallest value the energy consumption index and line smoothness of this problem has two objectives. Anel, Català, Serra, & Domenech (2022) propose a new matrix methodology to improve transparency when balancing ALs with straight-line configuration for the MMALB type-2 problem. Balancing is to succeed Algorithmic Transparency while using GA for solving operation times. A summary of the above-mentioned literature review is given in Table 3.1.

Table 3.1 Summary of studies on assembly line balancing

Author(s)	**Methodology**	**Problem Type**
Anel et al., 2022	GA	MMALB
Shadkam & Ghavidel, 2021	LIP	Hybrid model ALBP
B. Zhang & Xu, 2020	An improved flower pollination algorithm	Type-II UALBP
Michels et al., 2019	MILP	Multi-manned ALBP
Foroughi & Gökçen, 2018	A multiple rule-based GA	Stochastic ALBP
Küçükkoç, 2018	ACO	Two-sided MMALB containing incompatible workstations.
Atahan et al., 2018	IP	MMALB with bottlenecks
Roshani & Nezami, 2017	MIP and SA	Multi-manned MMALB
Martinez-Contreras, 2015	GA	UALBP
Kayar & Akalin, 2014	Position weight method	Simple assembly line balancing problem (SALBP)
Mete & Ağpak, 2013	MIP	Type I TALBP
Boctor, 1995	Four-rule heuristic	Type I ALBP
Shin, 1990	Heuristic approach	Type II stochastic ALBP
Baybars, 1986	Five step heuristic	SALBP
Raouf et al., 1980	CPM	Type I SALBP
Dar-El, 1973	West Ratio	Type I SALBP
Arcus, 1965	Comsoal	SALBP
Moddie and Young, 1964	Two-stage heuristic	Type II SALBP
Kilbridge & Wester, 1961	Kilbridge & Wester	SALBP
Helgeson and Birnie, 1961	Position weighted method	SALBP

3.2 Studies on Assembly Line Sequencing

ALS problem was analyzed in three groups as mixed-model sequencing (MMS), car sequencing, and level sequencing research.

First of all, studies dealing with the MMS problem will be examined. Since Boysen, Kiel, & Scholl (2011) proposed mixed-integer linear programming (MILP) and could not get an efficient result, they later suggested a raft and bound algorithm for problem with small and medium data set , and an intuitive tabu search approach for problem with large data set. The researches suggesting a heuristic solution for the MMS problem are as follows. Aroui, Alpan, & Frein (2014) proposed a linear programming model for operators with different characteristics in a different AL and made a case study. Cortez & Costa (2015) proposed the MIP and the GRASP metaheuristic method for MMALB with different workforces where people with disabilities work and job times depend on the worker. Mosadegh, Ghomi, & Süer (2020) propose both the IP model and the hyper-SA method to find the smallest value of iddle time and overload for the MMS problem with processing time.

Secondly, studies dealing with the car sequencing problem will be examined. Prandtstetter & Raidl (2008) present a hybrid variable neighborhood search approach that takes advantage of searching for large neighborhoods by combining LIP and rapidly searching traditional neighborhoods. Duarte, Carvalho, & Barbosa-Póvoa (2012) have integrated a new color spread heuristic into the IP to cluster car colors, trying to put all custom cars first. Golle, Rothlauf, & Boysen (2015) modeled car sequencing as a directed acyclic diagram and proposed an IBS (iterative beam search) algorithm. They improved the existing lower bounds by including the objective function and used the sliding window technique function as the objective function. X.-y. Zhang, Gao, Wen, & Huang (2018) proposed a hybrid algorithm based on tabu search and large neighborhood search, but compared it with previous studies and achieved a high success rate. Moya, Chica, & Bautista (2019) propose a greedy randomized adaptive search procedure, ACO, and variable neighborhood search metaheuristics for situations that are defined by dissimilar production plans, violating different problem constraints as they move from one scheme to another. Li, Tang, Liulianchao, & Yan (2021) proposed improved ACO for a two-objective problem and compared this proposed method with traditional ACO and GA.

Lastly, studies dealing with the level sequencing problem will be examined. Boysen, Fliedner, & Scholl (2009) presented a complete dynamic programming (CP) approach and heuristic SA procedure, observing storage constraints that can significantly limit the smoothing of part usage at stations of the line, in accordance with the principle of just in time (JIT). Nie, Bai, Jiang, & Pang (2015) proposed the GA method, taking into account these three objectives: lot supply, inventory cost, and maximum shipping load. The scheduling algorithm was used to transform the individuals in the GA into a candidate scheduling scheme. Yavuz & Ergin They (2018) combined the problem of car scheduling and level scheduling and developed an advanced constraint propagation algorithm. While developing this constraint, the branch-bound (B&B) algorithm was used. A summary of the above-mentioned literature review is given in Table 3.2.

Table 3.2 Summary of studies on assembly line sequencing

Author(s)	**Methodology**	**Problem Type**
Li et al., 2021	ACO and GA	Car sequencing problem
Mosadegh et al., 2020	IP and the hyper-SA	Mixed model sequencing problem
Moya et al., 2019	ACO and variable neighborhood search metaheuristics	Car sequencing problem
Yavuz & Ergin, 2018	Advanced constraint propagation algorithm	Level sequencing and car sequencing problem
Golle et al., 2015	IBS	Car sequencing problem as a directed acyclic diagram
Cortez & Costa, 2015	MIP and the GRASP	Mixed model sequencing problem with different workforces
Nie et al., 2015	GA	Level sequencing problem with three objectives: lot supply, inventory cost, and maximum shipping load
Aroui et al., 2014	Linear Programming (LP)	Mixed model sequencing with different characteristics operators
Duarte et al., 2012	A new color spread heuristic	Car sequencing problem
Boysen et al., 2011	MILP, Tabu search approach, and B&B	Mixed model sequencing problem
Boysen et al., 2009	DP and SA	Level sequencing problem with storage constraints
Prandtstetter & Raidl, 2008	IP and rapidly searching traditional neighborhoods	Car sequencing problem

3.3 Simultaneous Studies on Assembly Line Balancing and Sequencing

Assembly line balancing and sequencing problem (ALB/SP) addresses a problem that combines two separate issues in itself. Different methods are tried for both balancing and sequencing. There may be algorithms that handle two problems at the same time or at different times. Both balancing and sequencing problems are two different types of problems. It is among the subjects that are widely researched in the literature. Different types of ALs can be used when designing an AL.

When we classify the previous studies according to their objectives, the studies that try to minimize the number of stations ($\sum_{i=1}^{N} ti/C$) are as follows. Hamzadayi & Yildiz (2013) propesed the model strings of the line were based on the minimum set of parts (MPS) principle. Enhanced meta-heuristics were used to solve the type1 mixed model U line balancing and sequencing problem (MMUL / BS) problem. Ignored model ordering and developed this approach. The SA-based conformity assessment approach proposed by Hamzadayi and Yıldız (2012) was developed by adding the tabu list and placed in SA to solve the Type 1 MMUL / BS problem. Absolute deviation of workloads (ADW) is an inadequate performance criterion. The proposed suitability function has been simplified by removing the components of parallel workstation assignments to overcome the ADW-induced inadequacy and make comparisons. Unlike other studies, Hamzadayi & Yildiz (2012) deals with many alternatives together. In addition, there are some zoning restrictions within the line. Not every job is done at every station. To provide easy and effective suitability evaluations in the Priority-Based GA (PGA), a SA-based conformity assessment approach has been developed. Kucukkoc & Zhang (2014) proposed the parallel two-sided assembly line was used as an AL type. The purpose of such an approach is to even find the smallest value of workers required and increase the rate of production. The line on which the models will be produced is clear. Due to these situations, the cycle time of the line varies. Defersha & Mohebalizadehgashti (2018) was tried to obtain a common cycle time for the lines. The model strings of each line considered in this study are based on the MPS principle. The cost of assigning common tasks between various models to different workstations with task replication costs is called task replication cost. the goal is to minimize the number and length of workstations, as well as the total cost, which is the sum of the workstation cost and task replication cost. Özcan, Kellegöz, & Toklu (2011) proposed the U-type assembly line type was used. Since the deterministic processing time does not reflect the reality, the task times of the jobs in the models are stochastic variables. The model strings of every line thougt in this work are based on the MPS. Lian, Zhang, Gao, & Shao (2012) studied demand (m) for each model is indicated by Dm. Let Dm of the demand be the greatest common divisor of q. MPS's formula is d = (d1, d2, ..., dM), dm = Dm / q. The purpose of the model is to find the smallest valueof workstations opened, beside to minimize the ADW.

The continuation studies that tries to minimize the energy consumption ($F_2= E_p +E_n$) E_p =Processing energy consumption; E_n =Non-processing energy consumption. B. Zhang, Xu, & Zhang (2020) has three sub-problems. First problem is robot allocation. Secound problem is task assignment. And last problems is model sequencing. Goal is to reduce energy consumption and production time simultaneously. Unlike other studies, it aims to minimize the energy consumed by robots in the line. It transforms the MMU / BS (mixed-model U-type robotic assembly line) problem into a SULB (single model U-type robotic ALB) problem by combining the priority diagrams of the models into a combined priority diagram.

The continuation studies that try to maximizing line efficiency ($\sum_{i=1}^{N} ti/K * C$). Hwang & Katayama (2010) dealed with the MMALB and they dealed with both the ALB/SP. While dealing with these problems, they had identified two criteria as both line efficiency and workload variance. The cycle time differed for each station. When calculating the cycle time, it was determined by dividing the total work time by the sum of products to be produced on that line. The model strings of each line considered in this study are based on the principle of MSP. Unlike other studies, Mosadegh, Zandieh, & Ghomi (2012) proposed the model that tasks was processed at different times in each station. A new Mixed Integer Programming (MIP) model had been created. Faccio, Gamberi, & Bortolini (2016) worked an additional flexible workforce called "jolly operators" was used to manage work overloads. These supplementary workers couldn’t be assigned to a station on their own and can perform all tasks to assist the station's permanent workers. It focused on two different sequencing approaches that guarantee no overload and minimize job overload by keeping the number of jolly operators constant.

The contunation studies that try to minimize maximum completion time (min $Cmax = max\left(\sum_{j=1}^{n} x(i,j) * t(i,j)\right)$). Z. Zhang (2021) proposed MILP, a constraint programming (CP) model, and SA algorithm for the MMALB problem with station-dependent processing times. The purpose of this model is to minimize the duration of the last completed work.

The following studies that try to maximize the production rate ($\sum_{i=1}^{N} ti/N$). Uddin, Soto, & Lastra (2010) discussed with a two-stage balancing and sequencing integrated approach. While the first stage aimed at the minimum cycle time, the goal of the second stage, which provided the minimum balance delay, is to get the best solutions from the first stage. It distributed the workloads of mixed models to predefined workstations by considering SSAL (smoothed station assignment load). This findings in optimizing the assembly lines' shift timing for any combination of the various models. The main goal was an approach that maximizes the production rate. Lopes, Michels, Sikora, & Magatão (2019) used the OCRA index as an ergonomic risk method: MMALB, stochastic task times with parallel workstations. A summary of the above-mentioned literature review is given in Table 3.3.

Table 3.3 Summary of simultaneous studies on balancing and sequencing

Author(s)	Methodology	Problem	Objective(s)
Z. Zhang, 2021	MILP, CP, and SA	Station-dependent assembly times MMALB/S	Minimizing maximum completion time for tasks
B. Zhang et al., 2020a	A hybrid multi-objective dragonfly algorithm (HMODA)	Robotic MMULB/S	Minimizing energy consumption and production time
Lopes et al., 2019	MILP	Asynchronous MMALB/S with parallel stations	Maximizing production rate
Defersha & Mohebalizadehgashti, 2018	LP embedded hybrid GA	Manuel MMALB/S	Minimizing the number and cost of workstations
Tiacci & Mimmi, 2018	GA	Mixed-model stochastic asynchronous ALs	Minimize total design costs and maximizing production rate
Faccio et al., 2016	Innovative balancing and sequencing hierarchical approach	A hierarchical approach for paced MMALB/S	Minimizing the number of jolly operators and workload
Kucukkoc & Zhang, 2014	Agent-based ACO	Parallel two-sided MMALB/S	Minimizing the number of workers and maximizing the production rate
Hamzadayi & Yildiz, 2013	SA	MMULB/S	Minimizing the number of workstations
Lian et al., 2012	A modified colonial competitive algorithm	MMULB/S	Minimizing the number of workstations and ADW
Hamzadayi & Yildiz, 2012	GA	Parallel workstation and zoning constraints MMULB/S	Minimizing the number of workstations
Mosadegh et al., 2012	Co-evolutionary GA and SA	Station-dependent assembly times MMALB/S	Minimizing total utility work
Özcan et al., 2011	GA	Stochastic MMULB/S	Minimizing the number of workstations
Uddin et al., 2010	An integrated approach	MMALB/S	Maximizing production rate
Hwang & Katayama, 2010	Multi-objective evolutionary approach	MMALB/S and MMULB/S	Minimizing workload variance and maximizing line efficiency

3.4 Studies on Cobots

Despite the insufficient number of studies, among the benefits of worker-cobot cooperation, especially the ergonomic benefits attract attention (Maurice, 2015; Y.-J. Zhang, Liu, Huang, Radwin, & Li, 2021), planning of shared human cobot assembly tasks (Michalos, Spiliotopoulos, Makris, & Chryssolouris, 2018; Pearce, Mutlu, Shah, & Radwin, 2018; Zaki, Fathy, Carnevale, & Giberti, 2022), cobot usage in ALs (Dalle Mura & Dini, 2019; Gil-Vilda, Sune, Yagüe-Fabra, Crespo, & Serrano, 2017; Weckenborg, Kieckhäfer, Müller, Grunewald, & Spengler, 2020), lost cost incurred in the absence of the worker (Cohen & Shoval, 2020) and cost-oriented ALB problem with cobots (Z. Li, Janardhanan, & Tang, 2021).

Maurice (2015) focused on developing a different method to compare the benefits provided by cobots assisting workers, especially in quantitative terms. Gil-Vilda et al. (2017) first convert the straight line to a U-type line and then assign the cobots to the line. Contrary to popular belief, U-type cobots, which do not even take up much space, have shown that they increase productivity and reliability. Michalos et al. (2018) created a multi-criteria smart algorithm to organize cell layout and assignments of tasks. Menges, Sarrey, & Henaff (2018) suggested the use of cobots for problems where hard steel is processed, heavy loads are carried and exposed to high temperatures, that is, many ergonomic risks. As a result, they have seen that the risks in terms of ergonomics are reduced. Pearce et al. (2018) proposed MILP with task assignments and schedules to improve overall time and ergonomics. They used the hierarchical task analysis method for task assignments. They used the strain index table to calculate the risks. Dalle Mura & Dini (2019) using a GA solution approach, aimed to find the smallest value the cost of the AL with workers and cobots, as well as to find the smallest value the number of qualified workers and changing in the line. Cohen & Shoval (2020) assign a cobot to the temporary worker who replaces him so that the production speed and cost do not decrease in the absence of the worker. The reason for this is that it wants to prevent bottlenecks that may arise from inexperienced workers. Weckenborg et al. (2020) address both the balancing and sequencing problem as they assign cobots and workers to the station. MIP and hybrid GA approaches are suggested to analyze this problem, the aim of which is to find the smallest value the cycle time. Y.-J. Zhang et al. (2021) proposed a new combined model to both improve production rate and diminish ergonomic problems. On the AL, the combination of both independent and supporting is handled for human and cobot. Z. Li et al. (2021) first took cobots with different features and different purchasing costs and integrated them into the AL. This model, which aims to find the smallest value both the expense and the cycle time and, causes dissimilar situations. They developed a MIP and a multi-objective migratory bird optimization algorithm. Zaki et al. (2022) discussed a production facility that assembles products coming from a conveyor where workers, robots, and cobots work together. Efforts were made to increase productivity by reducing the waiting time of the robots on the AL. A summary of the above-mentioned literature review is given in Table 3.4.

Table 3.4 Summary of studies on cobots

Author(s)	**Methodology**	**The subject of the problem**
Zaki et al., 2022	Dynamic road-map algorithms	Planning of shared human cobot assembly tasks
Y.-J. Zhang et al., 2021	A Jointly Model of Efficiency and Ergonomic Performance	Ergonomic benefits of collaboration
Z. Li, Janardhanan, & Tang, 2021	MILP and multi-objective migrating birds optimization algorithm	Cost-oriented ALB problem with cobots
Cohen & Shoval, 2020	Learning curve	Absence of the worker
Weckenborg et al., 2020	MIP and hybrid GA	Cobot usage in ALs
Dalle Mura & Dini, 2019	GA	Cobot usage in ALs
Pearce et al., 2018	MILP	Planning shared human cobot assembly tasks and ergonomic benefits of the collaboration
Menges, Sarrey, & Henaff,2018	Empirical methodology	Ergonomic benefits of collaboration
Michalos et al., 2018	Multi-criteria	Planning shared human cobot assembly tasks
Gil-Vilda et al., 2017	Empirical methodology	Cobot usage in ALs
Maurice, 2015	Dynamic simulation and GA	Ergonomic benefits of collaboration

CHAPTER 4
PROBLEM DEFINITION

In this thesis study, collaborative assembly line balancing problem is considered where worker and cobot can work on the same job on the same line. The important thing in this collaborative work is to perform the task sharing correctly. In order to create an effective distribution of tasks, it is necessary to examine, create and design the cell layout after an in-depth research (Michalos et al., 2018). No additional security measures are required for co-workers and cobots. In this way, a safe working environment is provided to the workers.

4.1 Basic Problem Definition

A general representation of the assembly line with co-operative workers and cobots is shown in Figure 4.1.

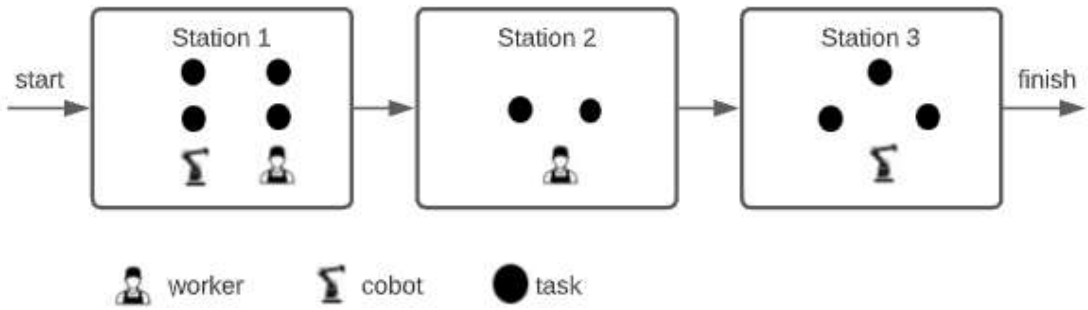

Figure 4.1 Workers-cobots in the assembly line

As seen in the figure, the worker and the cobot can be assigned to different stations as well as to the same station. When the worker and cobot are assigned to the same station, the tasks assigned to the cobot are different than the tasks assigned to the different worker. A set of n tasks $i \in I$ have to be allocated among the stations of the system. A set of $r \in R$ containing process alternatives is available. Process alternatives are assumed to be either a worker ($r \in 1$) or a cobot ($r \in 2$). The worker and cobot considered in the problem are of different types. Since each process is one of its alternative type, they can be assigned only once. A set of $w \in W$ refers to this type of process alternative. Processing times t_{irw} (in min) are not variable and stochastic and for each task i, resource r, and type w. The s_i is presented to define the start time of the task i at the station to which the task is assigned, which $(i, j) \in E$ about the priority relations of the tasks, guarantees that the i task in the station is done before the j task, so j can start at the earliest after the end j at the partner stations. The total duration of tasks assigned to stations must not exceed cycle time c (in min). x_{ikrw} tells us whether the task i is assigned to station k, resource r, and type w. y_{krw} indicates whether w type of resource r is assigned to station k or not. Z_{kij} gets value if task i assigned to station k comes before task j.

In order to better define and understand the problem under consideration, several assumptions should be identified. The assumptions of collaborative ALB problem are listed as follows:

- One type of product is assembled on the line; single model ALB problem.
- There are tasks that are deterministic and have known processing times.
- There is a priority diagram of the tasks.
- Processing times of jobs depend on the type of process alternative.
- Cycle time is known; type 1 ALB problem.
- A cobot and a worker may not be assigned to the different station. Actually, a cobot and a worker can accomplish different tasks simultaneously at the same station.
- The divisibility of the tasks was not accepted in this study.
- Transportation of the material requires some time, but it has been neglected in this study.
- A worker or a cobot can also be assigned to a station.
- Workers and cobots can do different work at the same time.
- The line configuration is a straight line. A parallel station is not allowed.

Before starting the study, a mind mapping was done to decide which topics to cover. This mind mapping is expressed in Figure 4.2.

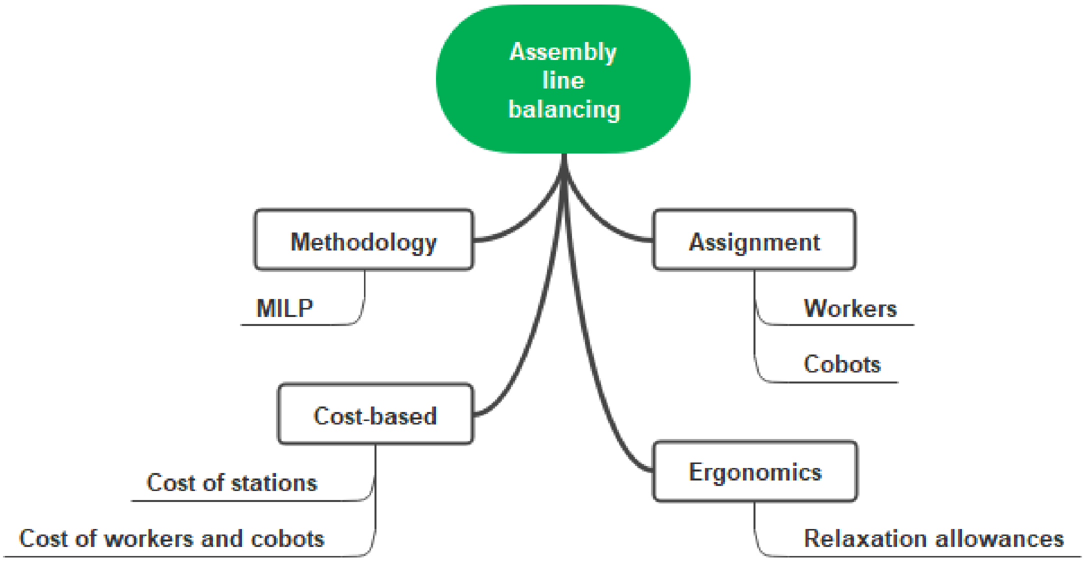

Figure 4.2 Mind map of the study

4.1.1 Economical Perspective

Economical perspective consists of two different group as cost of workstations and resources. Two types of costs are used while considering the economical perspective of collaborative ALB problem. The first one is associated with the operation of workstations and the second one is assocated with the resources, i.e. workers and cobots. Here are the detailed definitions of the costs;

- Cost of stations per minute denoted as CK is the interest and depreciation cost for a station's transportation and machinery system. This is the sum of the cost of capital. (Amen, 2006).
- Cost of type w of resource r denoted as C_{rw} is divided into two groups as workers and cobots. The first group refers to the cost per minute paid to workers. The other cost per minute is cobot's accessories, price, assembly, and interests.

4.1.2 Ergonomical Perspective: Energy Expenditure of Workstations

While workers are working on the AL, it is necessary to protect them from work accidents or occupational diseases, that is, to make the working environment more ergonomic, and this will become much more popular both today and in the future (Otto & Scholl, 2011). Previous studies have been taken into account and although the importance of ergonomics is indisputable, several concepts of ergonomics have been explained and used in the study. One of the important reasons for the occurrence of occupational diseases is exceeding the energy requirement. Of course, this situation, which causes extreme fatigue, will inevitably turn into an occupational disease over time. From this point of view, here are the detailed definitions used in this study;

- Energy expenditure denoted as ei is the amount of energy the worker needs to perform the task.
- The mean work rate (MWR) is the rate determined by the energy expenditure of the tasks performed by the workers (which is just a physical unit of measurement that is not financial).
- The relaxation allowances (RA) is the resting share in which the relaxation rate (RR) is also taken into account so that the worker's acceptable work level (AWL) is not exceeded. (Price, 1990).

While reviewing the literature, it is found that workers may maintain AWL = 4.3 $k$cal/min throughout their workday, while RR= 1.86 $k$cal/min are needed while relaxing in standing (Battini, Calzavara, Otto, & Sgarbossa, 2017).

As MWR= $\frac{e_i}{t_{irw}}$, where e_i (in kcal) is the energy expenditure of type w of worker r conducting task i. RA calculates to (4.1)

$$RA = max\left\{0 \middle| \frac{\sum_i e_i / \sum_i t_{irw} - AWL}{AWL - RR}\right\} \tag{4.1}$$

When considering RA, the final execution time for a type w of worker r is calculated as (4.2)

$$\sum_i x_{ikrw}.\, t_{irw}.\,(1 + RA) \qquad \forall k\in K,\ \forall r\in 1,\ \forall w\in W \qquad (4.2)$$

If we express the workstation time with a simpler formula (4.3)

$$\sum_i x_{ikrw}.\, t_{irw}.\left[1 + max\left\{0\,, (\sum_i x_{ikrw}.\, e_i \Big/ \sum_i x_{ikrw}.\, t_{irw} - 4.3)/(4.3 - 1.86)\right\}\right] \qquad (4.3)$$

$$\forall k\in K,\ \forall r\in 1,\ \forall w\in W$$

Since Equation (4.3) is non-linear, Finco et all. (2020) established the following constraints (4.4-4.9) to make this equation linear. In addition, the boolean variable B_{krw} has been added. (4.1), (4.2), and (4.3) do not apply for cobots.

Workstation time;

$$\sum_i x_{ikrw}.\, t_{irw} + RA'_{krw} \qquad \forall k\in K,\ \forall r\in 1,\ \forall w\in W \qquad (4.4)$$

RA**$_{krw}$**;

$$\frac{1}{4.3 - 1.86}.\sum_i x_{ikrw}.\, e_i - \frac{4.3}{4.3 - 1.86}.\sum_i x_{ikrw}.\, t_{irw} \qquad \forall k\in K,\ \forall r\in 1,\ \forall w\in W \qquad (4.5)$$

$$RA'_{krw} \geq RA_{krw} \qquad \forall k\in K,\ \forall r\in 1,\ \forall w\in W \qquad (4.6)$$

$$RA'_{krw} \geq 0 \qquad \forall k\in K,\ \forall r\in 1,\ \forall w\in W \qquad (4.7)$$

$$RA'_{krw} \leq RA_{krw} + M(1 - B_{krw}) \qquad \forall k\in K,\ \forall r\in 1,\ \forall w\in W \qquad (4.8)$$

$$RA'_{krw} \leq M.B_{krw} \quad \forall k \in K, \forall r \in 1, \forall w \in W \tag{4.9}$$

4.2 Problem Formulation

Following the basic problem definition, the problem is formulated in detailed by using MIP. For this purpose, first notations are explained and then the mathematical model is constructed.

4.2.1 Notations

The notations, i.e. sets, parameters and variables, addressed in this study are given in Table 4.1 together with their definitions.

Table 4.1 Sets, parameters, and variables

$i,j \in I$	Set of assembly task $\{1,\ldots,n\}$
$k \in K$	Set of station $\{1,\ldots,K\}$
$r \in R$	Set of process alternative $\{1,\ldots,R\}$. If r=1 it means worker, if r=2 it means cobot.
$w \in W$	Set of the type of process alternative to be assigned {1,…, W}
$(i,j) \in E$	Set of direct precedence relations $\{i,j\}$. Task i is the predecessor of task j
c	Cycle time (min)
t_{irw}	Processing time of task i on resource r and type w (in min)
s_i	Start time of task i at the corresponding station
C_{rw}	Minute cost of type w of resource r (EUR)
CK	Minute cost of station (EUR)
M	*Big M*
x_{ikrw}	Binary variable. 1, If job i is assigned to station k, resource r, and type w. 0, in other case
y_{krw}	Binary variable. 1, if type w of resource r is assigned to station k 0, in other case
Z_{kij}	Binary variable. 1, if task i comes before task j at station k. 0, in other case

4.3.2 Mathematical Model

Construction of the mathematical model representation of collaborative ALB problem with worker and cobot assignment is given below. Since the objective function (4.10) relies on the economical perspective, first the costs are explained in detail.

Min Z;

$$c. \sum_{k \in K} \sum_{r \in R} \sum_{w \in W} y_{krw} . C_{rw} + c. \sum_{k \in K} \sum_{r \in R} \sum_{w \in W} x_{nkrw} . k.CK \qquad (4.10)$$

Objective function in equation (4.10) aims to find the smallest value the cost of a cycle. It tries to minimize the types *w* of resources *r* assigned to station *k* and the cost of opening a station *k*. The objective function of the problem tries to minimize the two different costs mentioned earlier.. The first part represents minimizing the cost of station *CK* (interest and depreciation cost for a station's transportation and machinery system of one station). The second part tries to minimize the minute cost of worker and cobot types C_{rw}.

Following the objective function, the constraints are explained in detail.

Constraint 1 in (4.11): For each task *i* will be assigned to a station *k*, a resource *r*, and a type *w*.

$$\sum_{k \in K} \sum_{r \in R} \sum_{w \in W} x_{ikrw} = 1 \qquad \forall i \in I \qquad (4.11)$$

Constraint 2 in (4.12): When the start time s_i of a task *i* assigned to a station *k* and the processing time t_{irw} of that task *i* are added together, it can not exceed the cycle time *c*.

$$s_i + \sum_{k\in K}\sum_{r\in R}\sum_{w\in W} x_{ikrw}.t_{irw} \le c \qquad \forall i\in I \qquad (4.12)$$

Constraint 3 in (4.13): The total time of the tasks *(i,j)* assigned to the station cannot exceed the cycle time *c*.

$$\sum_{i\in I} x_{ikrw}.t_{irw} \le c \qquad \forall k\in K, \forall r\in R, \forall w\in W \qquad (4.13)$$

Constraint 4 in (4.14): It is a precedence relation constraint. Since task *i* is the predecessor of task *j*, task *i* must be assigned to the station *k* before task *j* is assigned or assigned to the station *k* to which task *j* is assigned.

$$\sum_{k\in K}\sum_{r\in R}\sum_{w\in W} x_{ikrw}.k - \sum_{k\in K}\sum_{r\in R}\sum_{w\in W} x_{jkrw}.k \le 0 \qquad \forall (i,j)\in E \qquad (4.14)$$

Constraint 5 in (4.15): Scheduling constraint for tasks assigned to the same station. If task *i* is performed before task *j* at the same station *k*, the earliest start time s_j of task *j* is found when the start time s_i of task *i* and the processing time t_{irw} are added.

$$s_i + \sum_{r\in R}\sum_{w\in W} x_{ikrw}.t_{irw} \le s_j + M(1 - Z_{kij}) \qquad \forall (i,j)\in I, \forall k\in K \qquad (4.15)$$

Constraint 6 in (4.16): Scheduling constraint for tasks *(i,j)* assigned to the same station. If task *j* is performed before task *i* at the same station *k*, the earliest start time s_i of task *i* is found when the start time s_j of task *j* and the processing time t_{jrw} are added.

$$s_j + \sum_{r\in R}\sum_{w\in W} x_{jkrw}.t_{irw} \le s_i + M(1 - Z_{kji}) \qquad \forall (i,j)\in I, \forall k\in K \qquad (4.16)$$

Constraint 7 in (4.17): Provides priority constraint for tasks $(i, j) \in E$ assigned to the same station. If task *i* is the predecessor of task *j*, task *i* must be done before task *j* if assigned to the same station.

$$Z_{kij} \geq 1 - M(1 - \sum_{r\in R}\sum_{w\in W} x_{ikrw}) - M(1 - \sum_{r\in R}\sum_{w\in W} x_{jkrw})$$

$$\forall (i,j)\in E,\ \forall k\in K \qquad (4.17)$$

Constraint 8 in (4.18): Scheduling constraint for tasks *(i,j)* assigned to the same station k.

$$Z_{kij} + Z_{kji} \geq 1 - M(1 - x_{ikrw}) - M\left(1 - x_{jkrw}\right)$$

$$\forall (i,j)\in I,\ \forall k\in K,\ \forall r\in R,\ \forall w\in W,\ i\neq j \qquad (4.18)$$

Constraint 9 in (4.19): Scheduling constraint for tasks *(i, j)* assigned to the same station. It is the constraint to find the value of Z_{kij}.

$$Z_{kij} \leq \frac{1}{2}(\sum_{r\in R}\sum_{w\in W} x_{ikrw} + \sum_{r\in R}\sum_{w\in W} x_{jkrw}) \qquad \forall (i,j)\in I,\ \forall k\in K \qquad (4.19)$$

Constraint 10 in (4.20): It guarantees that task *i* will be made of type *w* of the resource *r* at the opened station *k*.

$$x_{ikrw} \leq y_{krw} \qquad \forall i\in I,\ \forall k\in K,\ \forall r\in R,\ \forall w\in W \qquad (4.20)$$

Constraint 11 in (4.21): Express the relation between x_{ikrw} and y_{krw}. The constraint ensures that every task *i* is assigned to the type *w* of the resource *r* assigned to the opened station *k*.

$$\sum_{i\in I} x_{ikrw} \leq M.y_{krw} \qquad \forall k\in K,\ \forall r\in R,\ \forall w\in W \qquad (4.21)$$

Constraint 12 in (4.22): Express the relation between x_{ikrw} and y_{krw}. If the type *w* of source *r* is assigned to station *k*, then at least one task *i* must be assigned to that station *k*.

$$\sum_{i \in I} x_{ikrw} \geq y_{krw} \qquad \forall k \in K, \forall r \in R, \forall w \in W \tag{4.22}$$

Constraint 13 in (4.23): It guarantees that a maximum of 2 resources *r* will be assigned to each station. At most one type of worker and cobot *w* can be assigned to a station *k*.

$$\sum_{r \in R} \sum_{w \in W} y_{krw} \leq 2 \qquad \forall k \in K \tag{4.23}$$

Constraint 14 in (4.24): The number of workers to be assigned to the station must be at most 1.

$$\sum_{r \in 1} \sum_{w \in W} y_{krw} \leq 1 \qquad \forall k \in K \tag{4.24}$$

Constraint 15 in (4.25): The number of cobots to be assigned to the station must be at most 1.

$$\sum_{r \in 2} \sum_{w \in W} y_{krw} \leq 1 \qquad \forall k \in K \tag{4.25}$$

Constraint 16 in (4.26): Each worker and cobot type *w* can be assigned to a station only once.

$$\sum_{k \in K} y_{krw} \leq 1 \qquad \forall r \in R, \forall w \in W \tag{4.26}$$

Constraint 17 in (4.27): Domain of the decision variable.

$$\begin{gathered} x_{ikrw} \in \{0,1\}, \ y_{krw} \in \{0,1\} \\ Z_{kij} \in \{0,1\}, \qquad S_i \geq 0 \end{gathered} \tag{4.27}$$

CHAPTER 5

PROPOSED TWO-STEP SOLUTION METHODOLOGY

In order to provide a systematic stucture for this thesis, a two-step solution methodology is proposed to create an ALB solution that assigns workers and cobots of different characteristics and costs, while reducing the cost per cycle. This methodolgy is illustrated in Figure 5.1.

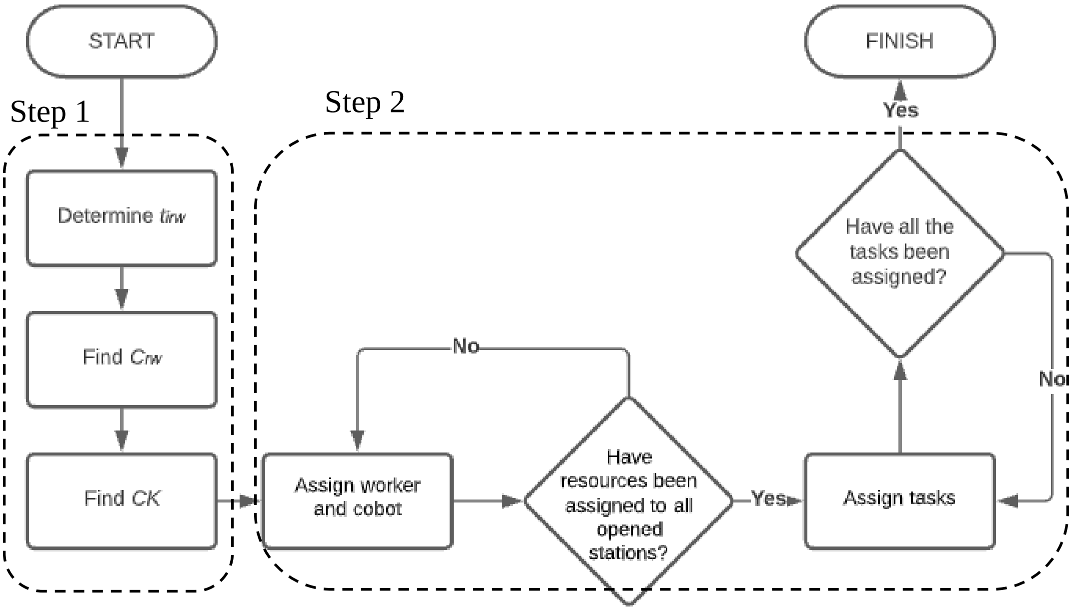

Figure 5.1 Collaborative assembly line balancing solution methodology

As stated in chapter 4, some preliminary calculation regarding to costs and energy expenditures need to be done first. Therefore, the first step of the proposed solution methodology requires preliminary calculations to find the parameters of the mathematical model. The second step is the solution of the MIP model that is constructed in sub section 4.2.

Here are detailed information about these steps;

Step 1 *Preliminary calculations*

- ***Step 1.1*** Determine processing times for each worker and cobot (t_{irw}).
- ***Step 1.2*** Find the cost per minute for each worker and cobot (C_{rw}).
- ***Step 1.3*** Find the cost per station (CK).

Step 2 *Solution of Mathematical modeling*

- ***Step 2.1*** Assign worker and cobot to the correct station stations least costly (dual or single)
- ***Step 2.2*** Assign priority-associated tasks.

Repeat Step 2.1 and Step 2.2 until you find the right process alternatives that will cost all the tasks the least.

CHAPTER 6
PERFORMANCE EVALUATION

In the first part of this chapter, to demonstrate applicability of the proposed methodology in reaching the solution under consideration and to obtain quantitative evidence, a known example problem from a recent study has been modified and solved. In the second part of this chapter, to evaluate the effectiveness of cobot usage, scenario analysis is performed while modifying some features of the illustrative example.

6.1 Illustrative Example

For illustrative purposes, a real case problem that has been considered in Weckenborg and Spengler's study (2019) is used in this study. Since the original problem (Weckenborg & Spengler, 2019) included data from Germany, Euro values were used during the calculations. For this purpose, a priority diagram consisting of a total of 17 work items is given in Figure 6.1. The cycle time suggested by Battini et al. (2017) was used in the study, which deals with a real-life problem. Cycle time (*c*) is found as three minutes per product. For the calculation purposes, it is considered that the company is working 230 days per year, eight-hour shifts in one day, and a total of 552,000 minutes, which corresponds to a five-year depreciation period.

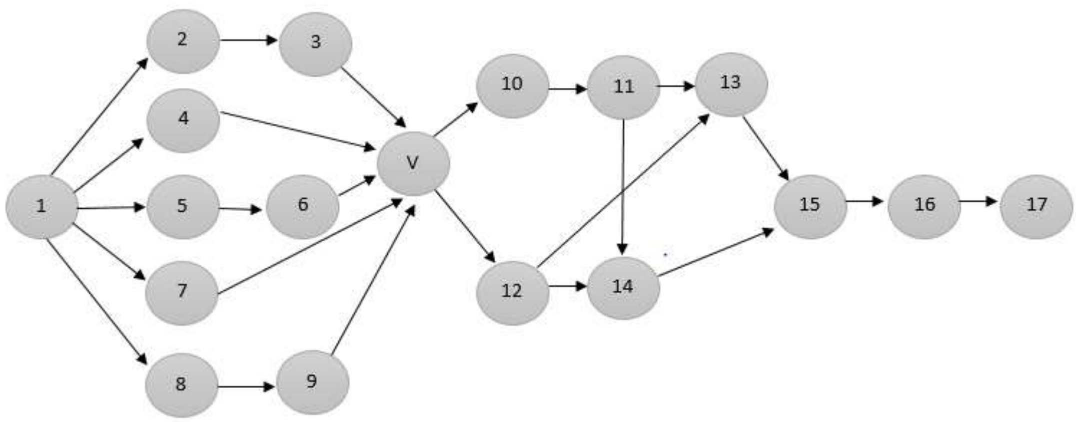

Figure 6.1 Task priority diagram of the sample problem

The energy expenditure e_i value required for each task is given in Table 6.1.

Table 6.1 The amount of energy expenditure for each task

Task (i)	Energy expenditure (e_i)
1	0.95
2	2.69
3	0.9
4	0.18
5	1.19
6	0.88
7	0.15
8	1.23
9	0.96
10	4.56
11	5.07
12	1
13	1.08
14	1.17
15	0.92
16	0.5
17	0.63

The two-step solution methodoly that was proposed in Chapter 5 is used to solve this illustrative example to show the applicability of the methodology.

6.1.1 Step 1: Preliminary Calculations

Some preliminary calculation regarding to costs and energy expenditures need to be done first.

- ***Step 1.1*** Determine processing times for each worker and cobot *(t_{irw})*.

In Step 1.1 , under consideration, each worker and cobot has different capabilities and costs. There are workers and cobots who do each task item at different times *(t_{irw})*. Therefore, the cost per minute is also different because the worker and cobot complete the task at different times. For the sample problem, four different workers and four different cobots were evaluated. The processing times of the first worker were taken as the benchmark proposed by Battini, Delorme, Dolgui, Persona, & Sgarbossa (2016). The times of the other three workers are additional adaptation inclusion of the times of the first worker. The processing times of the workers in Table 6.2 and the processing times of the cobots in Table 6.3 are given. While calculating the duration of the cobots, it has been observed that the worker works at a slow speed of almost two to three times as seen in previous studies. (Weckenborg et al., 2020).

Table 6.2 Processing times of workers in the sample problem

Task (*i*)	**Processing time of the first worker (t_{irw})**	**Processing time of the second worker (t_{irw})**	**Processing time of the third worker (t_{irw})**	**Processing time of the fourth worker (t_{irw})**
1	0.4	0.24	0.4	0.2
2	0.767	0.38	0.49	0.85
3	0.217	0.2	0.221	0.108
4	0.117	0.1	0.21	0.008
5	0.417	0.4	0.43	0.258
6	0.25	0.23	0.25	0.11
7	0.083	0.08	0.087	0.072
8	0.663	0.612	0.70	0.39
9	0.183	0.129	0.188	0.152
10	1.333	1.191	1.341	1.028
11	1.417	1.502	1.65	1.41
12	0.417	0.20	0.48	0.112
13	1	1.55	1.04	1.381
14	1.17	1.083	1.1	0.627
15	0.75	0.52	0.78	0.313
16	0.417	0.39	0.485	0.181
17	0.267	0.20	0.288	0.058

Table 6.3 Processing times of cobots in the sample problem

Task (*i*)	**Processing time of the first cobot (t_{irw})**	**Processing time of the second cobot (t_{irw})**	**Processing time of the third cobot (t_{irw})**	**Processing time of the fourth cobot (t_{irw})**
1	0.80	0.41	0.767	0.9
2	1.16	1.5	1.03	1.44
3	0.402	0.446	0.387	0.436
4	0.23	0.24	0.217	0.34
5	0.85	0.929	0.841	0.926
6	0.47	0.6	0.52	0.91
7	0.104	0.189	0.155	0.212
8	1.68	1.166	1.06	1
9	0.310	0.438	0.322	0.482
10	2.66	2.62	2.59	2.852
11	2.84	3	4	2.82
12	0.82	0.861	1.073	1.28
13	2	4	2.08	1.9
14	2.02	2	2.02	2.21
15	1.5	1.56	1.68	1.5
16	0.81	0.85	0.718	0.882
17	0.702	0.852	0.72	0.728

Because each worker and cobot complete their work at different times, the pay per minute varies accordingly. Since there are four different workers and four different cobots in the example problem, there are eight different costs in total. Table 6.4 shows the minute cost of workers and cobots.

Step 1.2 Find the cost per minute for each worker and cobot (*C_{rw}*).

In step 1.2, to find the minute cost of workers and cobots, German labor statistics published in 2020 were used for labor costs. In these statistics, the hourly cost of a worker in Germany in 2020 is calculated as 36.5 Euros (Eurostat, 2020). For this reason, the first worker's cost per minute is equivalent to 0.6 Euros. Costs of other types of workers are the additional adaptation inclusion of the cost of the first worker. Considering the price, accessories, installation, etc. costs of a cobot, the cost of the first cobot corresponds to 0.19 Euros per minute, since it will cost 100,000 Euros

(Bélanger-Barrette). Costs of other types of cobots are the additional adaptation inclusion of the cost of the first cobot. Table 6.4 shows the cost of workers and cobots.

Table 6.4 Minute costs of workers and cobots for the example problem

Resource (*r*)	**The first type of process alternative (*w*)**	**The second type of process alternative (*w*)**	**The third type of process alternative (*w*)**	**The fourth type of process alternative (*w*)**
Minute cost of workers (C_{rw})	0.6	0.775	0.652	0.552
Minute cost of cobots (C_{rw})	0.19	0.18	0.30	0.395

- ***Step 1.3*** Find the cost per station (*CK*).

In step 1.3, data to estimate investment in stations is difficult to obtain and, as it depends on assembly processes, we assume the cost per station is EUR 135,000, which includes its equipment and installation, material flow, and interest costs. The resulting depreciation is EUR 0.24/min per station.

6.1.2 Step 2: Solution of the Mathematical Modeling

The MIP model given in Chapter 4 that is constructed and solved for the collaborative ALB problem. This model is solved using GAMS (version 24.9.2). Calculations were run on a standard computer with an Intel® Core™ i5-3230M CPU @ 2.60 GHz and 8 GB RAM. Since the proposed model is linear, CPLEX Solver is used. The screenshot of the solution is given in Figure 6.2. When we add the ergonomic equations of 4.5-4.9 suggested in section 4.1 for workers, to the model, the cost per cycle is found to be 7.251 euros. The solution of the model took 7.33 minutes. The solution is optimal.

```
Proven optimal solution.

MIP Solution:            7.251000    (1362390 iterations, 4327 nodes)
Final Solve:             7.251000    (0 iterations)

Best possible:           7.251000
Absolute gap:            0.000000
Relative gap:            0.000000
```

Figure 6.2 GAMS solution for ergonomic collaborative assembly line

- ***Step 2.1*** Assign worker and cobot to the correct station stations least costly (dual or single)

In step 2.1 which assigns workers and cobots, this AL, which consists of three workstations, a configuration of two cobots and two workers is seen. The second worker and the second cobot are assigned to the first station. The first cobot is assigned to the second workstation. The fourth worker is assigned to the third workstation.

- ***Step 2.2*** Assign priority-associated tasks.

In step 2.2 which assigns priority-associated tasks and process alternatives to the correct station, the second cobot is assigned to the first workstation to do the 4th, 5th, and7th tasks. The second worker is assigned to the first workstation to do the 1st, 2nd, 3rd, 6th, 8th, 9th and 10th tasks. Since the 5th task is the successor of the 1st task, the 5th task was started with the completion of the 1st task The first cobot is assigned to the second workstation to do the 11th task. The fourth worker is assigned to the third workstation to do the 12th, 13th, 14th, 15th, 16th and 17th tasks. The total durations of the workstations are 2.982, 2.84, and 2.672, respectively. The cost per cycle is 7.251 Euro. The ergonomic collaborative assembly solution of the model is shown in Figure 6.3. As seen in this figure, the worker and the cobot work together on the AL. The assigned cobot or worker and also the task numbers are shown inside the workstations.

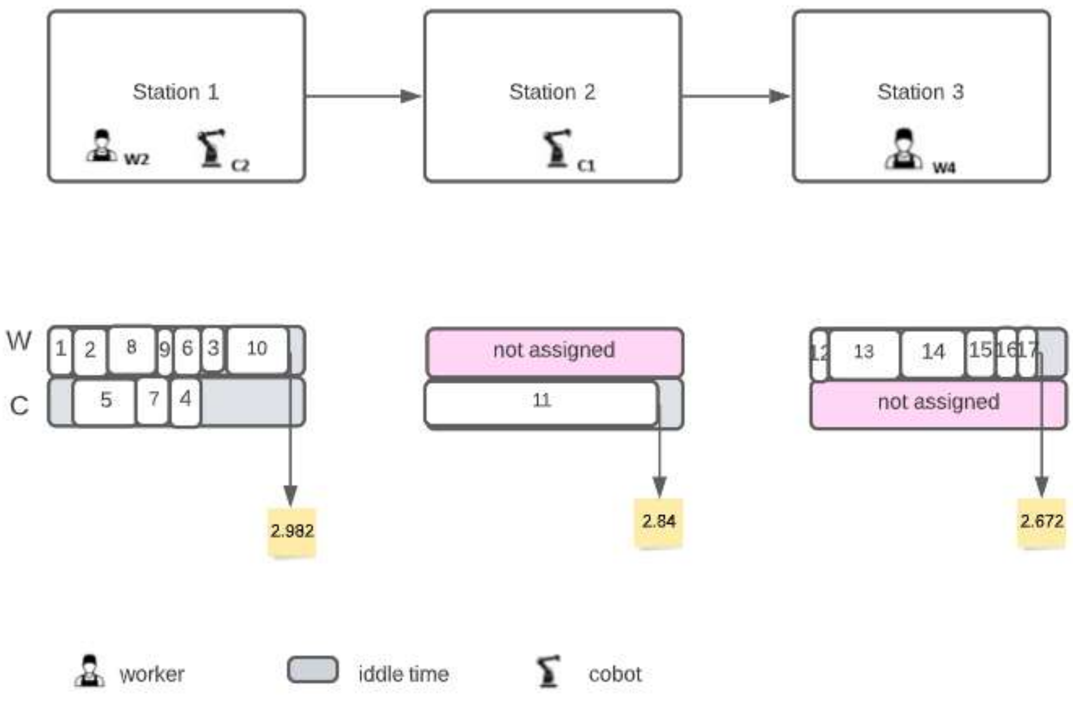

Figure 6.3 Ergonomic collaborative assembly line of sample problem

6.2 Scenario Analysis

For further analysis, to evaluate the effectiveness of the cobots in assembly lines, a total of four different scenarios; i.e. assembly line only with the manual workforce, the collaborative assembly line with the cobots where the ergonomics perspective is ignored, collaborative assembly line with the cobots where the ergonomics perspective is ignored with different parameters in objective function, and collaborative assembly line with the cobots where the ergonomics perspective is addressed-change in energy expenditures were considered and their results were compared.

6.2.1 Scenario 1

Scenario 1 is the manual ALB problem. The MIP model for a manual ALB problem is constructed and solved. Similiar to sub section 6.1.2, this model is also solved using GAMS (version 24.9.2). Calculations were also run on a standard computer with an Intel® Core™ i5-3230M CPU @ 2.60 GHz and 8 GB RAM. Since the proposed model is also linear, CPLEX Solver is used. The screenshot of the solution is given in Figure

6.4. The cost per cycle is found to be 7.572 Euros. The solution of the model took 0.05 minutes. The solution is optimal.

```
Proven optimal solution.

MIP Solution:            7.572000    (12461 iterations, 27 nodes)
Final Solve:             7.572000    (0 iterations)

Best possible:           7.572000
Absolute gap:            0.000000
Relative gap:            0.000000
```

Figure 6.4 GAMS solution for manual assembly line

The manual solution of the model is shown in Figure 6.5. As can be seen in the figure, this time an ALB problem in which only workers are employed is addressed. Assigned workers and job numbers are displayed in the station. Three types of workers are assigned to this AL, which consists of three stations in total. The third worker is assigned to the first station to do the 1st, 2nd, 3rd, 5th, 6th, 7th, 8th, and 9th jobs. The first worker is assigned to the second station to do the 4th, 10th, and 11th jobs. The fourth worker is assigned to the third station to do the 12th, 13th, 14th, 15th, 16th, and 17th jobs. The total durations of the workstations are 2.76, 2.867, and 2.672, respectively. The cost per cycle is 7.572 Euros.

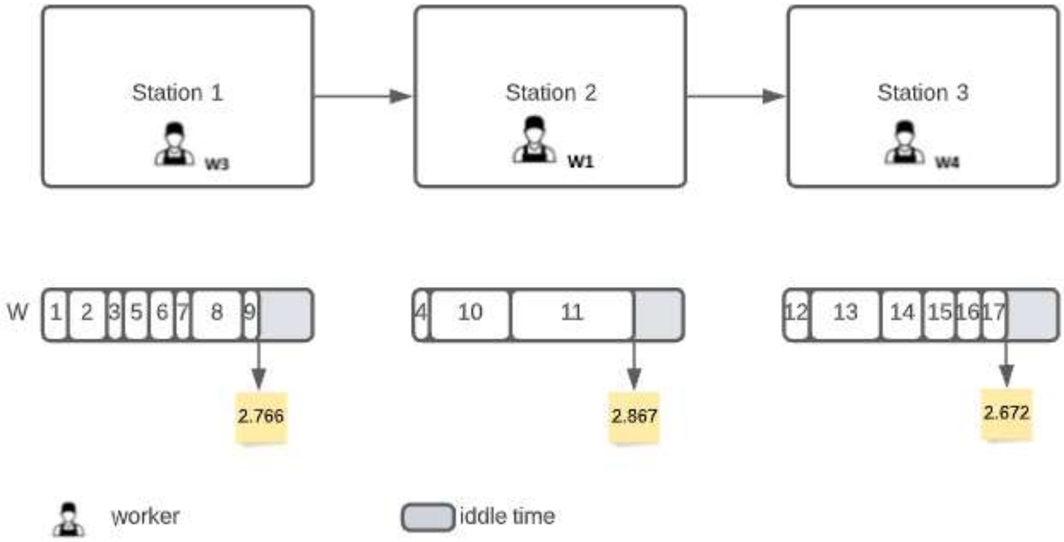

Figure 6.5 Manual assembly line of sample problem

The Gantt chart of the manual solution of the model is shown in Figure 6.6.

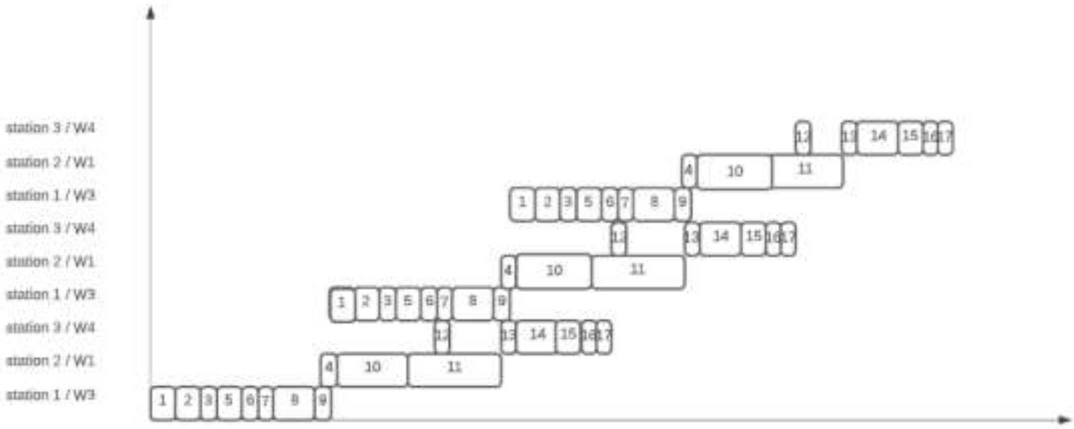

Figure 6.6 Gantt chart of the manual assembly line of sample problem

Comparison of solutions to the ergonomic collaborative and manual ALB problems: As can be seen from the solution of ergonomic collaborative AL in the illustrative problem and manual AL in scenario 1, the cost per cycle is lower in ALs with cobots. This is because cobots work slower than workers, but their minute cost is very low. ALs with cobots are very useful where mass production takes place. It is very beneficial for the cobots to perform the tasks that are constantly repetitive and boring, both for improving the cost and for the workers.

6.2.2 Scenario 2

Scenario 2 is the collaborative assembly line with the cobots where the ergonomics perspective is ignored. Similiar to sub section 6.1.2, this model is also solved using GAMS (version 24.9.2). Calculations were also run on a standard computer with an Intel® Core™ i5-3230M CPU @ 2.60 GHz and 8 GB RAM. Since the proposed model is also linear, CPLEX Solver is used. The screenshot of the solution is given in Figure 6.7. When we remove the ergonomic equations of 4.5-4.9 suggested in section 4.1 for workers, to the modell, the result is again 7.251. The solution is optimal. The solution of the model took 7.01 minutes.

```
Proven optimal solution.

MIP Solution:          7.251000    (1077577 iterations, 5072 nodes)
Final Solve:           7.251000    (0 iterations)

Best possible:         7.251000
Absolute gap:          0.000000
Relative gap:          0.000000
```

Figure 6.7 GAMS solution for collaborative assembly line

The second worker and the first cobot are assigned to the first station. The first cobot is assigned to the first workstation to do the 3rd, 5th and 9th tasks. The second worker is assigned to the first workstation to do the 1st,2nd, 4th, 6th, 7th, 8th and 10th tasks. Since the worker and the cobot work at the same time at the first workstation, the priority relations of the tasks assigned to this station are provided. For this reason, since the 2nd and 5th tasks are the successors of the 1st task, the 2nd and 5th tasks were started with the completion of the 1st task. The 10th and 12th tasks started according to the latest among the 9th and 6th tasks. Since the 9th task finished later than the 6th task, the completion time of the 9th task was taken into account. The second cobot is assigned to the second workstation to do the 11th task. The fourth worker is assigned to the third workstation to do the 12th, 13th, 14th, 15th, 16th, and 17th tasks. The total duration of the workstations are 3, 3, and 2.672 respectively. The cost per cycle is 7.251 euros. The collaborative assembly solution of the model is shown in Figure 6.8.

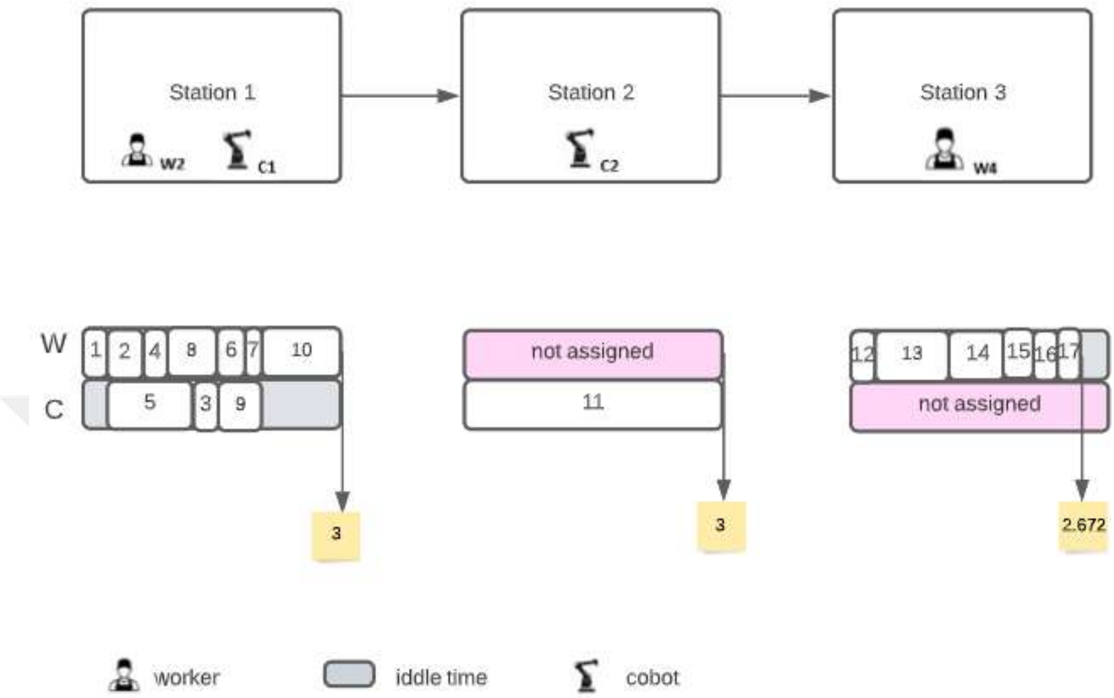

Figure 6.8 Collaborative assembly line of sample problem

6.2.3 Scenario 3

Scenario 3 is the collaborative assembly line with the cobots where the ergonomics perspective is ignored with different parameters in objective function. In this study, the effect of the change of some parameters on the objective function has been examined in detail within the scope of the second scenario analysis. The parameters are cost of workers, speed of cobot and cost of station. Each paramater has two value levels. Firstly, the cost of workers in the illustrative example is halfed and then doubled. Secondly, the spped of cobots is halfed and then doubled. Finally, the cost of station is halfed and then doubled.

These problems are also solved using GAMS (version 24.9.2). Calculations were also run on a standard computer with an Intel® Core™ i5-3230M CPU @ 2.60 GHz and 8 GB RAM. Since the proposed model is also linear, CPLEX Solver is used. The solution are optimal. Table 6.5 shows which parameters have changed, how much they have changed, and the reflection of this change on the objective function and the resource usage. W indicates that it is a worker and C indicates that it is a cobot.

Table 6.5 The effect of the change of parameters on the objective function

	Characteristics			
Parameter	**Cost of workers (Euro/min)**			
Levels	The cost of the sample problem (*1/2)		The cost of the sample problem (*2)	
Results	Type of Source Used	Objective Function	Type of Source Used	Objective Function
	W1,W3, W4	4.866	W4, C1, C2, C3, C4	10.107
Parameter	**Speed of cobots (min)**			
Levels	The speed of the sample problem (*1/2)		The speed of the sample problem (*2)	
Results	Type of Source Used	Objective Function	Type of Source Used	Objective Function
	W4, C1, C2	4.926	W1,W3, W4	7.572
Parameter	**Cost of station (Euro/min)**			
Levels	The cost of the sample problem (*1/2)		The cost of the sample problem (*2)	
Results	Type of Source Used	Objective Function	Type of Source Used	Objective Function
	W1,W4, C1,C2	6.006	W2,W4, C1,C2	9.411

When the minute costs of the workers in the illustrative example problem are divided by half, the total cycle cost decreases by 2.385 Euros. A total of three stations were opened. W3 is assigned to the first station. W1 is assigned to the second station. The third station is assigned W4. The 1st, 2nd, 4th, 5th, 7th, 8th, and 9th tasks are assigned to the w3 worker at the first station. The 3rd, 10th, and 11th tasks are assigned to the W1 worker at the second station. The 12th, 13th, 14th, 15th, 16th, and 17th tasks are assigned to the W4 worker at the third station.

When the completion times of the cobots in the example problem are divided by half, the total cycle cost decreases by 2.325 Euros. A total of three stations were opened. C1 is assigned to the first station. C2 is assigned to the second station. The third station is assigned W4. The 1st, 2nd, 3rd, 5th, 6th, 7th, 8th and 9th tasks are assigned to the C1 cobot at the first station. The 4th, 10th, and 11th tasks are assigned to the C2 cobot at the second station. The 12th, 13th, 14th, 15th, 16th and 17th tasks are assigned to the W4 worker at the third station.

When the cost of opening a station in the example problem is divided by half, the total cycle cost decreases by 1.245 Euros. A total of four stations were opened. C1 is assigned to the first station. C2 is assigned to the second station. The third station is assigned W1. W4 is assigned to the last station. The 1st, 2nd, 3rd, and 7th tasks are assigned to the C1 cobot at the first station. The 4th, 5th, 6th, and 8th tasks are assigned to the C2 cobot at the second station. The 9th, 10th and 11th tasks are assigned to the W1 worker at the third station. The 12th, 13th, 14th, 15th, 16th and 17th tasks are assigned to the W4 worker at the fourth station.

When the minute costs of the workers in the example problem are doubled, the total cycle cost increases by 2.856 Euros. A total of five stations were opened. C3 are assigned to the first station. C1 is assigned to the second station. The third station is assigned C4. C2 is assigned to the fourth station. W4 is assigned to the fifth station. The 1st, 2nd, 4th and 5th tasks are assigned to the C3 cobot at the first station. The 3rd, 6th, 7th, 8th and 9th tasks are assigned to the C1 cobot at the second station. The 10th tasks are assigned to the C4 cobot at the third station. The 11th task is assigned to the C2 cobot at the fourth station. The 12th, 13th, 14th, 15th, 16th and 17th tasks are assigned to the W4 worker at the fifth station.

When the completion times of the cobots in the example problem are doubled, the total cycle cost increases by 0.321 Euros. A total of three stations were opened. W3 is assigned to the first station. W1 is assigned to the second station. The third station is assigned W4. The 1st, 2nd, 3rd, 4th, 5th, 6th, 7th and 8th tasks are assigned to the W3 worker at the first station. The 9th, 10th and 11th tasks are assigned to the W1 worker at the second station. The 12th, 13th, 14th, 15th, 16th and 17th tasks are assigned to the W4 worker at the third station.

When the cost of opening a station in the example problem is doubled, the total cycle cost increases by 2.16 euros. A total of three stations were opened. W2 and C2 are assigned to the first station. C1 is assigned to the second station. The third station is assigned W4. The 1st, 2nd, 3rd, 4th, 6th, 8th, and 10th tasks are assigned to the W2 worker and the 5th, 7th, 9th, and 12th tasks are assigned to the C2 cobot at the first station. The 11th task is assigned to the C1 cobot at the second station. The 13th, 14th, 15th, 16th and 17th tasks are assigned to the W4 worker at the third station.

6.2.4 Scenario 4

Scenario 4 is the collaborative assembly line with the cobots where the ergonomics perspective is addressed-change in energy expenditures. As a result of solving the illustrative example for ergonomic constraint, it has been found that the cost of ALs to which workers' rest is added increases. In this study, the effect of the change in the energy expenditure parameter on the objective function was examined in detail within the scope of the experimental design. Table 6.6 shows how much the energy expenditure parameter has changed and the reflection of this change on the objective function. In addition, it is seen how much relaxation allowance is given to the appointed workers. The letter W represents the worker and the letter C the cobot. W1 is used to describe the first worker and C1 is used to describe the first cobot.

Table 6.6 The effect of the change of energy expenditure

	Energy expenditure (kCal)				
Characteristics	**e_i*0.75**	**e_i*1**	**e_i*1.25**	**e_i*1.5**	**e_i*2**
Station where workers are assigned	W2-S1, W4-S3	W2-S1, W4-S3	W2-S1, W4-S3	W1-S1, W4-S4	W1-S1, W4-S4
Total RA of workers (min)	W2-0, W4-0	W2-0, W4-0	W2-0, W4-0	W1-0, W4-0	W1-0.775, W4-0
Objective function (Euro/cycle)	7.251	7.251	7.251	7.446	8.346

Adding the proposed equations for the energy expenditure for the tasks assigned to the workers, additional recovery time must be provided to the worker if the worker works above a certain energy. As the energy amount of work increases, so does the need for workers to rest. Especially when the energy expenditure of the tasks are doubled, the first worker is given 0.775 additional relaxation allowance time. The objective function is over 1.095 Euros. The first worker was assigned to the first station, and the fourth worker was assigned to the fourth station.

Because of this cause, the cost per cycle also ascends. To reduce the cost, as the energy expenditure for the task increases, more cobots are assigned to the station rather than workers. But after somewhere, there will be no cobot to be appointed and workers will be assigned to the station. The more uniform the amount of energy consumed by the workers, the more equitable work sharing. This helps workers to be more motivated and to reduce their injustice. In the stations where the total energy expenditure of the s assigned to the worker is high, the injustice is prevented to some extent by giving the worker a break time.

Although taking ergonomic factors seriously increases the cost, having a safe working environment is more efficient and risk-free. Taking a break in proportion to the amount of energy expenditure by the workers protects the musculoskeletal system of the worker. Although it is costly for the employer, ergonomic evaluations are very important in terms of human value today.

CHAPTER 7
CONCLUSION

Along with the support of the workers by the cobots, it has been very beneficial to the improvement in automation in the sectoral sense. This integration has many purposes. Cobots working with the worker bring many benefits to the AL. There are many benefits in terms of saving workers from monotony by doing repetitive jobs, providing ergonomic benefits by doing heavy work, and cheap labor, and these examples can be increased.

The real importance of cobots, which entered our lives rapidly with Industry 4.0, will be with Industry 5.0 (Demir, Döven, & Sezen, 2019). The reason for this is that while mass production has gained importance in Industry 4.0, personalized products will gain importance with Industry 5.0. The presence of cobots will come into play in many areas that come to mind or not (for example, in shopping, hospitals, schools, etc.). To give an example, taking blood in the hospital is a very common procedure and the use of cobots is recommended for this (Maddikunta et al., 2021). At the same time, Industry 5.0 focuses on creating more agile and flexible industries that respect basic human rights. It advocates the creation of protective and inclusive working environments for people. For this reason, humans and cobots work together, giving priority to human mental and physical health, and at the same time increasing work efficiency, safety, and satisfaction (Coronado et al., 2022). All these studies now mention that cobots will enter our lives quickly and take up a lot of space and explain the importance of the subject.

Although ALB has been discussed many times from different perspectives, this study focuses on its ergonomic and economic aspects. As stated in the previous paragraph, these two features are two very important parameters, especially for the advancing industrial revolution periods. Studies on cobots, which will provide many ergonomic improvements in the AL, have been examined and their inadequacy has been observed. Since improving the working environment of the workers, that is, making them ergonomic, will reduce occupational diseases, more work is necessary for the organization of workplaces.

First, the problem was made more specific by drawing a mind map. In the first step, a two-step solution approach is proposed, which requires preliminary calculations to find the parameters of the mathematical model, and in the second step, which consists of the desired solution steps from the mathematical modeling. To understand the effectiveness of this mathematical model, the proposed ergonomic collaborative AL and the manual AL were compared. As a result of this comparison, it has been observed that ergonomic collaborative assembly lines are more economical. Linear version of an equation rarely used in previous studies has been used to calculate workers' relaxation allowances.

An ergonomic constraint for workers has been removed to the model since workers do not need recovery times that cobots do not need. When the two cases are compared (ergonomic collaborative assembly line and collaborative assembly line), it is seen that the results do not change and the cost per cycle is the same. But ergonomic collaborative assembly line model is slower than other.

To understand the effectiveness of the ergonomic constraint added to the equation, the energy consumption factor of the task was handled with different values, and it was observed that as this value increases, both the cost increases and the worker needs break time. Although it was explained that the importance of the rest period for the workers could not be discussed, no matter how much the cost increased, it was mentioned that the ergonomic working conditions of the workers were given importance in Industry 5.0.

Different studies can be done for future research. For example, while the problem addressed in the study is a type 1 problem, future work may be a type 2 problem. Also, different layout configurations such as U type assembly line balancing problem (UALBP) and TALBP can be considered when using a straight AL in this study. The MMALB problem, which is handled more in real life, can be solved. While the number of data of the problem increases, the proposed model will not give the optimal result, so an appropriate heuristic approach can be suggested by increasing the size of the problem. Finally, different criteria can be taken into account for the energy calculation.

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