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# SUSTAINABLE APPLICATIONS FOR DISASSEMBLY LINE BALANCING PROBLEMS WITH HUMAN-ROBOT COLLABORATION: TRIPLE BOTTOM LINE APPROACH

**M.Sc. THESIS**

**IN**

**INDUSTRIAL ENGINEERING**

**BY**

**DURSUN EMRE EPCİM**

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**M.Sc. Thesis**

**in**

**Industrial Engineering**

**Gaziantep University**

**Supervisor**

**Assoc. Prof. Dr. Süleyman METE**

**Co-Supervisor**

**Asst. Prof. Dr. Mustafa DEMİRBİLEK**

**by**

**Dursun Emre EPCİM**

**August 2024**

**I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.**

**Dursun Emre EPCİM**

**ABSTRACT**

# SUSTAINABLE APPLICATIONS FOR DISASSEMBLY LINE BALANCING PROBLEMS WITH HUMAN-ROBOT COLLABORATION: TRIPLE BOTTOM LINE APPROACH

**EPCIM, Dursun Emre**
**M.Sc. in Industrial Engineering**
**Supervisor: Assoc. Prof. Dr. Süleyman METE**
**Co-Supervisor: Asst. Prof. Dr. Mustafa DEMİRBİLEK**
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**61 pages**

The sustainable management of end-of-life (EOL) products is a significant concern. The current period widely acknowledges the imperative for the advancement of economically, socially, and environmentally sustainable practices. The thesis motivation is to recycle end-of-life (EOL) products into a more sustainable and habitable environment. By focusing on the disassembly line balancing (DLB) problem, which is a key aspect of recycling procedures for EOL products, it addresses sustainable applications of U-shaped and two-sided DLB problems. Additionally, two distinct mixed-integer linear programming models are developed to solve the U-shaped DLB problem with human-robot collaboration (UDLBP-HRC) and the two-sided DLB problem with human-robot collaboration (TDLBP-HRC). Moreover, the model developed for TDLBP-HRC is designed and solved in accordance with the triple bottom line (TBL) approach, which provides a sustainable framework by considering economic, social, and environmental objectives. The proposed models are tested on cases found in the literature, and the results are interpreted. The results reveal the critical importance of disassembly lines in terms of sustainability as well as the potential contributions of human-robot collaboration in these processes.

**Key Words:** Disassembly Line Balancing, U-Shaped Line, Two-Sided Line, Human-Robot Collaboration, Triple Bottom Line.

# ÖZET

## İNSAN-ROBOT İŞBİRLİĞİ İLE DEMONTAJ HATTI DENGELEME PROBLEMLERİ İÇİN SÜRDÜRÜLEBİLİR UYGULAMALAR: ÜÇLÜ SONUÇ YAKLAŞIMI

**EPCIM, Dursun Emre**
**Yüksek Lisans Tezi, Endüstri Mühendisliği**
**Danışman: Doç. Dr. Süleyman METE**
**İkinci Danışman: Dr. Öğr. Üyesi Mustafa DEMİRBİLEK**
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Ömrünü tamamlamış ürünlerin sürdürülebilir yönetimi önemli bir endişe kaynağıdır. İçinde bulunduğumuz dönem, ekonomik, sosyal ve çevresel açıdan sürdürülebilir uygulamaların ilerletilmesi zorunluluğunu yaygın bir şekilde kabul etmektedir. Tezin motivasyonu, ömrünü tamamlamış ürünleri daha sürdürülebilir ve yaşanabilir bir çevre için geri dönüştürmektir. Ömrünü tamamlamış ürünlerin için geri dönüşüm prosedürlerinin önemli bir parçası olan demontaj hattı dengeleme (DHD) problemine odaklanarak, U-tipi ve çift taraflı DHD problemlerinin sürdürülebilir uygulamaları ele alınmıştır. Ayrıca, bu tez insan-robot iş birliği ile U-tipi DHD problemini (UDHDP-İRİ) ve insan-robot iş birliği ile çift taraflı DHD problemini (TDHDP-İRİ) ele almak için iki farklı karma tam sayılı doğrusal programlama model önerilmektedir. Buna ek olarak, TDHDP-İRİ için geliştirilen model, ekonomik, sosyal ve çevresel hedefleri göz önünde bulundurarak sürdürülebilir bir çerçeve sağlayan üçlü çözüm yaklaşımına uygun olarak tasarlanmış ve çözülmüştür. Önerilen modeller literatürde bulunan örnekler üzerinde test edilmiş ve sonuçlar yorumlanmıştır. Sonuçlar, demontaj hatlarının sürdürülebilirlik açısından kritik önemini ve bu süreçlerde insan-robot iş birliğinin potansiyel katkılarını ortaya koymaktadır.



**Anahtar Kelimeler:** Demontaj Hattı Dengeleme, U Tipi Hat, Çift Taraflı Hat, İnsan-Robot İş Birliği, Üçlü Sonuç Yaklaşımı.

*" Dedicated to my family and those whom I consider as family."*

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## LIST OFABBREVIATIONS

| | |
|---|---|
| **EOL** | End of Life |
| **TBL** | Triple Bottom Line |
| **HRC** | Human Robot Collaboration |
| **MILP** | Mixed Integer Linear Programing |
| **DLB** | Disassembly Line Balancing |
| **TDLBP** | Two-sided Disassembly Line Balancing Problem |
| **TDLBP-HRC** | Two-sided Disassembly Line Balancing Problem with Human – Robot Collaboration |
| **UDLBP-HRC** | U-shaped Disassembly Line Balancing Problem with Human – Robot Collaboration |

# CHAPTER 1
# INTRODUCTION

## 1.1 Motivation of Thesis

In today's world, the increasing consumption brings along many problems. The waste generated from products manufactured to meet demand is one of the leading issues. The recycling of these wastes, considered as end of life (EOL) products, emerges as a problem that needs to be addressed. Recycling these products prevents waste and contributes to making the world a more livable place. However, the high volume of EOL products makes it challenging to plan recycling processes in a sustainable and optimal manner. At this point, balancing disassembly lines for the recycling, reuse, and remanufacturing of EOL products is of great importance (Guo et al., 2022)

Another critical point to consider, regardless of the field of study, is sustainability, one of the most crucial common issues of our time. The quality of the results obtained is directly proportional to how sustainable they are. If the results achieved in the studied subject are not sustainable, they lose their significance. Sustainability, which is of great importance in this context, is influenced by many parameters. However, as highlighted in Budak's study on reverse logistics from a sustainability perspective, economic, environmental, and social factors can be considered the three main elements affecting sustainability (Budak, 2020)

Disassembly centers, which are part of reverse logistics, are among the key points directly affecting the sustainability of production. To achieve sustainability goals, it is necessary to consider every aspect of production (Kazancoglu & Ozkan-Ozen, 2020). Therefore, evaluating the disassembly line balancing problem from the perspectives of economic, environmental, and social factors the three main elements affecting sustainability emerges as a necessity. While many disassembly line balancing studies separately evaluate these three factors, there are few studies that consider them together and address sustainability.

The motivation of this thesis, as stated above, is to conduct the recycling processes of EOL products, which are important for a more livable world, in a sustainable manner. In this context, this thesis focuses on the disassembly line balancing problem, initially integrating human-robot collaboration into the U-shaped line balancing problem and evaluating the results. Subsequently, the two-sided disassembly line balancing problem with human-robot collaboration was solved using a triple bottom line (TBL) approach, considering the economic, social, and environmental objectives that constitute the three main pillars of sustainability. New models were developed for both mentioned problems, and the findings were presented by evaluating the results.

### 1.2 Disassembly Line Balancing

Production is continuously increasing, and recycling products is of great importance to create a more livable environment and prevent waste. In this context, the significance of disassembly lines, which can be defined as a systematic process of breaking down a product into its individual parts, components, subassemblies, or other groups, is understood (Özceylan et al., 2019). As emphasized in the studies by Johnson and Wang (1995), disassembly lines play a crucial role in providing opportunities for material recycling.

A review of the literature shows that the line balancing problem was first utilized in Salveson (1955) study on assembly line balancing . Regarding assembly lines, the disassembly line balancing problem was initially addressed in the work of Gungor and Gupta (1999). Since it was first addressed, many researchers have conducted studies on disassembly line balancing, which is of great importance in the recycling of end of life (EOL) products. This problem is challenging and significant due to factors such as product deterioration, recycling quality, and various unpredictable risk factors.

Fundamentally, this problem has been explored by researchers for different types of main lines, including straight lines, parallel lines, U-shaped lines, and two-sided lines. Moreover, hybrid models that combine these lines have also been developed. In this thesis, the disassembly line balancing problem is addressed for U-shaped lines and two-sided lines, considering human-robot collaboration.

### 1.2.1 U-Shaped Disassembly Line

As shown in Figure 1.1, U-shaped lines derive their name from their distinctive U-shaped configuration, in contrast to straight lines. One of the biggest advantages of U-shaped lines is the flexibility gained from operators being able to control both the entry and exit points of the line. The research of Miltenburg (2001) on U-shaped lines in US and Japan indicated that efficiency increased by 76%. This increase in efficiency can be attributed to the reduced space requirements and more compact arrangement achieved through enhanced interaction among workers in U-shaped lines. The distinctive features of U-shaped lines include flexibility, reduced space requirements, and increased operator interaction.

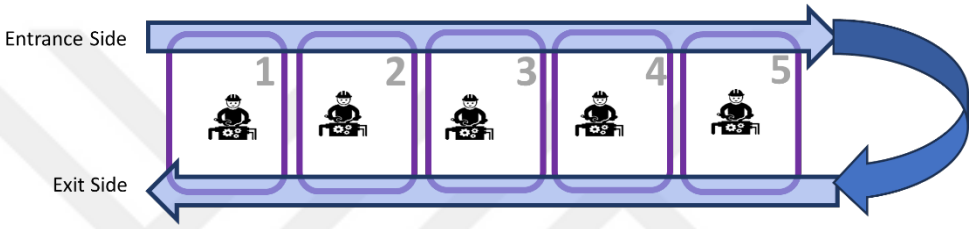


**Figure 1.1** Schematic representation of U-shaped line

Despite their many benefits, working on the balancing problem of U-shaped lines can be challenging. The assignment and balancing of tasks in lines with two directions (entry and exit) must correspond to each other in both directions. This is one of the main challenges in U-shaped lines. As part of this thesis, the problem of balancing U-shaped lines with human-robot collaboration has been studied, and a new model has been proposed.

### 1.2.2 Two-Sided Disassembly Line

As shown in Figure 1.2, two-sided lines consist of mated station configurations, which allow operations to be performed simultaneously on both sides. This setup is frequently used in the assembly and disassembly operations of large products, such as cars and buses, as noted by Baykasoglu and Dereli (2008). The primary advantage of two-sided lines is the ability to conduct operations on both sides simultaneously, significantly reducing the total task completion times. This advantage also minimizes the problems associated with moving large parts. Alongside simultaneous task execution, the flexibility in task assignments is another benefit of two-sided lines.

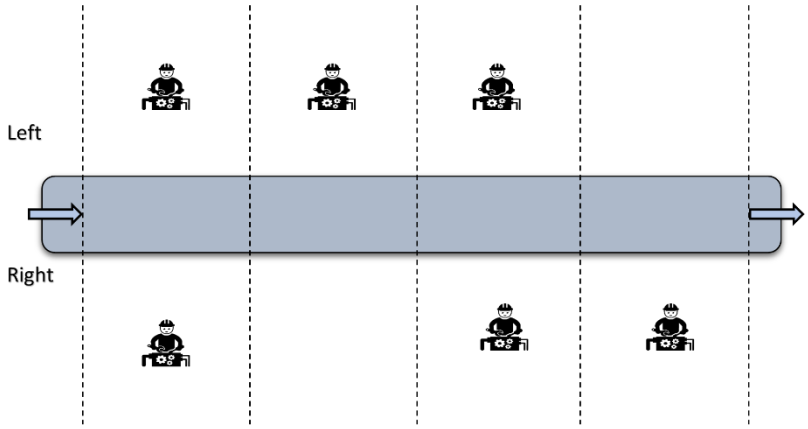


**Figure 1.2** Schematic representation of two-sided line

However, similar to U-shaped lines, two-sided lines also present some challenges. Ensuring tasks are performed according to precedence relationships and resolving sequencing difficulties in mated stations with simultaneous operations are among the primary challenges (Kim et al., 2000)

As part of this thesis, a model has been developed for the two-sided disassembly line balancing problem with human-robot collaboration. This model was solved using a triple bottom line approach, and the results were analyzed and discussed.

### 1.2.3 Disassembly Line Balancing with Human-Robot Collaboration

The development of the manufacturing sector has made robots necessary nowadays. In terms of accuracy, speed, quality, and efficiency, robots perform superior to people, which is the most important factor. In regards to these major factors, when performing risky tasks, robots are preferred over people. Robots have sensitive sensors, so any harm that might be caused by dangerous jobs is minimized. Furthermore, fatigue may also influence a person's capacity to perform repetitive tasks well. These repetitive tasks can therefore be completed by people in different times. Contrarily, robots possess the ability to operate continuously for a predetermined duration, completing monotonous tasks within the same timeframe. Therefore, robots are preferred for such repetitive duties. Simple tasks that would cost more for a human to complete can also be carried out by a robot. It is therefore more appropriate to collaborate with humans, especially in the manufacturing sectors, due to the high cost of operating robots despite the benefits highlighted.

Cobots or robotic assistants are other names for these collaborative robots (Vysocky & Novak, 2016). Colgate et al. (1996) created this Cobot idea of industrial robots in 1996. The HRC concept establishes the task balance between humans and robots in the production sector. Human Robot Collaboration (HRC) is a concept that complements the advantages of both by compensating the disadvantages of human and robot from each other (Ajoudani et al., 2018). Through HRC, which has taken on a significant role, particularly in the industrial sector, several benefits have been brought about, including rising productivity, offering flexibility, and offering security.

Different human-robot interactions are classified according to five features by Wu et al. (2023), as shown in Table 1.1. These features are described as follows:

- **Shared Workspace:** Indicates whether humans and robots share the same workspace.
- **Shared Task:** Shows whether humans and robots are performing the same task.
- **Shared Time:** Specifies whether humans and robots share the same time frame due to synchronized operations.
- **Contacted:** Indicates whether there is physical contact between humans and robots.
- **Context Awareness:** Demonstrates whether there is awareness of collaboration between humans and robots. This feature pertains to whether robots have the ability to react to the humans they work with and the surrounding environment.

**Table 1.1** Characteristics of different human-robot interactions

| **Human - Robot Interaction** | | | |
|---|---|---|---|
| **Coexistence** | **Cooperation** | | **Collaboration** |
| | **Sequential** | **Parallel** | |
| No Shared Workspace | No Shared Workspace | Shared Workspace | Shared Workspace |
| Unrelated Task | Linked Task | Unrelated Task | Shared Task |
| No Shared Time | No Shared Time | No Shared Time | Shared Time |
| Without Contact | Without Contact | Without Contact | Contacted |
| No Context Awareness | No Context Awareness | Context Awareness | Context Awareness |

Among the different human-robot interactions illustrated in Figure 1.3 (Wu, Zhang, Zhang, et al., 2023), human-robot collaboration is addressed in this thesis.

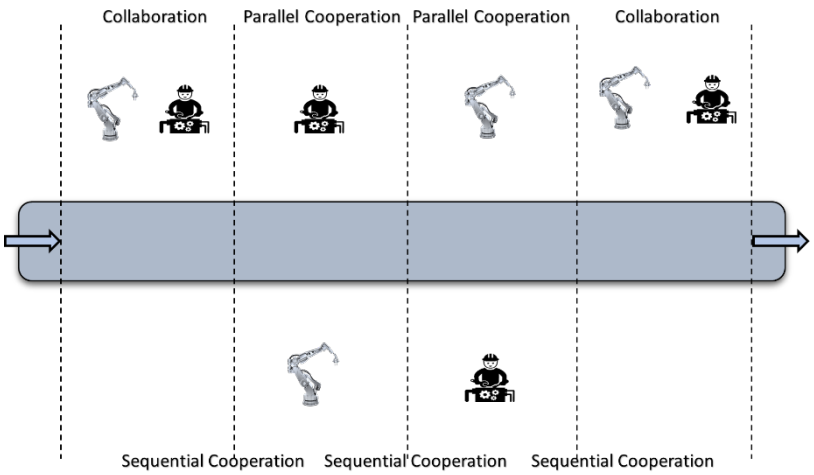


**Figure 1.3** Representation of different human-robot interactions on a two-sided line

## 1.3 Triple Bottom Line Approach

The Triple Bottom Line (TBL) approach, as explained in Elkington (1998) work, involves considering social, environmental, and economic impacts in decision-making processes. The research conducted by Giang et al. (2022) examines the impacts and diverse uses of the TBL strategy on company sustainability, emphasizing the substantial influence this approach exerts on sustainability. The concept of sustainability, which depends on numerous parameters, is fundamentally composed of three essential elements: economic, social, and environmental aspects. This focus on the three dimensions in research underscores the importance of the TBL approach for obtaining findings related to sustainability and ensuring its achievement. In this context, applying the TBL approach to disassembly line balancing problems will contribute to the literature on sustainability.

A review of the literature reveals that there are very few studies applying this approach to disassembly lines. One such study by Kazancoglu and Ozkan-Ozen (2020) addresses the disassembly line balancing problem using the TBL based approach along with the multi-criteria decision-making method TODIM. Another study by Budak (2020) focuses on reverse logistics optimization, including disassembly line balancing, and achieves results using the TBL approach. The scarcity of studies employing the TBL method in the context of disassembly line balancing problems highlights one of the main contributions of this thesis.

## 1.4 Structure of the Thesis

This thesis comprises five primary chapters: introduction, literature review, methodology, results and discussion, and conclusions and recommendations. In the introduction, the thesis keywords are discussed together with citations from the literature and supporting visuals. The second chapter of the thesis provides an overview of the relevant literature on three primary topics: U-shaped lines, two-sided lines, and human robot collaboration in ALB and DLB. The thesis emphasizes the gaps in the literature and highlights its focus. The third chapter of the thesis provides a definition of the UDLBP-HRC and TDLBP-HRC problems, which are two distinct studies included in the research. Additionally, the chapter explains the two proposed models. The third chapter of the thesis provides an explanation of the technique employed. This is followed by the fourth chapter, which details the instances selected from the literature to evaluate the two suggested models and presents the achieved results. The data are further analyzed using several tables and graphs. The final chapter highlights the overall findings of the thesis and emphasizes the inferences derived from these findings. Furthermore, the thesis's limitation and merits are explicitly identified. Furthermore, the thesis is ended by acknowledging potential for future research. The structure of the thesis mentioned in this chapter is presented in figure 1.4.

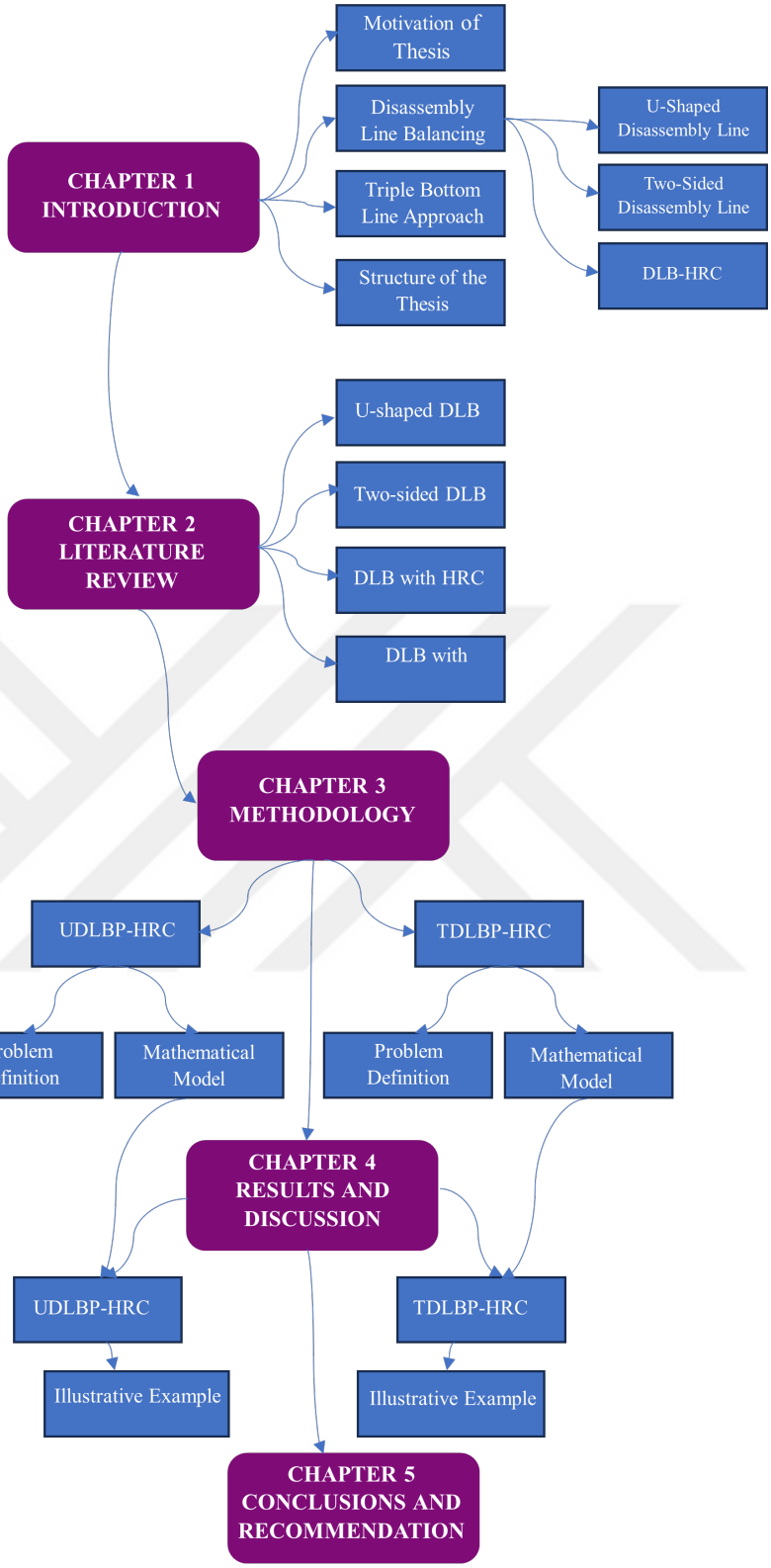


**Figure 1.4** Structure of the thesis

# CHAPTER 2
# LITERATURE REVIEW

This chapter is divided into three sub-sections, each focusing on the research topic of the chapter is subdivided into four distinct sections, each dedicated to a specific research topic addressed in the thesis.

- **U-shaped DLB:** This subsection provides the literature review for the U-shaped disassembly line balancing problem, which is examined in one of the models proposed in the thesis. The literature review highlights the specific contribution that the thesis makes to the existing body of literature.
- **Two-sided DLB:** This subtitle provides a literature review for the two-sided disassembly line balancing problem addressed in the other proposed model. The existing gap in the literature is highlighted and the proposed model is described as filling this gap.
- **DLB with HRC:** This section focuses on human-robot collaboration, a prominent and significant problem for sustainability, which has gained attention in recent times. It is examined in relation to both proposed models, with a specific emphasis on DLB. The literature highlights the existing gap and identifies the position of the proposed models within the literature.

The papers referenced in these three subheadings are categorized and displayed in a table.

- **Overview of DLB literature with a focus on sustainability:** This subheading marks the final part of this chapter. This section of the thesis focuses on sustainability in relation to the DLB problem. The search through Scopus yields the results, highlighting the current status of the research concept.

## 2.1 Review on U-Shaped DLB

This section initially scrutinizes the literature on U-shaped line disassembly line balancing problems, which emerged alongside Miltenburg and Wijngaard's (1994) work on assembly line balancing. Agrawal and Tiwari (2008) conducted the first study

in this compilation of literature, which focused on disassembly line balancing. Examining the literature on U-shaped lines for the disassembly line balancing problem reveals knowledge that spans over 16 years.

Avikal et al. (2013) highlighted the significance of disassembly lines. The authors mentioned the challenge of finding the optimum solution because of the NP hardness of the disassembly line balancing problems. To address this, they devised a heuristic approach to solve the U-shaped disassembly line balancing problem. Wang et al. (2020) introduced destructive mode and uncertain disassembly time to the disassembly line and solve the disassembly line balancing problem for partially destructive mode and U-shaped lines. The model they developed aims to increase the disassembly profit while reducing the number of stations and energy consumption, as well as balancing the workload. Furthermore, they propose a new multi-objective discrete flower pollination algorithm to address this issue. Li and Janardhanan (2021) solved the profit-oriented U-shaped partial disassembly line balancing problem (PUPDLBP) for the first time. The problem is solved using a binary integer programing model and a novel metaheuristic, the discrete cuckoo search (DCS) algorithm, is developed. Yao and Gupta (2021c) used the small world optimization algorithm (SWOA) to solve the U-shaped disassembly line balancing problem. In their results, they both revealed the advantages of U-shaped lines compared to straight lines and stated that SWOA gave superior results compared to other meta-heuristics. Wang et al. (2021) integrated multi-criteria decision making (MCDM) and variable neighborhood search (VNS) into the U-shaped disassembly line in their study. After combining the MCDM method with Fuzzy set theory, gray relational analysis and Choquet fuzzy integral, a special VNS approach was developed to balance the U-shaped line with three hierarchical objectives. Yao and Gupta (2021a) emphasized the importance of efficient disassembly in the recovery of end-of-life products. They suggested the use of U-shaped lines to solve this problem more efficiently. In addition, they used the ant colony algorithm to solve the U-shaped disassembly line balancing problem. They also used the pareto front to evaluate the four different objectives. Yao and Gupta (2021b) employed the invasive weed optimization algorithm (IWO) to address the U-shaped disassembly line balancing problem. Both studies demonstrated the benefits of U-shaped lines over straight lines and concluded that IWO outperformed other meta-heuristics. Wu et al. (2021) considered the multi-product partial U-shaped disassembly

line balancing problem (MP-UDLB). In their mathematical model, they aimed to minimize energy consumption while maximizing disassembly profit. A multi-objective discrete brainstorming optimizer (MDBO) algorithm was proposed to solve this problem. They applied their model to real world examples of ballpoint pen and washing machine disassembly. Qin et al. (2021) considered the three-product partial U-shaped disassembly line balancing problem (MPUD) in their study. In their model, they aimed to maximize disassembly profit while minimizing resource utilization. They proposed a meta-heuristic algorithm, a multi-objective discrete migratory birds optimizer (MDMBO), to solve this problem. Xu et al. (2021) developed a model to solve the U-shaped disassembly line balancing problem in their study. They developed this model by considering the disassembly task priority relationship, personnel training cost, and cycle time of disassembly workstations for multi-objective optimization objectives. A cooperative resource allocation strategy algorithm (MOEA/D-CRA) is proposed for a multi-objective evolutionary algorithm based on decomposition with the goal of solving the problem. Wang et al. (2021) studied destructive and non-destructive modes in the multi-product partial U-shaped disassembly line balancing problem. The developed model has two purposes: maximizing the disassembly profit and minimizing energy consumption. The speed of convergence is increased by using an elitist strategy and crowded distance mechanism to find non-dominated solutions. The established model was tested on a ballpoint pen and radio set. Bai et al. (2021) developed a model to solve the U-shaped disassembly line balancing problem, taking into account the objectives of cycle time constraint, disassembly profit maximization and idle time minimization. An S-metric selection evolutionary multi-objective optimization algorithm (SMS-EMOA) has been proposed to solve this problem. Li et al. (2021) developed a mathematical model to solve the U-shaped disassembly line balancing problem in their study, which aims to maximize the disassembly profit and minimize the disassembly time of dangerous parts. In this study, an improved multi-objective salp swarm algorithm based on Pareto combined with a stochastic simulation method was used to solve the U-shaped disassembly line balancing problem. Huang et al. (2021) developed a model to solve the U-shaped disassembly line balancing problem, aiming to maximize disassembly profit and minimize energy consumption. In this model, task assignments are based on hazardous risks. Accordingly, tasks with high hazard risks are considered to be done manually by the robot and tasks with low hazard risks are considered to be done manually. A multi-objective discrete bat

algorithm was proposed to solve the problem. Li et al. (2023) used the U-shaped line, which is more flexible than the conventional straight line, for the disassembly line balancing problem. To solve this problem, they first developed a mixed integer linear program (MILP) model to formulate AND/OR priority relationships to minimize the number of stations. The model was then extended to a nonlinear mixed integer model to optimize four objectives. A two-stage bee colony algorithm is proposed to solve this NP-hard problem and the results of this algorithm are compared with 13 different algorithms. According to the results obtained, it is observed that the proposed algorithm is competitive. Guo et al. (2023) developed a MILP mathematical model for the U-shaped disassembly line balancing problem, which aims to maximize the disassembly profit while optimizing the balancing of the human fatigue index. A multi-objective evolutionary cooperative resource allocation strategy algorithm is proposed for solving this problem. Qin et al. (2024) conducted research on the problem of balancing a U-shaped disassembly line with multiple robots and multiple products, known as the Multi-Robotic Multi-Product U-Shaped Disassembly Line Balancing Problem. The authors presented a MIP with the objective of maximizing profits from disassembly while minimizing carbon emissions. The Improved Multi objective Multiverse Optimizer (IMMO) employs the sigmoid activation function in neural networks to efficiently address large-scale issues. Wang et al. (2024) studied the Hybrid Disassembly Line Balancing Problem (HDLBP), which considers multi-skilled labor requirements using both linear and U-shaped lines. A model is constructed to maximize the disassembly profit and a Soft Actor-Critic (SAC) algorithm is proposed to solve this model. Wang et al. (2024) studied a Hybrid technique that combines linear and U-shaped lines in their investigation. The study focused on the disassembly line balancing, taking into account the presence of workers with multiple skills, as well as the impact on profit and carbon emissions. The researchers presented a novel approach by integrating non-dominated ranking directly into the reward function of a metaheuristic algorithm. They applied this actor-critic algorithm to solve the model and conducted a comparative analysis with other commonly used metaheuristics. Wang et al. (2024) highlighted the advantages of robots and U-shaped lines and presented a mixed integer linear programming model for the problem of balancing U-shaped robotic disassembly lines. In addition, they devised a deep reinforcement learning technique known as the deep Q network (DQN), which leverages issue features to achieve dynamic balancing.

In the literature review on U-shaped disassembly lines, it was found that human robot collaboration, which is one of the trending topics of recent times, has not been addressed in U-shaped disassembly lines. This gap is addressed as in Section 3.1 in order to obtain sustainable applications in the disassembly line balancing problem.

### 2.2 Review on Two-Sided DLB

This section provides a comprehensive assessment of the literature on two-sided lines, which enable simultaneous operation on both sides of the station, specifically in the context of the disassembly line balance problem. There is a limited amount of research available on the topic of balancing disassembly lines using two-sided lines. This section includes the TDLBP literature as a consequence of this review.

Wang, Li and Gao (2019) investigated the challenge of balancing a disassembly line with multiple objectives, multiple constraints, and unpredictable stochastic conditions on both sides. In their model, they regarded optimizing task allocation, energy consumption, and profit as objectives. The researchers suggested a multi-objective discrete flower pollination algorithm that relies on Pareto dominance relations to solve the created model. Liang, Guo and Xu (2021) established a stochastic mixed model two-sided assembly lines that considers the cost of activating workstations, the level of uniformity in workload between workstations, and the sequence in which hazardous tasks are carried out. To address the problem, they introduced a novel meta-heuristic called the multi-objective genetic flatworm algorithm. This method incorporates two distinct mechanisms, namely flatworm genetic operations and regeneration operations, to generate new individuals and solve the model. Liang et al. (2021) conducted research on the topic of balancing a two-sided assembly line with complex execution limitations. A novel MIP model was introduced to address this challenge, taking into account weighted length, workload smoothness index, and overall energy usage. They developed a novel multi-objective pairwise individual simulated annealing algorithm to solve the model. This was achieved by creating two distinct neighbor structure strategies and implementing a two-point matching information exchange mechanism. The performance of the new metaheuristic was then compared to single-objective and multi-objective simulated annealing methods, as well as the widely recognized NSGA-II algorithm. Liang et al. (2021) introduced a novel fuzzy multi-objective model for the two-sided disassembly line balance problem. This model incorporates the parallel

operation constraint and takes into account the equilibrium loss rate, smoothness index, and energy consumption of dismantling activities. A novel multi-objective flat worm algorithm was devised, incorporating growth, splitting, and regeneration mechanisms, based on the pareto-dominance relationship. The method's efficacy was demonstrated by successfully addressing two-sided disassembly line problems. Zhang et al. (2022) introduced a mixed integer programming model to address the two-sided disassembly line balance problem. The suggested model comprises four distinct objectives: the count of paired stations, the idleness index, the demand index, and the hazard index. Furthermore, the hazard and demand indexes are redefined, and additional time-related constraints are incorporated. The researchers introduced a multi-objective enhanced whale method that incorporates two distinct crossover operators to address the problem. To prevent the occurrence of local optima, a disturbance component is incorporated into the suggested model. Liang et al. (2022) conducted a study that addressed the issue of balancing a two-sided disassembly line. They established a probabilistic task destructive disassembly model. The model aims to minimize the total cost of disassembly, the smoothness index, and the negative impact of destructive disassembly tasks on neighboring tasks. A multi-objective restart genetic flatworm algorithm is proposed to solve the problem. Zhang et al. (2022) conducted research on the problem of balancing a disassembly line that operates on the two-sided line. Initially, a novel coding and decoding technique was devised for the purpose of disassembly scheme design. Subsequently, they presented a model that incorporates the variables of workstation count, idle time, smoothness index, and auxiliary indicator. They devised a metaheuristic utilizing a novel artificial bee colony (ABC) algorithm to effectively solve the problem. Çil et al. (2022) emphasized the advantages of two-sided disassembly lines for large-sized products. In this context, they studied the two-sided disassembly line balancing problem with sequence-dependent setup time (TDLBP-SDST). The authors proposed two new mixed integer linear programming models and a new constraint programming (CP) model for solving the problem and used a genetic algorithm, an artificial bee colony algorithm and improved versions of both algorithms for solving large-scale problems. They also propose a new CP model for standard TDLBP that does not consider sequence-dependent setup times and compare it with existing models in the literature. Zhang et al. (2023) conducted a study on the benefits of parallel and bilateral lines and focused on combining these two line types. Within this specific framework, a mixed integer

programming model was formulated to address the parallel two-sided disassembly line balancing problem. The model incorporated fixed common stations and was subsequently evaluated in small-scale scenarios. They suggested an enhanced multi-objective optimization technique called the moth-flame optimization algorithm for scenarios involving large-scale problems. According to Chao et al. (2023) , failing to consider problems such as corrosion and deformation of products in disassembly lines is not in accordance with actual situations. Within this framework, a novel mathematical model was formulated by including a partial destructive mode into the mixed model bilateral disassembly line balancing problem. The model aims to optimize the number of workstations, smoothness index and profit. An NSGA-II is proposed to ensure high quality of the resulting disassembly scheme. Wu et al. (2023) studied the two-sided disassembly line balancing problem. In this context, a mixed integer programming model is proposed that optimizes robot energy consumption and disassembly costs while minimizing the number of workstations and smoothness index with human-robot interaction constraints. A discrete squirrel search algorithm (DSSA) is developed to solve an innovative two-sided disassembly line balancing problem (TDLBP-HRI) model with human-robot interaction constraints in large-scale situations. Xu and Han (2024) pointed out that longer rest periods for workers on disassembly lines at certain intervals are directly proportional to the completion of tasks with high quality. In this context, a two-sided disassembly line balancing problem with worker rest time (TDLBP-RTW) was studied for the first time. In this study, a new model is proposed to optimize the dismantling profit, number of workstations, number of sub-workstations, workload uniformity and hazard index. A multi-objective evolutionary algorithm that takes into account feasible solution distribution and real-time search resource allocation is obtained by improving the NSGAII algorithm for solving the proposed model. Qin et al. (2024) proposed a human-robot collaborative disassembly line balancing problem approach that considers various techniques for hazardous and sensitive parts. In this context, a mixed integer programming mode is developed with the objective of minimizing the total disassembly time. For the solution of this model, a new metaheuristic method is proposed by improving the Q-learning algorithm in reinforcement learning.

As explained in section 1.2.2, although there are many advantages There is a limited body of literature spanning around six years that addresses the issue of balancing two-

sided disassembly lines. Hence, while there has been a notable rise in the quantity of research conducted in recent times, the current body of literature has significant gaps. Two-sided lines, which have economic benefits such as shortening the line length, constitute an important field of study for the disassembly line balancing problem. One of the gaps in this area, the problem of two-sided disassembly line balancing with human-robot collaboration, is addressed as in section 3.2.

### 2.3 Review on DLB with HRC

With the rapid development of technology in the globalizing world, robots have become increasingly widespread in the field of production as in every field. For this reason, human-robot cooperation, which has become the focus of academic studies today, constitutes one of the important parts of sustainability in many fields. In this section, human-robot collaboration is analyzed for assembly and disassembly line balancing problems. In order to develop sustainable applications for disassembly line balancing problems, the focus is especially on disassembly lines. The literature review prepared in this context is presented in this section.

Xu et al. (2020) highlighted the advantages and drawbacks of employing both humans and robots in disassembly lines, and specifically noted the benefits of their collaboration. Within this particular framework, a mathematical model was proposed with the aim of minimizing consumption, addressing disassembly problems, and improving profit by reducing the number of workstations. To address the proposed model, they additionally devised an innovative ABC method. Xu et al. (2021) highlighted disassembly faults and emphasized the significance of human-robot collaboration in this context. They collaborated on a disassembly line balance model that incorporated human-robot cooperation while prioritizing the safety of the human operator. They expanded upon this concept and resolved the developed model by employing a discrete bees method. The researchers confirmed the proposed model's validity by conducting a case study that focused on a bearing coupler. Fan et al (2022) proposed a mathematical model for the disassembly line balancing problem with human-robot collaboration for multiple products. IBM's CPLEX was used to test the proposed model. A new discrete shuffled frog leader algorithm is proposed for large-scale problems. Xiang et al. (2022) proposed a mathematical model for the multiproduct hybrid disassembly line balancing problem with human robot

collaboration. In order to solve the model, the parallel greedy search algorithm was used. Huang et al. (2024) highlighted that human-robot collaboration is a developing technology that seeks to enhance production efficiency and decrease ergonomic hazards. The researchers examined the mixed-model two-sided assembly line balance problem. A novel model was developed with the objective of reducing ergonomic risk, energy consumption, and cycle time. The researchers introduced a novel meta-heuristic technique named the Multi-Objective Discrete Artificial Bee Colony Algorithm with Specialist Bees (MDABCSB) to address the problem at hand.

As a result of the literature research classified in Table 2.1, a gap was identified in the literature on the problem of human-robot collaboration for disassembly line balancing on U-shaped and two-sided lines. One of these gaps, UDLBP-HRC, whose results are presented and interpreted in section 4.1, has been one of the topics addressed. Another one of these gaps, TDLBP-HRC, is addressed together with the triple bottom line approach, which allows to evaluate economic, social and environmental objectives together

**Table 2.1** Literature classification

| Papers | Line Type | | | | | Operator Type | | | Objective Function | | Product Type | | | Stracture of Parametres | | | Solution Method | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Straight | Parallel | U-Shaped | Two-Sided | Hybrid | Human | Robot | Human-Robot | Single | Multi | Single | Mixed | Multi | Determinisitic | Stochastic | Fuzzy | Exact | Heuristic/ Metaheuristic |
| Agrawal and Tiwari (2008) | | | ✓ | | | ✓ | | | | ✓ | | ✓ | | ✓ | | | | (CACO) |
| Avikal et al. (2013) | | | ✓ | | | ✓ | | | ✓ | | ✓ | | | ✓ | | | | (Unnamed) |
| Wang, Li and Gao (2019) | | | | ✓ | | ✓ | | | | ✓ | ✓ | | | | ✓ | | | (MOFPA) |
| Li, Kucukkoc and Zhang (2019) | | | ✓ | | | ✓ | | | | ✓ | ✓ | | | ✓ | | | | (ILS) |
| Kucukkoc (2020) | | | | ✓ | | ✓ | | | ✓ | | ✓ | | | ✓ | | | (MILP) | (GA) |
| Xu et al. (2020) | ✓ | | | | | | | ✓ | | ✓ | ✓ | | | | ✓ | | | (MOABC) |
| Wang, Gao, Li (2020) | | | ✓ | | | ✓ | | | | ✓ | ✓ | | | | ✓ | | | (MOFPA) |

**Continued**

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Liang et al. (2021) | | | | ✓ | | ✓ | | | | ✓ | ✓ | | | ✓ | | | | (DMOSA) |
| Li and Janardhanan (2021) | | | ✓ | | | ✓ | | | ✓ | | ✓ | | | ✓ | | | (MILP) | (DCS) |
| Yao and Gupta (2021a) | | | ✓ | | | ✓ | | | | ✓ | ✓ | | | ✓ | | | | (ACO) |
| Yao and Gupta (2021b) | | | ✓ | | | ✓ | | | | ✓ | ✓ | | | ✓ | | | | (IWO) |
| Yao and Gupta (2021c) | | | ✓ | | | ✓ | | | | ✓ | ✓ | | | ✓ | | | | (SWOA) |
| Wu et al. (2021) | | | ✓ | | | ✓ | | | | ✓ | | | ✓ | ✓ | | | | (MDBO) |
| Qin et al. (2021) | | | ✓ | | | ✓ | | | | ✓ | | | ✓ | ✓ | | | | (MDMBO) |
| Xu et al. (2021) | | | ✓ | | | ✓ | | | | ✓ | ✓ | | | | ✓ | | | (MOEA/D-CRA) |
| Wang et al. (2021) | | | ✓ | | | ✓ | | | | ✓ | | | ✓ | ✓ | | | | (MODCROA) |
| Wang et al. (2021) | | | ✓ | | | ✓ | | | | ✓ | ✓ | | | | | ✓ | | (MCDM, VNS) |
| Bai et al. (2021) | | | ✓ | | | ✓ | | | | ✓ | | | ✓ | | ✓ | | | (SMS-EMOA) |
| Li et al. (2021) | | | ✓ | | | ✓ | | | | ✓ | | | ✓ | | ✓ | | | (MSSA) |
| Huang et al. (2021) | | | ✓ | | | | | ✓ | | ✓ | ✓ | | | ✓ | | | | (MODBA) |
| Liang, Guo and Xu (2021) | | | | ✓ | | ✓ | | | | ✓ | | ✓ | | | ✓ | | | (MOGFA) |
| Xu et al. (2021) | ✓ | | | | | | | ✓ | | ✓ | ✓ | | | ✓ | | | | (IDBA) |
| Liang et al. (2021) | | | | ✓ | | ✓ | | | | ✓ | ✓ | | | | | ✓ | | (MOFA) |
| Zhang et al. (2022) | | | | ✓ | | ✓ | | | | ✓ | ✓ | | | ✓ | | | | (WOA) |
| Liang et al. (2022) | | | | ✓ | | ✓ | | | | ✓ | ✓ | | | ✓ | | | | (RGFA) |
| Zhang et al. (2022) | | | | ✓ | | ✓ | | | | ✓ | ✓ | | | ✓ | | | | (IMOABC) |
| Çil et al. (2022) | | | | ✓ | | ✓ | | | ✓ | | ✓ | | | ✓ | | | (CP, MILP) | (IGA, IABC) |
| Fan et al (2022) | ✓ | | | | | | | ✓ | ✓ | | | | ✓ | ✓ | | | (MILP) | (DSFLA) |
| Xiang et al. (2022) | | | | | ✓ | | | ✓ | ✓ | | | | ✓ | ✓ | | | | (MNPGSA) |
| Jin et al. (2022) | ✓ | | | | | | | ✓ | | ✓ | | | ✓ | | ✓ | | | (B-DMOEA) |
| Guo et al. (2023) | | | ✓ | | | ✓ | | | | ✓ | ✓ | | | ✓ | | | (MILP) | (MOEA/D-CRA) |
| Zhang et al. (2023) | | | | | ✓ | ✓ | | | | ✓ | | | ✓ | ✓ | | | | (IMFO) |
| Chao et al. (2023) | | | | ✓ | | ✓ | | | | ✓ | | ✓ | | ✓ | | | | (NSGA-II) |
| Wu et al. (2023) | | | | ✓ | | | | ✓ | | ✓ | ✓ | | | ✓ | | | (MILP) | (HLSGA) |

**Continued**

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wu et al. (2023) | | | | ✓ | | | | ✓ | | ✓ | ✓ | | | ✓ | | | (MILP) | (DSSA) |
| Liang et al. (2023) | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | ✓ | ✓ | | | | ✓ | | (MILP) | (NSGA-II, AFSA, DE) |
| Li et al. (2023) | | | ✓ | | | ✓ | | | | ✓ | ✓ | | | ✓ | | | (MILP) | (TABC, TBA) |
| Xu et al. (2023) | | | ✓ | | | ✓ | | | | ✓ | | | ✓ | | ✓ | | | (INSGA-II) |
| Wang et al. (2023) | ✓ | | | | | | | ✓ | | ✓ | | ✓ | | ✓ | | | | (IAFSA) |
| Guo et al. (2023) | ✓ | | | | | | | ✓ | | ✓ | ✓ | | | | ✓ | | | (MSFLA) |
| Qin et al. (2024) | | | ✓ | | | | ✓ | | | ✓ | | | ✓ | ✓ | | | | (IMMO) |
| Wang et al. (2024) | | | | | ✓ | ✓ | | | | ✓ | | ✓ | | ✓ | | | | (MO-A2C) |
| Wang et al. (2024) | | | | | ✓ | | | ✓ | ✓ | | | | ✓ | ✓ | | | | (DDPG, PPO, A2C) |
| Wang et al. (2024) | | | ✓ | | | | ✓ | | ✓ | | ✓ | | | ✓ | | | (MILP) | (DQN) |
| Kose, Ayyildiz and Cevikcan (2024) | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | ✓ | ✓ | | | | | ✓ | (MILP) | (FF-SWARA, FF-WASPAS) |
| Qin et al. (2024) | | | | ✓ | | | | ✓ | ✓ | | ✓ | | | ✓ | | | (MILP) | (QL) |
| Xu and Han (2024) | | | | ✓ | | ✓ | | | | ✓ | ✓ | | | ✓ | | | | (NSGAII-FSDRSA) |
| Huang et al. (2024) | | | | ✓ | | | | ✓ | | ✓ | | ✓ | | ✓ | | | | (ABC) |
| Zhao et al. (2024) | ✓ | | | | | | | ✓ | | ✓ | ✓ | | | ✓ | | | (MILP) | (IBO) |
| Zhang et al. (2024) | | ✓ | | | | | | ✓ | | ✓ | | | ✓ | ✓ | | | (MILP) | (IMFO) |
| Wu et al. (2024) | ✓ | | | | | | | ✓ | | ✓ | ✓ | | | ✓ | | | (MILP) | (MIGA) |
| Jiao, Feng and Yuan (2024) | | ✓ | | | | | | ✓ | | ✓ | ✓ | | | ✓ | | | | (FOA) |
| Shen et al. (2024) | ✓ | | | | | | | ✓ | | ✓ | ✓ | | | ✓ | | | | (MODBA) |
| Wu et al. (2024) | ✓ | | | | | | | ✓ | | ✓ | ✓ | | | | ✓ | | | (HEA) |
| Guo et al. (2024) | | | | | ✓ | | | ✓ | | ✓ | ✓ | | | ✓ | | | (MILP) | (IGWO) |
| **Proposed Model 1 (UDLBP-HRC)** | | | ✓ | | | | | ✓ | ✓ | | ✓ | | | ✓ | | | **(MILP)** | |
| **Proposed Model 2 (TDLBP-HRC)** | | | | ✓ | | | | ✓ | | ✓ **(TBL)** | ✓ | | | ✓ | | | **(MILP)** | |

## 2.4 Overview of DLB Literature with A Focus on Sustainability

The motivation of this thesis is that disassembly lines play an important role in the recycling of EOL products, which are of great importance for a more livable world. Undoubtedly, ensuring the long-term sustainability of this method is a factor that

enhances this incentive. Consequently, a comprehensive review of the pertinent scholarly works has been conducted in order to investigate sustainable strategies inside disassembly line balancing. This section presents an overview of the 49 papers obtained from a search with following query on Scopus.

"(TITLE-ABS-KEY ("sustainability" OR "green" OR "sustainable") AND TITLE-ABS-KEY ("disassembly line balancing")) AND (EXCLUDE (DOCTYPE, "cp") OR EXCLUDE (DOCTYPE, "cr"))"

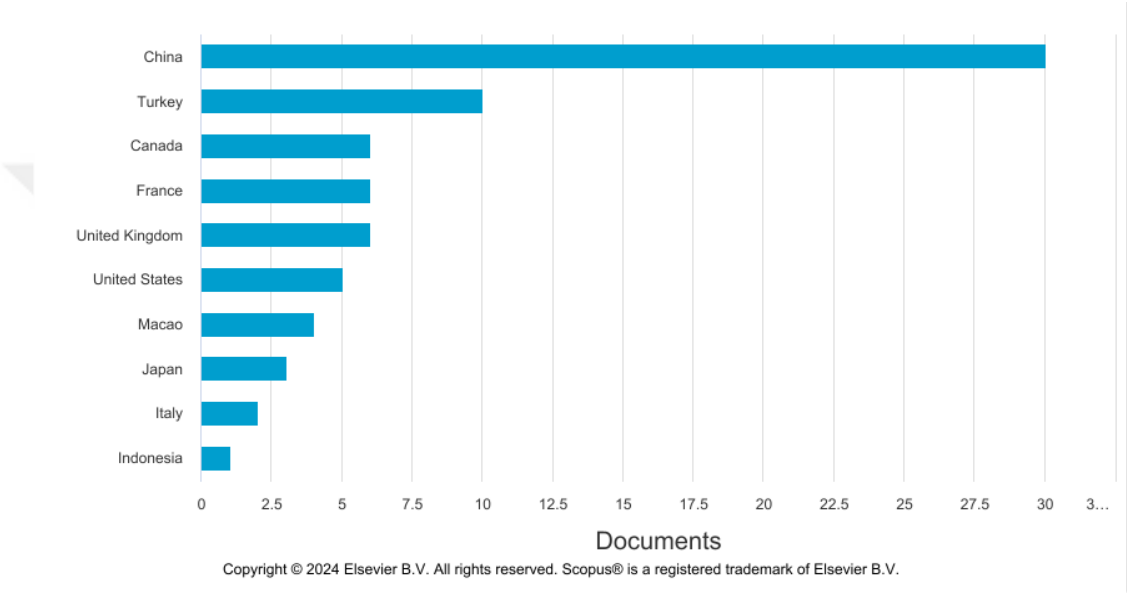


**Figure 2.1** Distribution of papers according to countries

As depicted in Figure 2.1, a significant proportion of scholarly papers within this particular domain are authored by academics from China. Chinese researchers have conducted three times as many studies as their Turkish counterparts, who rank second. Nevertheless, this phenomenon can be attributed to the substantial disparity in population between the two nations, which exceeds sixteenfold.

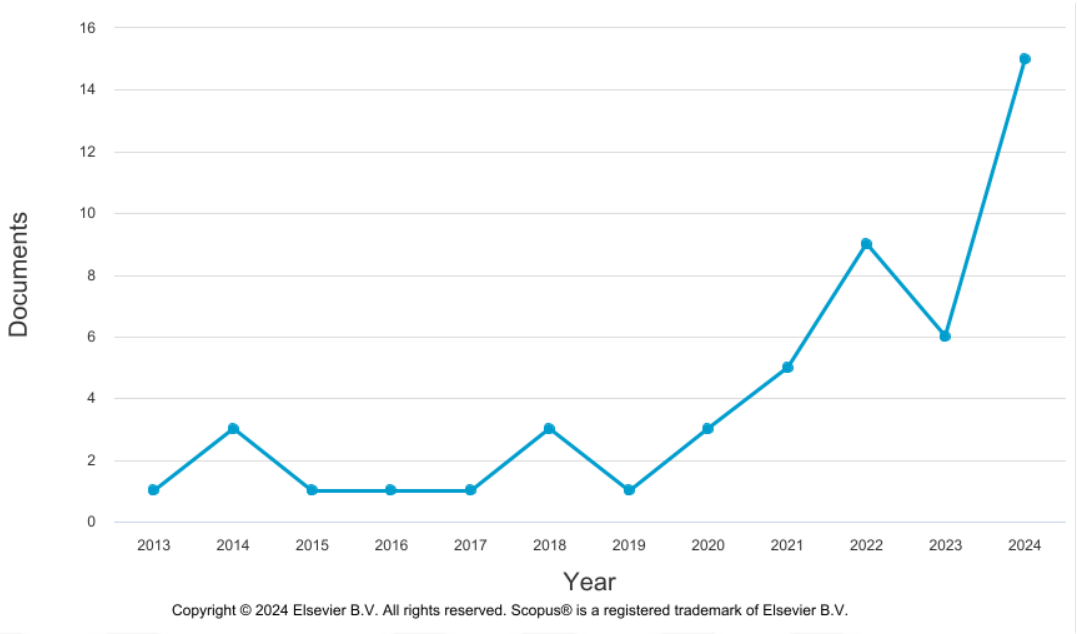


**Figure 2.2** Distribution of papers according to years

The data presented in Figure 2.2 illustrates a significant rise of more than 100% in sustainability-focused DLB research in recent years. Specifically, although not yet concluded, it is evident that the research undertaken in 2024 has achieved a remarkable surge of 15 papers. Considering that the previous peak number of papers was 9, it is clear that studies focusing on sustainability have gained significant importance and are currently exhibiting a noteworthy trend.

The statistics presented in this study provide convincing evidence of the exponential growth in the significance of sustainable disassembly line balancing problems, which serves as the thesis's focal point. So far, a comprehensive literature review has led to the investigation of two identified gaps. The present study introduces two novel Mixed Integer Linear Programming (MILP) models for UDLBP-HRC and TDLB-HRC.

# CHAPTER 3
# METHODOLOGY

## 3.1 U-Shaped Disassembly Line Balancing Problem with Human–Robot Collaboration

This section outlines the technique used in the study to address the gap in the existing literature about sustainable remedies to the U-shaped disassembly line balancing challenge. Human-robot collaboration, which plays a significant role in promoting sustainability, is incorporated into U-shaped disassembly lines in this particular situation. The specification of the problem under study and the newly developed mixed integer mathematical programming (MILP) model obtained for UDLBP-HRC are described in the following subsections of this framework.

### 3.1.1 Problem Definition of UDLBP-HRC

The primary focus of this issue is on disassembly lines, which play a significant role in the recovery of end-of-life (EOL) products. The issue of balancing U-shaped lines, a form of disassembly line noted for its benefits resulting from enhanced operator engagement, is being examined. Unlike linear paths, this problem is composed of two distinct sections, namely the entrance and outflow, which can be manipulated by an operator. Thus, task assignments must adhere to precedence relations and other specific restrictions, and the paths from both the inlet and the exit must be congruent with each other. This is the most challenging component of this problem. This study aims to determine whether the operators allocated to the tasks, while lowering the number of stations, must be human, robot, or human-robot cooperative swarm alternatives.

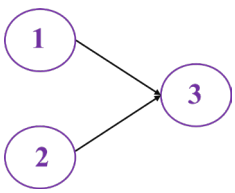


**Figure 3.1** A descriptive example of the AND precedence relationship

In tasks involving the AND precedence relation, the beginning of the task is contingent upon the completion of all preceding tasks. According to the descriptive example in Figure 3.1, the task 3 can not start before the completion of tasks 1 and 2. In this research, a mathematical model is proposed for the human robot collaboration U-shaped disassembly line balancing problem. The model developed in this paper solves the U-shaped disassembly line balancing problem with human-robot collaboration for situations involving tasks with AND precedence graphs. The proposed model is based on Li et al. (2023)'s study. The calibration constraints in the model were added to the system by making use of the mentioned study and the assignment differences in U-shaped lines were prevented. In this model, the process alternative index (p) was integrated into the model by taking advantage of another study by Li et al. (2023). If this index (p) is 1, it means that only the human operator performs the task, if it is 2, it means that the robot operator performs the task, and if it is 3, it means that the task is performed in co-operation. The following constitutes the mathematical model's underlying presumptions developed in this study:

- Cycle time is given
- There is no limitation on the capabilities of the robots
- Tasks cannot be divided
- The process times for tasks are known and deterministic
- Human's workforce is homogeneous
- Robots' workforce is homogeneous
- The precedence relationships between tasks are known

### 3.1.2 Mathematical Model for UDLBP-HRC

The problem is formulated in this section, where the notations to be used are first introduced in table 3.1.

**Table 3.1** Notations for UDLBP-HRC model

| **Notations** | |
|---|---|
| $i, j, v$ | Task index $i, j, v \in \{1,2,3 \dots G\}$ ,G is the total number of tasks |
| $k, l$ | Workstation index $k, l \in \{1,2,3 \dots K\}$ |
| $p$ | Process alternative index $p \in \{1,2,3\}$ |
| $T_C$ | Cycle time |
| $t_{ip}$ | Completion time of ith task by pth process alternative |
| $ANDP(i,j)$ | The set of i, j pairs where task j is the AND predecessor of i |

| | |
|---|---|
| $w_k$ | 1, if the kth station is opened; 0, otherwise |
| $x_{ikp}$ | 1, if the ith task is performed by the pth process alternative at kth station in forward of the line; 0, otherwise |
| $y_{ikp}$ | 1, if the ith task is performed by the pth process alternative at kth station in backward of the line; 0, otherwise |
| $D_{ij}$ | 1, if task i is completed before task j, and 0 otherwise. |
| $s_i$ | Sequence of task i in the result |

Objective Function

The equation (3.1) minimizes the number of stations

$$W = \sum_{k=1}^{K} w_k \tag{3.1}$$

Subject to

Constraint (3.2) ensures that each task is assigned to a station with a process alternative.

$$\sum_{p=1}^{p_{max}} \sum_{k=1}^{K} x_{ikp} + y_{ikp} = 1 \qquad \forall i \tag{3.2}$$

Constraint (3.3) ensures that the sum of the task times does not exceed the cycle time for each station.

$$\sum_{p=1}^{p_{max}} \sum_{i=1}^{i_{max}} t_{ip} \cdot \left(x_{ikp} + y_{ikp}\right) \leq w_k \cdot T_C \qquad \forall k \tag{3.3}$$

Constraints (3.4 and 3.5) guarantee that tasks are assigned according to priority relationships.

$$\sum_{p=1}^{p_{max}} x_{ikp} \leq \sum_{l=1}^{l_{max}} \sum_{p=1}^{p_{max}} x_{jlp} \qquad \forall k, i, j \in ANDP(i,j) and\ l \leq k \tag{3.4}$$

$$\sum_{p=1}^{p_{max}} y_{jkp} \leq \sum_{l=1}^{l_{max}} \sum_{p=1}^{p_{max}} y_{ilp} \qquad \forall k, i, j \in ANDP(i,j) and\ l \leq k \tag{3.5}$$

Constraints (3.6 – 3.10) ensure that the assignments for the input and output path are appropriate.

$$D_{ii} = 0 \qquad \forall i \in K \tag{3.6}$$

$$D_{ij} + D_{ji} \leq 1 \qquad \forall i, j \; and \; i < j \tag{3.7}$$

$$D_{ij} \leq 1 \qquad \forall j \in ANDP(i,j) \tag{3.8}$$

$$x_{ik} + x_{jl} - 1 \leq D_{ij} \qquad \forall i, j, k, l, k < l \tag{3.9}$$

$$D_{iv} + D_{vj} - 1 \leq D_{ij} \qquad \forall i, j, v, i \neq v, v \neq j \; and \; i \neq j \tag{3.10}$$

Constraint (3.11) Calculates the sequence of tasks.

$$s_i = G - \sum_{j=1}^{G} D_{ij} \qquad \forall i \tag{3.11}$$

Constraint (3.12) indicates binary and integer variables.

$$w_k, x_{ikp}, y_{ikp}, D_{ij} \in \{0,1\} \qquad \forall k, i, p, l, j, v \tag{3.12}$$

## 3.2 Two-Sided Disassembly Line Balancing Problem with Human–Robot Collaboration

This section presents the methods used to solve the two-sided disassembly line balance problem, which was identified as a gap in the existing literature. A novel MILP model is developed for TDLBP-HRC. The proposed model is designed and solved in accordance with the triple bottom line (TBL) approach, which enables the examination of economic, social, and environmental objectives. The TDLBP-HRC is described and the proposed model is explained in the following subsections.

### 3.2.1 Problem Definition of TDLBP-HRC

Two-sided disassembly lines, which offer various advantages for the disassembly of large products, have been extensively studied. In this context, the study by Kucukkoc (2020), which proposes a model for the two-sided disassembly line balancing problem (TDLBP), has been utilized. Additionally, due to its benefits, the popular research

topic of human-robot collaboration has been integrated into the TDLBP. To facilitate this integration, the process alternative index (d) used in the studies by Li et al. (2023) has been employed. This index, which takes values of 1, 2, and 3, respectively represents human, robot, and human-robot collaboration.

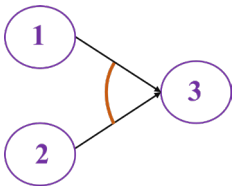


**Figure 3.2** A descriptive example of the OR precedence relation

Within this framework, a new mixed-integer mathematical model for the two-sided disassembly line balancing problem with human-robot collaboration (TDLBP-HRC) has been proposed. The proposed model also considers the constraint related to which side of the station tasks can be performed. The model solution employs a triple bottom line approach, addressing three main objectives economic, social, and environmental and solving for all possible priority combinations. Furthermore, the proposed model considers both the AND precedence relation, which involves tasks that must be started after the completion of all dependent and preceding tasks, and the OR precedence relation, which involves tasks that can be started after the completion of any one of the dependent and preceding tasks. According to the descriptive example in Figure 3.2, task 3 can start after completing either task 1 or 2.

The assumptions for the TDLBP-HRC model are as follows:

- The risks of tasks and the risk coefficients of different process alternatives are known.
- Humans and robots are homogeneous in terms of their working capabilities.
- The precedence relationships of tasks are known.
- The energy consumption of robots when they are working is known.
- The cycle time is known.

- The times for tasks to be performed by different process alternatives are known.

- Tasks are indivisible.

### 3.2.2 Mathematical Model for TDLBP-HRC

The TDLBP-HRC model, which utilizes the notations presented in Table 3.2, is based on the two-sided disassembly line balancing model introduced by Kucukkoc (2020). A novel TDLBP-HRC model was developed by incorporating human-robot collaboration into the mentioned model. The proposed new model has three distinct primary objective functions in alignment with the triple bottom line approach (TBL).

**Table 3.2** Notations for TDLBP-HRC model

| **Notations** | |
|---|---|
| $i, h, p$ | Task indices |
| $j$ | Mated station index |
| $k$ | Station side index (right, left) |
| d | Process alternative index |
| AR | The list of tasks to be performed on the right side of the station |
| $AL$ | The list of tasks to be performed on the left side of the station |
| AE | The list of tasks that can be performed on both the right and left sides of the station |
| ANDPT | The list of tasks with AND precedence relationships |
| ORPT | The list of tasks with OR precedence relationships |
| $ANDP_i$ | The list of AND predecessors for task $i$ |
| $ORP_i$ | The list of OR predecessors for task $i$ |
| $T_{id}$ | The processing time of task $i$ with process alternative $d$ |
| $K_i$ | The list containing sub lists that indicate on which side of the station task $i$ can be performed |
| $R_i$ | A list of 0s and 1s indicating whether task $i$ is risky (1) or not (0) |
| $A_{id}$ | A list containing the risk weights of tasks across different process alternatives |
| CT | Cycle Time |
| GREC | Energy consumption for the working robot (kW/min) |
| M | A large number |
| $S_{ijkd}$ | 1 if task $i$ is performed at side $k$ of mated station $j$ with process alternative $d$; 0 otherwise |
| $X_{ijd}$ | 1 if task $i$ is performed at mated station $j$ with process alternative $d$; 0 otherwise |
| $W_{ikd}$ | 1 if task $i$ is performed on side $k$ with process alternative $d$; 0 otherwise |

| | |
|---|---|
| $Z_{ih}$ | 1 if task $h$ is a predecessor of task $i$ or if both tasks are assigned to the same station and task $h$ is performed before task $i$; 0 otherwise |
| $U_{jk}$ | 1 if the station on side $k$ of mated station $j$ is opened; 0 otherwise |
| $EC_{jk}$ | The total energy consumption resulting from the operation of robots at a station |
| $T_i^S$ | The start time of task $i$ |
| $F_j$ | 1 if both sides of mated station $j$ are opened; 0 otherwise |
| $G_j$ | 1 if only one side of mated station $j$ is opened; 0 otherwise |
| $TR_i$ | The total risk of task $i$ when multiplied by the operator weights |

Equation 3.15 aims to minimize the number of stations opened, while Equation 3.14 aims to minimize the station length. The economic objective of the model is Equation 3.13, which aims to minimize the sum of Equation 3.14 and Equation 3.15.

$$Min\ f_1 = f_{1.1} + f_{1.2} \tag{3.13}$$

$$f_{1.1} = Min \sum_j F_j + G_j \tag{3.14}$$

$$f_{1.2} = Min \sum_j \sum_k U_{jk} \tag{3.15}$$

Equation 3.16 is the social objective by aiming to minimize the total risk of the tasks.

$$Min\ f_2 = \sum_d \sum_j \sum_i \sum_{k \in K_i} S_{ijkd} + R_i + A_{id} \tag{3.16}$$

The environmental objective of the model is achieved by Equation 3.17, which aims to minimize the total energy consumption resulting from the operation of robots, as calculated in Constraint 3.39.

$$Min\ f_3 = \sum_j \sum_k EC_{jk} \tag{3.17}$$

Constraints 3.18 and 3.19 are assignment constraints. Constraint 3.18 ensures that each task is assigned to a mated station and a process alternative, while Constraint 3.19 ensures that each task is assigned to a side of the station and a process alternative.

$$\sum_{j}\sum_{d} X_{ijd} = 1 \qquad \forall i \qquad (3.18)$$

$$\sum_{k}\sum_{d} W_{ikd} = 1 \qquad \forall i \qquad (3.19)$$

Constraints 3.20-3.24 are precedence constraints. Constraint 3.20 is used to calculate the start times of tasks considering their precedence relationships. Constraints 3.21 and 3.22 work together: Constraint 3.22 sets $Z_{hi}$ to 1 when task h is a predecessor of task i, while Constraint 3.21 ensures that $Z_{ih}$ , which represents the opposite scenario, is 0 in this case. Constraint 3.23 regulates situations involving OR precedence relationships. Constraint 3.24 arranges the precedence relationships among three different tasks.

$$T_i^S + M * (1 - Z_{hi}) \geq T_h^S + \sum_{j}\sum_{d} T_{hd} * X_{hjd} \qquad \forall i, h, i \neq h \qquad (3.20)$$

$$Z_{hi} + Z_{ih} = 1 \qquad \forall i \in ANDPT,\ h \in ANDP_i \qquad (3.21)$$

$$Z_{hi} = 1 \qquad \forall i \in ANDPT,\ h \in ANDP_i \qquad (3.22)$$

$$\sum_{h \in ORP_i} Z_{hi} \geq 1 \qquad \forall i \in ORPT \qquad (3.23)$$

$$Z_{ih} + Z_{hp} - 1 \leq Z_{ip} \qquad \forall i, h, p,\ i \neq h, h \neq p,\ i \neq p \qquad (3.24)$$

Constraints 3.25-3.27 regulate task assignments. Constraints 3.25 and 3.26 work together: Constraint 3.26 manages the precedence relationships for tasks assigned to the same station, while Constraint 3.25 ensures that $Z_{hi}$ and $Z_{ih}$ are not both 1 simultaneously. Additionally, Constraint 3.27 arranges the start times of tasks, taking into account precedence relationships when tasks are assigned to the same station.

$$Z_{ih} + Z_{hi} \leq 1 \qquad \forall i, h, i \neq h \qquad (3.25)$$

$$Z_{ih} + Z_{hi} + M * \left(2 - \sum_d X_{ijd} + X_{hjd}\right) + M * \left(2 - \sum_d W_{ikd} + W_{hkd}\right) \geq 1 \qquad \forall i, h, j, k \in K_i \cap K_h, i \neq h \qquad (3.26)$$

$$T_p^S + M * \left(2 - \sum_d X_{ijd} + X_{pjd}\right) + M * \left(2 - \sum_d W_{ikd} + W_{pkd}\right) + M * (1 - Z_{ip}) \geq T_i^S + \sum_{k \in K_i} \sum_d T_{id} * W_{ikd} \qquad \forall i, p, j, k \in K_i \cap K_p, i \neq p \qquad (3.27)$$

Constraints 3.28-3.29 relate to cycle time. Constraint 3.28 ensures that the start time of a task, when considered cumulatively, is greater than the cycle time of the previous station to which it is assigned. Constraint 3.29 ensures that the completion time of a task is less than the cycle time of the station to which it is assigned.

$$T_i^S \geq CT * \sum_d \sum_j (j-1) * X_{ijd} \qquad \forall i \qquad (3.28)$$

$$T_i^S + \sum_j \sum_d T_{id} * X_{ijd} \leq CT * \sum_d \sum_j j * X_{ijd} \qquad \forall i \qquad (3.29)$$

Constraints 3.30-3.32 regulate the opening of stations. Constraint 3.30 ensures that if a task is assigned to a mated station and side with any process alternative, the respective station side is opened. Constraint 3.31 manages the relationship between different station assignment variables. Constraint 3.32 is a sequencing constraint that ensures stations are opened in order.

$$U_{jk} \geq \left(\sum_d X_{ijd} + W_{ikd}\right) - 1 \qquad \forall i, j, k \qquad (3.30)$$

$$\sum_{k} U_{jk} - 2 * F_j - G_j = 0 \qquad \forall j \qquad (3.31)$$

$$F_j + G_j \geq F_{j+1} + G_{j+1} \qquad \forall j \qquad (3.32)$$

Constraint 3.33 ensures that tasks controlled by two different variables are assigned to the same process alternative in both variables.

$$\sum_{j} X_{ijd} = \sum_{k \in K_i} W_{ikd} \qquad \forall i, d \qquad (3.33)$$

Constraints 3.34-3.38 are used to control the assignments of tasks to stations through the variable $S_{ijkd}$ and ensure consistency with other assignment variables. Constraints 3.34-3.36 ensure that the variable $S_{ijkd}$ is 1 only if both $X_{ijd}$ and $W_{ikd}$ are 1 simultaneously. Constraint 3.37 ensures that if a task is assigned to a station with a process alternative, that station is opened. Constraint 3.38 ensures that if a station is opened, at least one task with a process alternative is assigned to it.

$$S_{ijkd} \leq X_{ijd} \qquad \forall i, j, k, d \qquad (3.34)$$

$$S_{ijkd} \leq W_{ikd} \qquad \forall i, j, k, d \qquad (3.35)$$

$$S_{ijkd} \leq X_{ijd} + W_{ikd} - 1 \qquad \forall i, j, k, d \qquad (3.36)$$

$$U_{jk} \geq S_{ijkd} \qquad \forall i, j, k, d \qquad (3.37)$$

$$U_{jk} \leq \sum_{i} \sum_{d} S_{ijkd} \qquad \forall j, k \qquad (3.38)$$

Constraint 3.39 calculates the amount of energy consumption resulting from the total working times of robots for each station.

$$EC_{jk} = GREC * \sum_{i} S_{ijk2} * T_{i2} + S_{ijk3} * T_{i3} \qquad \forall j, k \qquad (3.39)$$

# CHAPTER 4
# RESULTS AND DISCUSSION

## 4.1 U-Shaped Disassembly Line Balancing Problem with Human–Robot Collaboration

The model created for UDLBP-HRC is evaluated in a case involving 25 tasks sourced from the literature. The subsequent subsection presents the utilized data, the achieved results, and includes tables, visualizations, and corresponding comments.

### 4.1.1 Illustrative Example for UDLBP-HRC

As an example, the disassembly of a Samsung SCH-3500 mobile phone consisting of 25 tasks solved with the proposed mathematical model for different cycle times. From the data shown in Table 4.1, the task durations for the human operator are taken from the example, while the durations for the robot and collaboration are randomly generated. The precedence relations of the solved example are as shown in Figure 4.1 (Kalayci & Gupta, 2013).

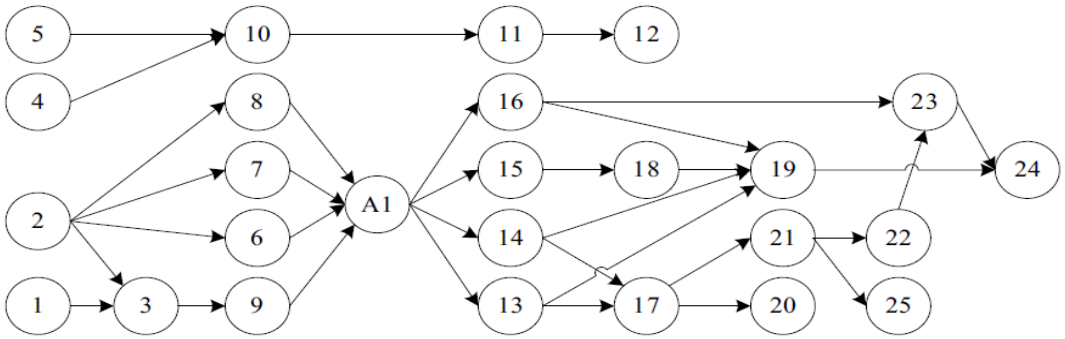


**Figure 4.1** Precedence relations diagram for the 25 tasks scenario

**Table 4.1** Part removal times for the 25 tasks scenario

| Task | Part name | Part removal time | | |
|---|---|---|---|---|
| | | **Human Operator (1)** | **Robot Operator (2)** | **Human Robot Collaboration (3)** |
| 1 | Antenna | 3 | 5 | 10 |
| 2 | Battery | 2 | 8 | 4 |
| 3 | Antenna guide | 3 | 10 | 5 |
| 4 | Bolt (type 1) A | 10 | 16 | 11 |
| 5 | Bolt (type 1) B | 10 | 12 | 18 |
| 6 | Bolt (type 2) 1 | 15 | 14 | 3 |
| 7 | Bolt (type 2) 2 | 15 | 20 | 7 |
| 8 | Bolt (type 2) 3 | 15 | 15 | 16 |
| 9 | Bolt (type 2) 4 | 15 | 3 | 19 |
| 10 | Clip | 2 | 7 | 5 |
| 11 | Rubber seal | 2 | 4 | 2 |
| 12 | Speaker | 2 | 1 | 8 |
| 13 | White cable | 2 | 3 | 9 |
| 14 | Red/blue cable | 2 | 2 | 6 |
| 15 | Orange cable | 2 | 4 | 10 |
| 16 | Metal top | 2 | 6 | 4 |
| 17 | Front cover | 2 | 2 | 7 |
| 18 | Back cover | 3 | 10 | 2 |
| 19 | Circuit board | 18 | 22 | 24 |
| 20 | Plastic screen | 5 | 9 | 11 |
| 21 | Keyboard | 1 | 9 | 6 |
| 22 | LCD | 5 | 11 | 4 |
| 23 | Sub-keyboard | 15 | 15 | 9 |
| 24 | Internal IC board | 2 | 6 | 9 |
| 25 | Microphone | 2 | 5 | 9 |

Taking into account the precedence relations in Figure 4.1 and the part removal times in Table 4.1, the case solved for 24, 30 and 40 units of cycle time respectively. The objective function value (number of stations) is found in 5 stations for cycle time 24, 4 for cycle time 30, and 3 for cycle time 40.

When the case is solved by taking cycle times 24, 30 and 40, the robot and human operators to be assigned to the stations are shown in Figures 4.2, 4.3 and 4.4, respectively. In addition, the tasks assigned to the station according to the inlet and outlet sides of the stations to be considered in U-shaped lines are also indicated in Figures 4.2, 4.3 and 4.4.

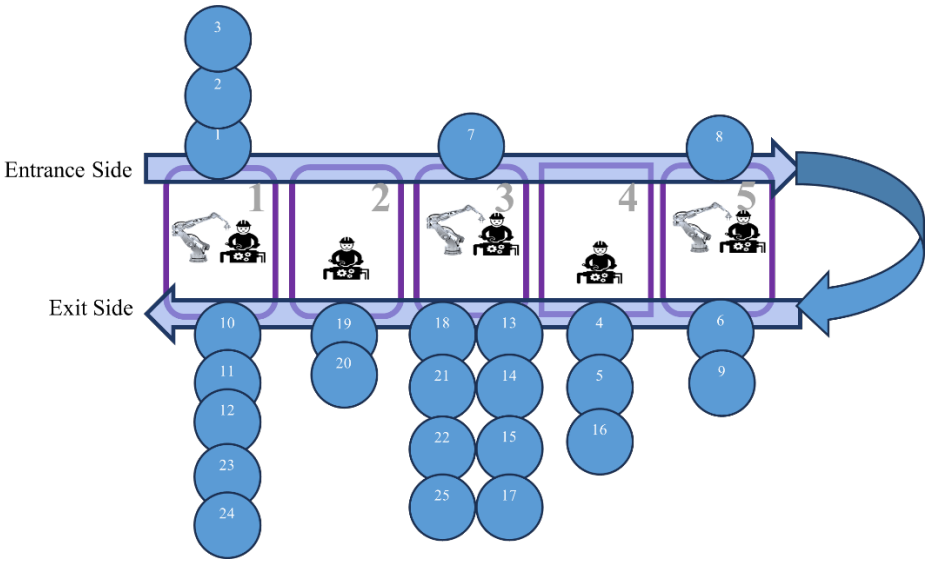


**Figure 4.2** Assignments results for cycle time 24

As seen in Figure 4.2, when the cycle time is 24, 5 stations must be opened to solve the problem. While the 1st, 3rd and 5th stations are double-sided, the 2nd and 4th stations are single-sided, only the exit side. However, while only human operator works at the 2nd and 4th stations, both robot and human operator work at the other stations.

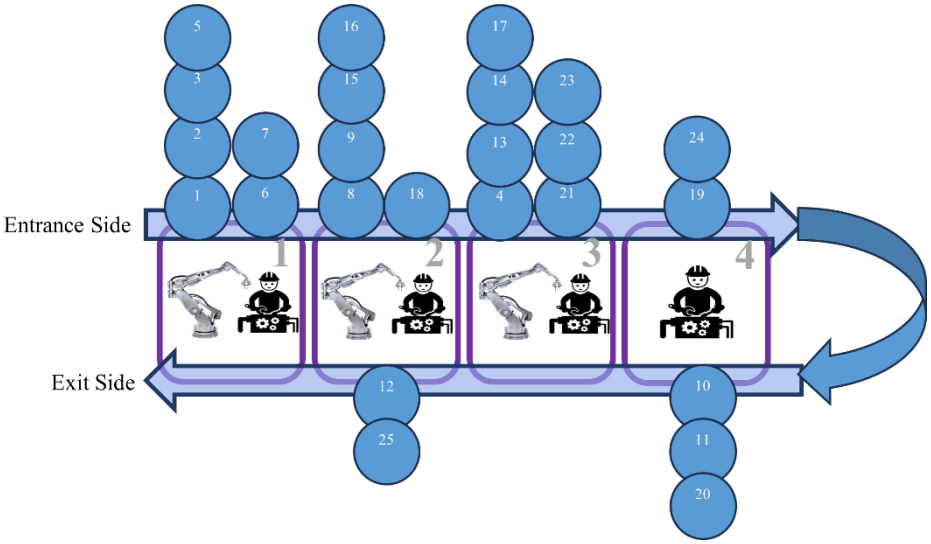


**Figure 4.3** Assignments results for cycle time 30

When the cycle time was 30, 4 stations were opened. While both human and robot operators work at the 1st, 2nd and 3rd stations, only human operator works at the 4th

station. In addition, while the 2nd and 4th stations are double-sided, the 1st and 3rd stations are single-sided as the entrance side.

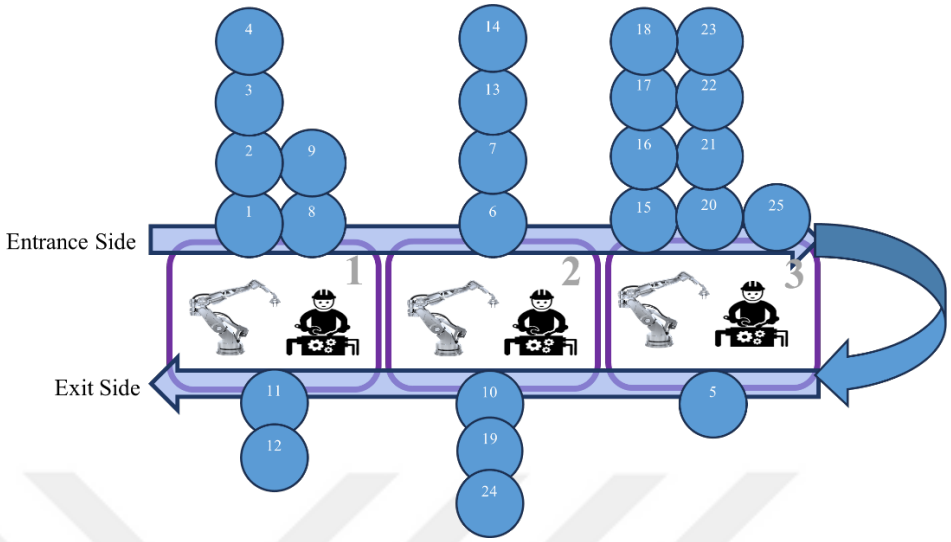


**Figure 4.4** Assignments results for cycle time 40

When the cycle time is 40, 3 stations are opened. In all of these stations, both human and robot operators are working. In addition, all of these stations are opened on the double side

**Table 4.2** Selection process alternatives

| Task | Process Alternative | | |
|---|---|---|---|
| | Human Operator (1) | Robot Operator (2) | Human Robot Collaboration (3) |
| 1 | ✓ | | |
| 2 | ✓ | | |
| 3 | ✓ | | |
| 4 | ✓ | | |
| 5 | ✓ | | |
| 6 | | | ✓ |
| 7 | | | ✓ |
| 8 | ✓ | | |
| 9 | | ✓ | |
| 10 | ✓ | | |
| 11 | ✓ | | ✓ |
| 12 | | ✓ | |
| 13 | ✓ | | |
| 14 | ✓ | | |
| 15 | ✓ | | |

| | | | |
|---|---|---|---|
| 16 | ✓ | | |
| 17 | ✓ | ✓ | |
| 18 | | | ✓ |
| 19 | ✓ | | |
| 20 | ✓ | | |
| 21 | ✓ | | |
| 22 | | | ✓ |
| 23 | | | ✓ |
| 24 | ✓ | | |
| 25 | ✓ | | |

The selection of process alternatives is linked to the part removal times in the proposed model. Therefore, the model selects the alternative with the lowest time. As seen in table 4.2, 2 different alternatives are selected for 3 different cycle time cases solved for the 11th and 17th tasks. For the 11th task, Alternative 1 was selected in the case of cycle time 24, while Alternative 3 was selected in the case of 30 and 40. For the 17th task, Alternative 1 was selected for the case with a cycle time of 24, while Alternative 2 was selected for the cases with cycle times of 30 and 40. The reason for this situation is that the part removal times of Alternatives 1 and 3 for task 11 and Alternatives 1 and 2 for task 17 are equal.

## 4.2 Two-Sided Disassembly Line Balancing Problem with Human–Robot Collaboration

The model developed for TDLBP-HRC is initially evaluated on a 22-task instance taken from the literature. Consequently, it was determined that the model necessitates heuristics for handling large-scale problems due to the inability to achieve an optimal solution within a reasonable timeframe. The outcomes of the model, which was tested on a smaller sample from the literature, are detailed in the subsequent subsection. Furthermore, the model solved using the triple bottom line approach yields six distinct outcomes as a result of varying prioritization of the objective functions. These outcomes are then analyzed and visualized using radar plots.

### 4.2.1 Illustrative Example for TDLBP-HRC

Firstly, the developed model was coded using the Gurobi library in Python. Subsequently, the P22-OR scenario, as presented in the precedence diagram by Kalaycılar et al.(2016) , was solved using a system equipped with a 12th Gen Intel(R) Core(TM) i7-12700H 2.70 GHz processor and 16 GB of RAM. Despite efforts, an

optimal solution was not reached within an extended duration of 86,400 seconds (1 day). Consequently, the P10-OR scenario, as presented by McGovern and Gupta (2004) , was solved by generating the necessary data for the model developed in this study, including the task-to-station side suitability data used in Kucukkoc (2020) work. The solution times for scenarios A, B, C, D, E, and F, depicted in radar charts in Figures 4.12, 4.13, and 4.14, were recorded as 0.83, 1.78, 0.73, 4.87, 5, and 4.40 seconds, respectively, on the aforementioned system.

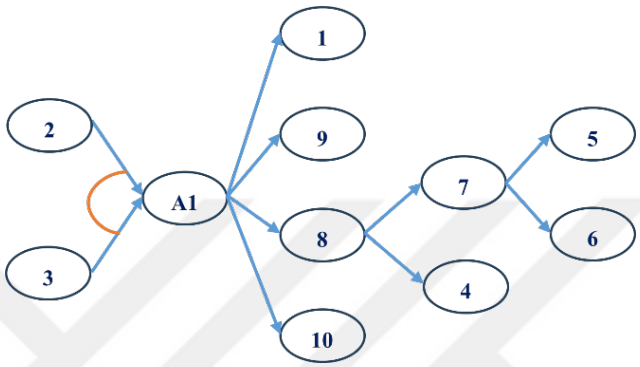


**Figure 4.5** Precedence relationships diagram for P10-OR scenario

As illustrated in Figure 4.5 (McGovern & Gupta, 2004), the 10-task scenario includes both OR and AND precedence structures. Tasks 2 and 3 are connected to Tasks 1, 8, 9, and 10 through an OR precedence structure. Task 8 is linked to tasks 7 and 4 through an AND precedence structure, while task 7 is connected to tasks 5 and 6 through another AND precedence structure.

**Table 4.3** The data used in solving the 10-task scenario

| Task | Task Risk (0,1) | Tasks to Suit Which Sides of the Station | Risk Coefficients for Different Process Alternatives | | | Processing Time for Process Alternatives | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| 1 | 0 | Left | 0 | 0 | 0 | 14 | 36 | 12 |
| 2 | 1 | Either | 0.42 | 0.52 | 0.06 | 10 | 19 | 11 |
| 3 | 1 | Right | 0.13 | 0.53 | 0.34 | 12 | 16 | 29 |
| 4 | 1 | Either | 0.16 | 0.12 | 0.72 | 18 | 9 | 21 |
| 5 | 0 | Left | 0 | 0 | 0 | 23 | 15 | 14 |
| 6 | 1 | Either | 0.46 | 0.1 | 0.44 | 16 | 31 | 13 |
| 7 | 1 | Right | 0.15 | 0.65 | 0.2 | 20 | 15 | 36 |
| 8 | 0 | Either | 0 | 0 | 0 | 36 | 13 | 8 |
| 9 | 0 | Either | 0 | 0 | 0 | 14 | 10 | 17 |
| 10 | 0 | Left | 0 | 0 | 0 | 10 | 30 | 18 |

In the 10-task scenario, the cycle time is set to 36 units, while the amount of energy consumed by the robots during operations is taken as 0.05 kW per unit. Besides these two data points and the precedence relationships, the additional data required for solving the model such as task risk, suitability of the task for specific sides of the station, risk coefficients for different process alternatives, and task completion times are provided in Table 4.3.

**Table 4.4** Priorities of objective functions in different scenarios

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Economic | 1 | 1 | 2 | 2 | 3 | 3 |
| Social | 2 | 3 | 1 | 3 | 1 | 2 |
| Environmental | 3 | 2 | 3 | 1 | 2 | 1 |

The model encompasses three main objectives economic, social, and environmental in alignment with the Triple Bottom Line (TBL) approach. Different prioritizations of these objectives during the model solution yield varying results. This situation results in six distinct scenarios for the model, which includes the three objectives. Table 4.4 presents these six scenarios resulting from different prioritizations. In the table, the objectives are assigned priority numbers 1, 2, and 3, with the highest priority objective being the one with the largest number. For instance, in Scenario A, the priority order is environmental, social, and economic. For Scenario A, the solution begins with the environmental objective, followed by the social objective while preserving the previously obtained results as much as possible, and finally, the economic objective is addressed to derive the final results.

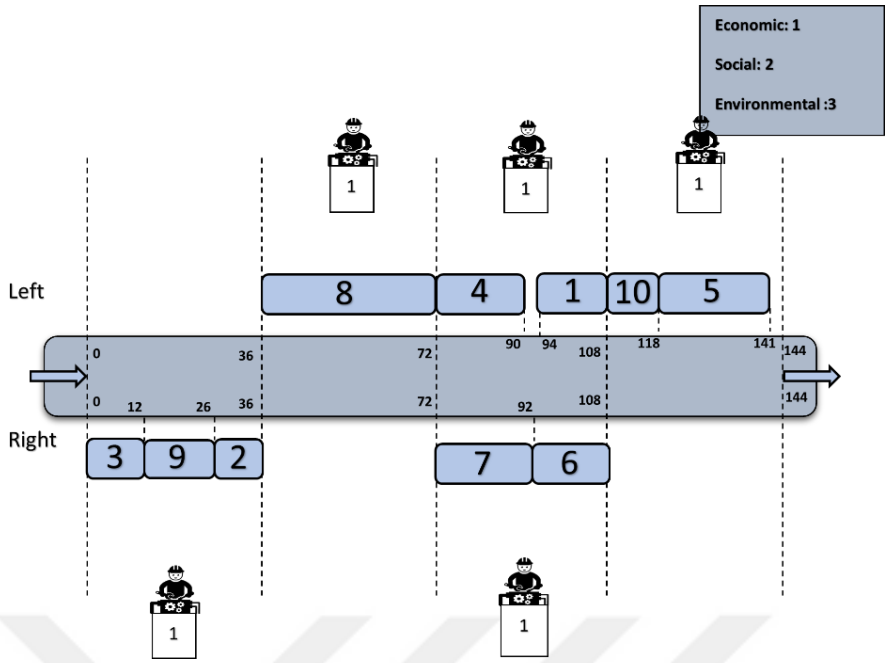


**Figure 4.6** Task and operator assignments of scenario A on a two-sided line

As depicted in Figure 4.6, in Scenario A, a total of four mated-stations are opened, with only one of them being both side of mated-station while the remaining three are single side. Of the opened stations, three are on the left side and two are on the right side. Each of the five stations has been assigned one human operator, totaling five human operators. All tasks have been completed in 141 time units.

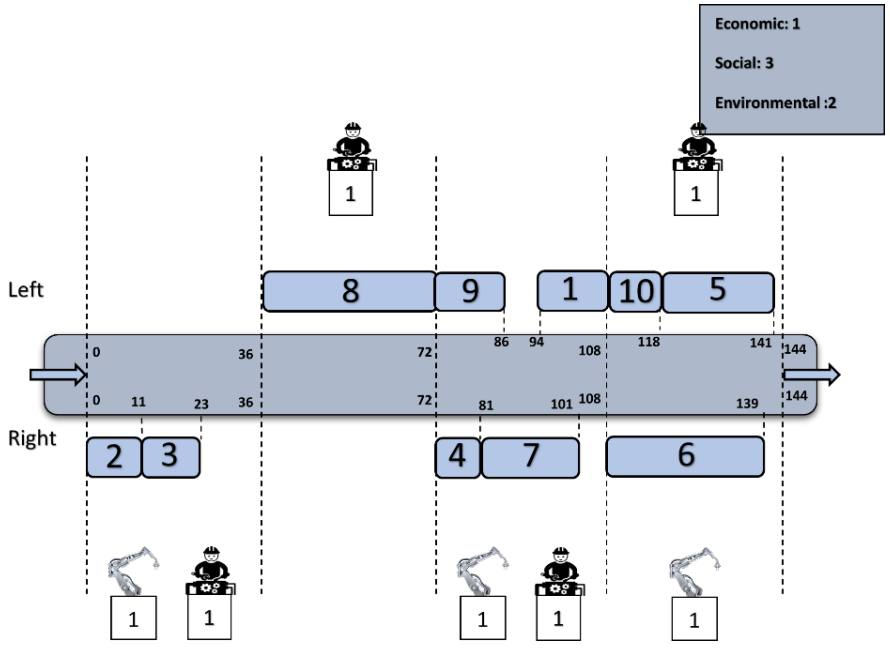


**Figure 4.7** Task and operator assignments of scenario B on a two-sided line

Figure 4.7 shows the assignment results for Scenario B. Similar to Scenario A, four mated stations are opened; however, unlike Scenario A, two of these mated stations have both sides opened, while the other two are single-sided. In total, of the six opened stations, three are on the right side and three are on the left side. A total of three robots and four human operators have been assigned to these stations. Observing the product flow, in the right sides of the first and third mated stations, robots and human operators share the same station. All tasks have been completed in 141 time units.

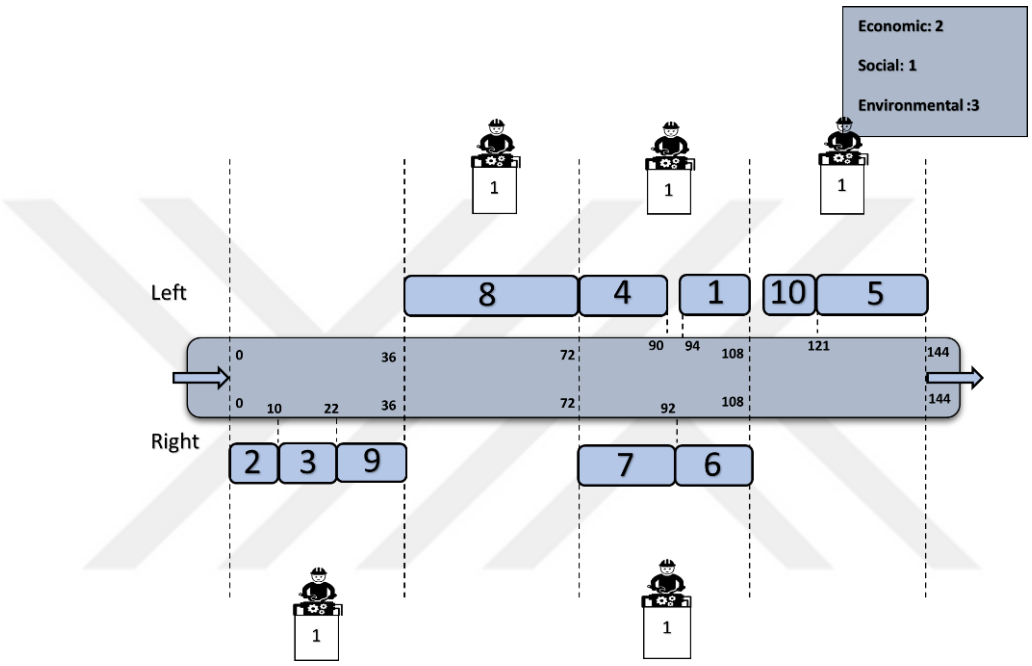


**Figure 4.8** Task and operator assignments of scenario C on a two-sided line

Figure 4.8 shows the assignment results for Scenario C, where, similar to Scenarios A and B, four mated stations are opened. Like in Scenario A, only one of the mated stations is two-sided, while the other three are single-sided. Of the opened stations, two are on the right side and three are on the left side. Similar to Scenario A, each of the five stations has been assigned one human operator, totaling five human operators. All tasks have been completed in 144 time units.

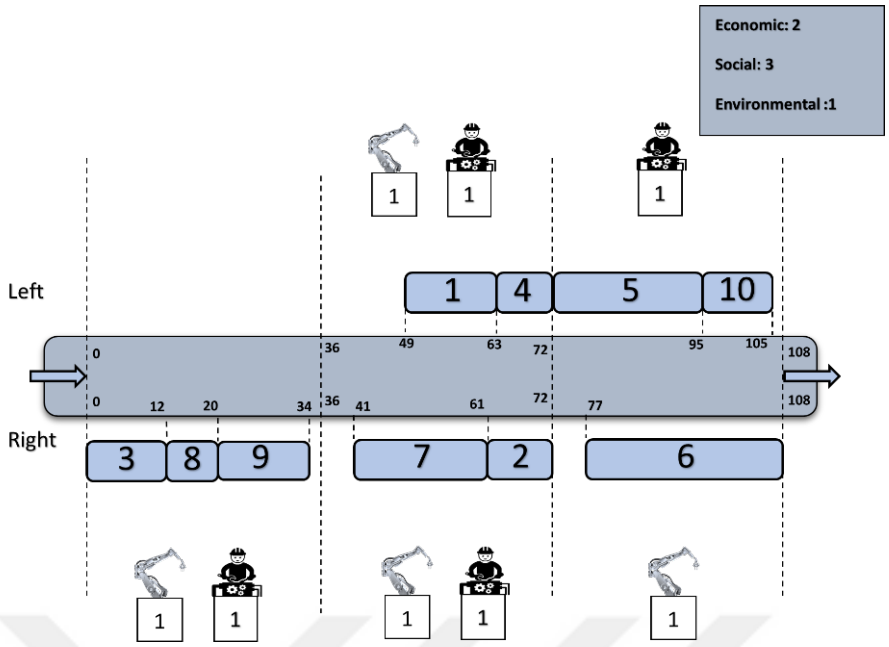


**Figure 4.9** Task and operator assignments of scenario D on a two-sided line

As shown in Figure 4.9, Scenario D stands out as the only scenario among the six where three mated stations are opened. This can largely be attributed to the economic objective being considered of secondary importance in the solution. Examining the priority rankings in Scenario C, where the economic objective is also ranked second, reveals that four stations were opened instead of three. This difference can be explained by the environmental objective being prioritized as the most important objective in Scenario C. In Scenario D, out of the three mated stations opened, two are two-sided while one is single-sided. Among the five opened stations, three are on the right side and two are on the left side. Each of these stations has been assigned four human and robot operators. Observing the task flow, in the right side of the first mated station and both sides of the second mated station, human and robot operators share the same space. All tasks have been completed in a total of 108 time units.

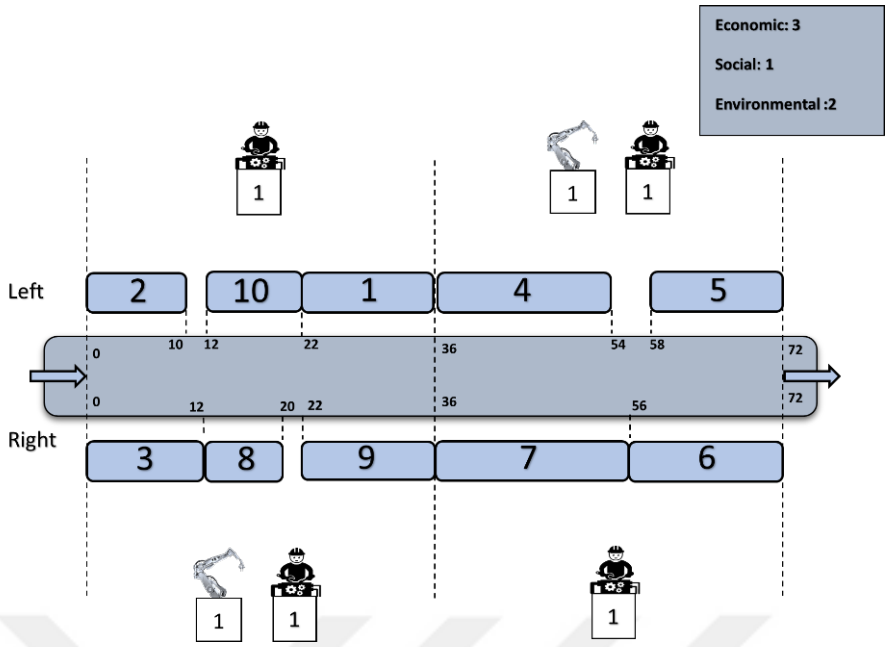


**Figure 4.10** Task and operator assignments of scenario E on a two-sided line

In Scenario E, where the economic objective is prioritized as the primary objective, two mated stations have been opened as shown in Figure 4.10. Both of these mated stations are two-sided, resulting in a total of four stations. Two robots and four human operators have been assigned to these stations. Observing the task flow, human and robot operators share the same space on the right side of the first mated station and the left side of the second mated station. All tasks have been completed in 72 time units.

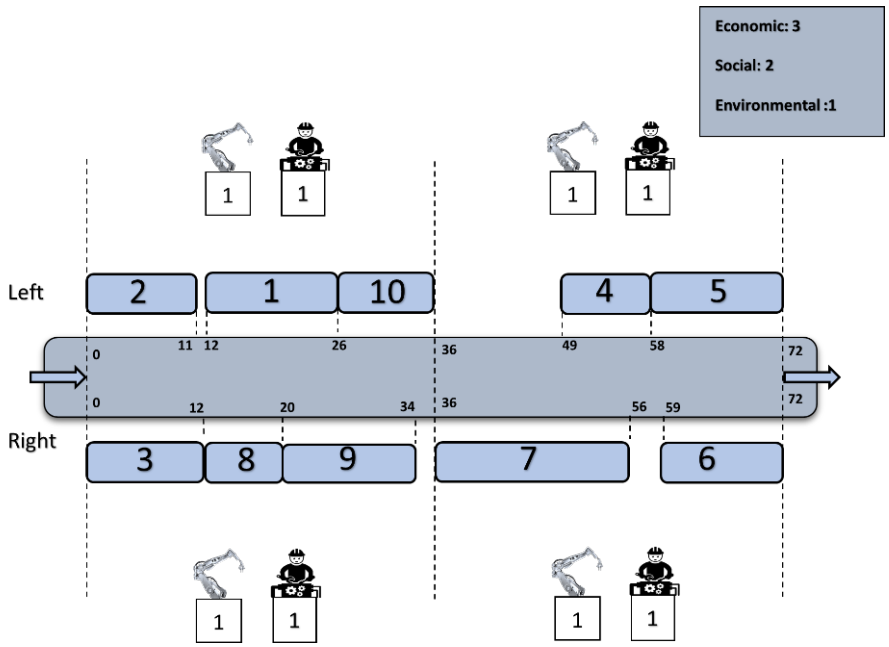


**Figure 4.11** Task and operator assignments of scenario F on a two-sided line

Scenario F, depicted in Figure 4.11, is one of the two scenarios among the six where two mated stations are opened. The primary reason for opening two stations can be attributed to the economic objective being prioritized as the main objective, which aims to shorten the line length. Both of the opened mated stations are two-sided, resulting in a total of four stations. Each station has been assigned one robot and one human operator, totaling four human operators and four robot operators. All tasks have been completed in 72 time units.

**Table 4.5** Assignment of tasks to process alternatives in different scenarios

| TASK | Scenario A | | | Scenario B | | | Scenario C | | | Scenario D | | | Scenario E | | | Scenario F | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| 1 | ✓ | | | ✓ | | | ✓ | | | ✓ | | | ✓ | | | ✓ | | |
| 2 | ✓ | | | | | ✓ | ✓ | | | | | ✓ | ✓ | | | | | ✓ |
| 3 | ✓ | | | ✓ | | | ✓ | | | ✓ | | | ✓ | | | ✓ | | |
| 4 | ✓ | | | | ✓ | | ✓ | | | | ✓ | | ✓ | | | | ✓ | |
| 5 | ✓ | | | ✓ | | | ✓ | | | ✓ | | | | | ✓ | | | ✓ |
| 6 | ✓ | | | | ✓ | | ✓ | | | | ✓ | | ✓ | | | | | ✓ |
| 7 | ✓ | | | ✓ | | | ✓ | | | ✓ | | | ✓ | | | ✓ | | |
| 8 | ✓ | | | ✓ | | | ✓ | | | | | ✓ | | | ✓ | | | ✓ |
| 9 | ✓ | | | ✓ | | | ✓ | | | ✓ | | | ✓ | | | ✓ | | |
| 10 | ✓ | | | ✓ | | | ✓ | | | ✓ | | | ✓ | | | ✓ | | |

Table 4.5 shows the process alternatives assigned to tasks for different scenarios. Process alternative 1 represents human, process alternative 2 represents robot, and process alternative 3 represents human-robot collaboration. When examining the assignments, the effects of the priority conditions of the objectives in the different scenarios given in Table 4.4 on the assignment of operators can be observed. In scenarios A and C, where the environmental objective is the most prioritized, all tasks are assigned to humans. In Scenarios B and D, where the social objective is prioritized, the risks of tasks are more prominent in the assignments. In scenarios E and F, where the economic objective is prioritized, the completion times of the tasks are emphasized.

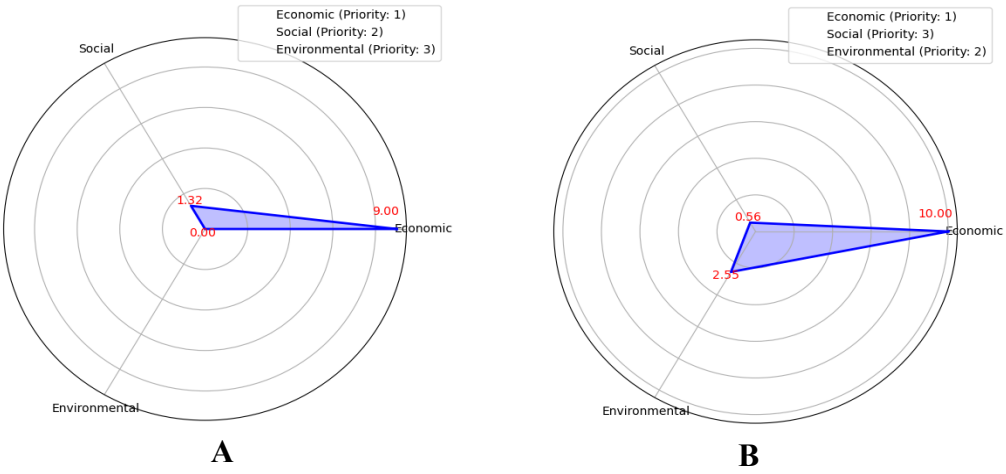


**Figure 4.12** The radar charts displaying scenarios where the economic objective is of least importance

Figure 4.12 displays the radar charts for Scenarios A and B, where the economic objective is of least priority. Due to the low prioritization of the economic index, the radar charts show high values for the economic objective. Additionally, it is observed that the environmental objective in Scenario A has a value of zero. This is because the environmental objective is the highest priority, leading to all tasks being assigned to human operators to minimize energy consumption from robot operation. Similarly, in Scenario B, it is observed that the social objective is nearly zero. This can be attributed to the social objective being the highest priority, leading to tasks being assigned to alternatives with the lowest risk coefficients to minimize the social objective.

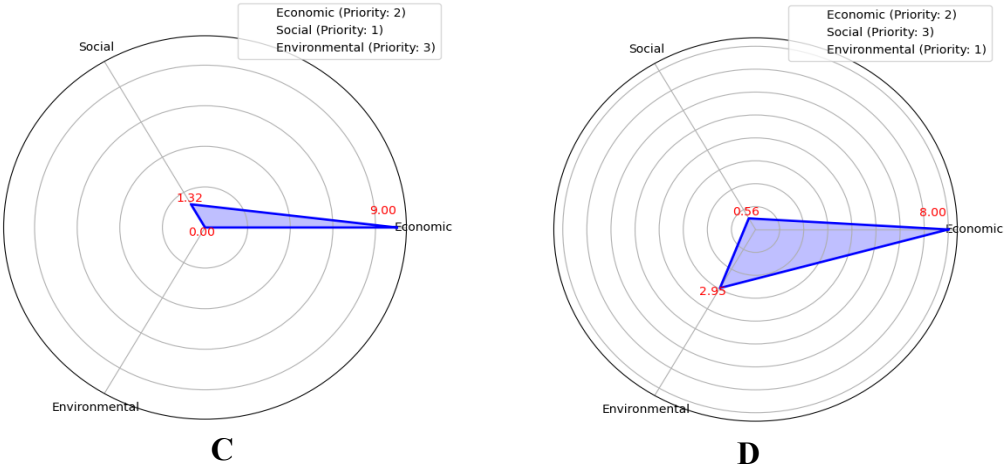


**Figure 4.13** The radar charts displaying scenarios where the economic objective is of secondary importance

The radar charts for Scenarios C and D, where the economic objective is of secondary priority, are shown in Figure 4.13. This prioritization does not result in a decrease in the economic objective value for Scenario C, whereas a decrease in the economic objective value is observed for Scenario D. Additionally, similar to Scenario A, the prioritization of the environmental objective as the highest priority in Scenario C results in an environmental objective value of zero. Similarly, the prioritization of the social objective as the highest priority in Scenario D, similar to Scenario B, results in a social objective value that is nearly zero.

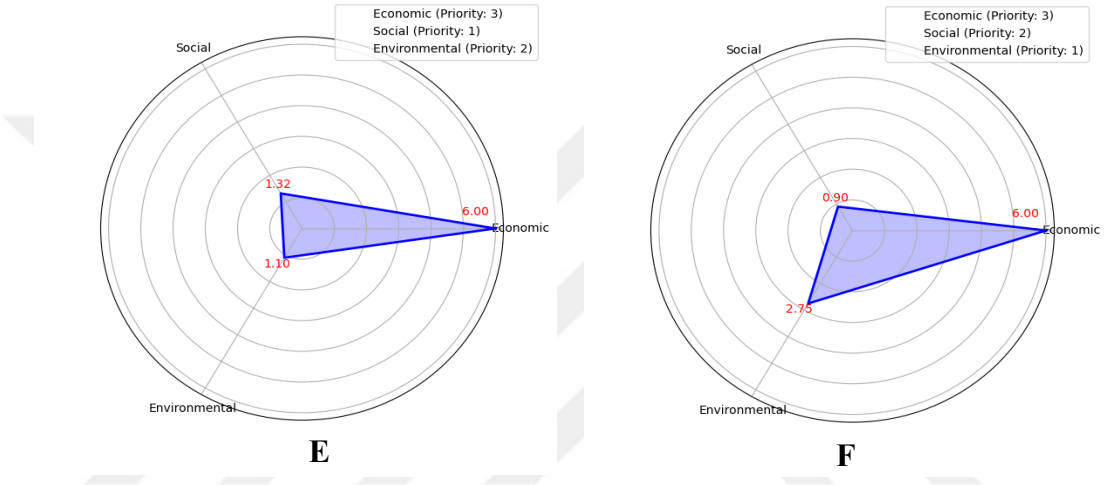


**Figure 4.14** The radar charts displaying scenarios where the economic objective is of primary importance

Figure 4.14 presents the radar charts for Scenarios E and F, where the economic objective is the highest priority. Due to the prioritization of the economic objective, a significant reduction in the economic objective values is observed in these scenarios. In Scenario E, the second priority is the environmental objective, which results in a lower environmental objective value compared to Scenario F. Conversely, in Scenario F, the second priority is the social objective, leading to a lower social objective value compared to Scenario E.

# CHAPTER 5
# CONCLUSIONS AND RECOMMENDATION

The recycling of end-of-life (EOL) products is undoubtedly crucial for creating a more sustainable environment. One of the most important aspects of this process is making it sustainable. As it is well-known, the quality and efficiency of an operation or service are directly proportional to its sustainability. This thesis focus on the disassembly line balancing, which are critical in the recycling processes of EOL products, and establish this process on sustainable foundations. In this context, two different studies have been conducted.

In both studies, Human-Robot Collaboration (HRC), a hot topic in the production world, has been addressed. As Liu et al. (2019) have found, HRC contributes significantly to sustainable production. Consequently, the first study of this thesis involves the development of a new model for the U-Shaped Disassembly Line Balancing Problem with Human-Robot Collaboration (UDLBP-HRC). The model was tested on a well-known scenario from the literature involving 25 tasks, yielding successful results. The proposed model and results for UDLBP-HRC reaffirmed the contributions of HRC to sustainability.

The second study in this thesis focuses on the two-sided disassembly line balancing problem with human-robot collaboration (TDLBP-HRC). The HRC was integrated into the TDLBP model. Additionally, what makes this study unique is the design of the model according to the Triple Bottom Line (TBL) approach. By integrating HRC, the study enhances sustainability and grounds it on a more robust foundation by incorporating the TBL approach, which focuses on the three main dimensions of sustainability: economic, social, and environmental aspects.

The proposed model was tested on a scenario involving 22 tasks, revealing that solving this NP-hard model requires heuristic methods for large-scale cases. Subsequently, a well-known scenario with 10 tasks was solved using the TBL approach, resulting in six different situations due to the varying priorities of economic, social, and

environmental objectives. This method allows flexibility in the solution by enabling different priorities to be utilized according to need.

The results from these two studies demonstrate that the use of HRC and TBL approaches in balancing production lines greatly contributes to making processes more sustainable. The proposition of two new models, the inclusion of HRC one of the hot topics of today into the models, and the application of the TBL approach, which is rarely used in production line studies, are the strengths of this thesis.

Conversely, testing the developed models on a single scenario and the inability to achieve optimal results for large-scale examples due to the need for heuristic methods are considered the limitation of this study.

The findings obtained from this research also guide potential future studies. Developing heuristic methods for both models, diversifying the content of the social, economic, and environmental goals that constitute the TBL, and using different combinations of objective functions are just a few of the future research directions. Additionally, working on stochastic and dynamic models to make disassembly line balancing more consistent with real-world applications is another potential area for future research.

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## CURRICULUM VITAE

### Dursun Emre Epcim

### Professional Summary

I am an Industrial Engineer and Project Consultant. I graduated from Gaziantep University, Department of Industrial Engineering. During my undergraduate studies, I completed an Erasmus period at Mondragon University in Spain. I have intermediate and basic competencies in Python, SQL, GAMS, MATLAB, Adobe Premiere Pro and Adobe Acrobat. I had the opportunity to work as a scholarship holder in two separate TUBITAK projects. I am passionate about projects as much as I am in the academic field. I have been in the process of writing 7 projects so far. I have succeeded in getting a project accepted with my team from the KA220 code. While I am currently working on finishing my master's degree, I am also working as a project consultant in my accepted project and at the Gaziantep University Social Awareness Projects (TDP) Center.

### Education

- Master Degree
  - Gaziantep University / Industrial Engineering (2022- )
- Bachelor's Degree
  - Gaziantep University / Industrial Engineering (2017-2022)
  - Mondragon University / Spain (2022 - 2022 Spring Semester Erasmus Program)

### Experience

- Project Consultant

February 2024 –

I am working as a project consultant for "Scholarship Program for Syrian Students" supported by the Kingdom of the Netherlands at Gaziantep University Social Sensitivity Projects (TDP) Center.

- Scholar

June 2023 - January 2024

I worked as a scholarship holder in the project titled "Optimization and Improvement of the Design of a Robot-Based Compact Storage and Unloading System" carried out within the scope of the TÜBİTAK ARDEB 3501 - Career Development Program under the TÜBİTAK Together We Work, Together We Achieve Grant (BİÇABA) program.

- Scholar

October 2022 - February 2024

I worked as a scholarship holder in the project titled "Development of a Data-Driven and Web-Based Decision Support System for the Integrated Optimization of Vector Combat Process" accepted under the University-Industry Collaboration Support Program with the code 1505. Within the project, I am actively involved in completing tasks assigned to the industrial engineering team. These tasks encompass the following areas:

  - Vehicle Routing
  - Scheduling
  - Stock Management

**Volunteer Work**

October 2018 - May 2019

For 2 semesters, I taught the Algo Digital course, which covers algorithm logic and basic coding training for 4th grade students.

**Academic Studies**

- International Congress
  - **Epcim, D. E.,** Bulut, U., Yüksel, Z., Mete, S., Özceylan, E., Serin, F., & Açıkgöz, M. Y. (2023). Analysis of the pest control processes of municipalities and potential improvement issues: The case of Gaziantep Municipality. *In 6th International Conferences on Engineering Sciences*
  - **Epcim, D. E.,** Yüksel, Z., & Mete, S. (2023, July 14). A mathematical model for human–robot collaborative U-shape disassembly line balancing problem. *In 6th International Conference on Sustainable Science and Technology (ICSuSaT 2023).*
  - Yüksel, Z., **Epcim, D. E.,** & Mete, S. (2023, September 14). Multi-depot vehicle routing problem with drone collaboration in humanitarian logistics. *In International Conference on Science, Engineering Management and Information Technology*
  - Yüksel, Z., **Epcim, D. E.,** & Mete, S. (2023, October 19). Optimizing post-disaster relief operations: Integrating unmanned aerial vehicles in vehicle routing problem*. In The 21st International Logistics and Supply Chain Congress.*
  - Yüksel, Z., Bulut, U., **Epcim, D. E.,** Mete, S., Özceylan, E., & Serin, F. (2024, February 9–10). Optimal and fair personnel scheduling with a 0-1 integer programming: The case of Gaziantep Municipality. *In 7th International Conference on Engineering Sciences (ICES 2024).*
- Papers
  - Yüksel, Z., **Epcim, D.E.,** & Mete, S. (2023). First Cluster Second Route Approach with Collaboration Unmanned Aerial Vehicle in Post-Disaster Humanitarian Logistic. Journal of Transportation and Logistics, 8(2), 97-111. https://doi.org/10.26650/JTL.2023.1372701
  - Yüksel, Z., **Epcim, D. E.,** & Mete, S. (2024). Multi-Depot Vehicle Routing Problem with Drone Collaboration in Humanitarian Logistic. Journal of Optimization and Decision Making, 3(1), 438-448.

**Projects**

01 June 2023 – 30 November 2026

Erasmus+ KA220 / E-4Prosperity / Researcher – Expert

- The project aims to provide employment opportunities for young people with socio-economic differences through e-sports and offer a sustainable professional roadmap in the field of e-sports. Secondary objectives include enhancing partners' capacity for international cooperation, developing an e-sports curriculum and screening test, and fostering healthy youth development in e-sports. Activities encompass needs analysis, curriculum development, digital platform creation, and youth training. Expected outcomes include an online e-sports training curriculum and screening test, a professional roadmap for youths, and increased international networking capacity for project partners.