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A two-objective setting for reducing costs and ergonomic risks of U-shaped assembly line balancing collaborated by robots and human workers

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Abstract

Balancing the production system's resources like budget, equipment, and workers is one of the most important concerns of production managers. Managers seek to find an optimal way to balance their resources in production systems. By evaluating U-shaped assembly line papers, this investigation adds the literature on U-shaped assembly lines to the simultaneous examination of the balance ergonomic risks of human workers and current costs in the system when government offers tax benefits for using disabled workers. The mentioned outlook was not considered in previous papers. This study proposes a two-objective model to evaluate the effects of considering both robots and human workers in a U-shaped assembly line. The first objective is to minimize the system costs, and the second is to minimize the ergonomic risks. Human workers are divided into normal and disabled. The disabled workers are hired to enable tax benefits from the government. The constraint programming model for small and medium-sized problems and the grasshopper optimization algorithm (GOA) for big problems are developed to dissolve the problem. Numerical results show that two objective functions can also level system costs and ergonomic risks. The sensitivity analysis section analyzes three effective parameters (Production cycle time, Fatigue rate of human workers, and government tax benefit). It is shown that production cycle time directly affects using a robot or human workers (due to their mean time of speed), fatigue rate determines the allocation of tasks, and tax benefit helps to determine whether using disabled workers or not according objective functions. Also, it should be noticed the efficiency of GOA is shown by a comparison of several examples. Therefore, it is used for big-scale test problems.

Keywords: U-shaped assembly line; ergonomic risks; human and robot workers; constraint programming; grasshopper optimization algorithm.

Paper Type: Original Research

1. Introduction

Manufacturers face different challenges, which have played an important role in their efficiency. Allocating resources (i.e., equipment, workers, budget, etc.), production planning, and Ergonomic issues are three basic challenges that management of manufacturing industries should find some strategies to cope with (Samuels Group, 2021). These days manufacturing industries have been remodeled due to increasing power competition. They want to increase their market share while their workers have a high level of satisfaction and use all system capacity (Samuels Group, 2021). Each task in the assembly line could be considered hard, normal, or easy (Mokhtarzadeh et al., 2021). If the management of manufacturing industries does not consider this fact when s/he assigns tasks to human workers, the workers may be damaged physically and mentally (Chutima and Khotsaenlee 2022). Manufacturers can decrease their costs by adopting appropriate strategies. Government considers tax benefits for manufacturers that use disabled workers and assign tasks to them (Chutima and Khotsaenlee 2022; Abolfazli et al., 2022). This condition could prepare a situation where normal and disabled workers collaborate simultaneously. Moreover, Manufacturers offer tax benefits by using disabled workers and decreasing the system costs. Also, sometimes, manufacturers should use robot workers to enhance work speed and fulfill all tasks in a cycle time. The collaboration of robots and human workers makes some challenges emerge that this study aims to solve.

In this study, like (Urban and Chiang 2006), one U-shaped assembly line is assumed with several stations so that some tasks are available and have to be done on assembly lines 'stations. It should be noticed that the operation time of each task is uncertain. Workers consist of humans and robots, and as mentioned using disabled workers

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could enable government tax benefits. The chief focus of this investigation is adding consideration of system costs and ergonomic issues while workers are divided into humans (normal and disabled workers) and robots to the U-shaped assembly line's literature. Moreover, the GOA is developed to solve U-shaped assembly line problems in big-sized problems.

Therefore, this study contributes to the literature in several ways. First, evaluation of economic and ergonomic objectives in one U-shaped assembly line is considered, which has not been studied in the previous studies. Second, the consideration of robots and human workers in a U-shaped assembly line in this area with the considered aspects is for the first time. Third, the government offers a tax benefit for using disabled human workers. Finally, the GOA is deployed to solve big-sized test problems. The mentioned contributions were not considered simultaneously in U-shaped assembly line literature.

The main questions of this investigation are written below:

- How does the management of a U-shaped assembly line allocate tasks between robot and human (Normal and Disabled) workers by consideration of ergonomic and economic issues?

- How could government tax benefits for disabled workers affect the U-shaped assembly line's strategy?

- Which approach is adopted in the U-shaped assembly line to determine whether one task is considered hard for one human worker or not?

To answer the above research questions, this paper studies one U-shaped assembly line in which workers are divided into human and robot workers. The government offers tax benefits to encourage management to use disabled workers. In our study, we focus on allocating different tasks to human (normal and disabled) and robot workers to minimize the ergonomic risks and cost of the assembly line system. Therefore, our paper studies a multi-objective problem (Ergonomic risks and Cost of the system), and the LP-metric method is used as a solution method.

In the rest of the paper, the previous papers about U-shaped assembly lines and ergonomic risks literature in production systems are reviewed in section 2. The problem description and mathematic model are developed in section 3, and section 4 determines the solution method. Sections 5 and 6 show the numerical examples and sensitivity analysis in order. The paper's managerial insights and conclusion are written in sections 7 and 8 in order.

2. Literature review

In this section, we review papers about ergonomic issues in the manufacturing line and assembly lines. By evaluating the mentioned papers, we will show the research gap area.

2.1. Ergonomic issues in the manufacturing line

Firstly, ergonomic issues in the manufacturing line will be reviewed. Carnahan et al. (2001) offered some heuristic algorithms to prevent the upsetting balance of the assembly lines by considering of time of each task and physical demand criteria. Task-worker incompatibilities and assignment of workers were addressed by (Mirallas et al. 2008). Bautista et al. (2016) presented two models to increase operators' comfort. The first one focused on minimizing the maximum ergonomic risks on the whole system, and the second one minimized the total average ergonomic risk deviations in each station (Average absolute deviation). Job rotation offering to mitigate the ergonomic risks was offered by (Moussavi et al. 2018) and (Hochdörffer et al. 2018). Deigo-Mas (2020) investigated the assignment of a group of workers to different tasks with job rotation scheduling of workers. Three objective problems were designed by (Sana et al. 2019). In this paper, the author minimized the ergonomic risks of NOISH method. Asensio-Cuesta et al. (2012) presented a genetic algorithm (GA) to help schedule job rotations. Finco et al. (2018) considered the cost of human energy and rest allowance to propose three heuristic approaches for assembly line balance. Nazri et al. (2021) focused on improving the workstation of manual assembly in the production system. It aimed to improve the ergonomic issues and line balancing and finally improve the productivity of the production system. Productivity and ergonomic issues play a critical role in manufacturing systems (Zhang et al., 2021). The mentioned investigation evaluated ergonomic issues and productivity performance with the collaboration of robot workers. Caterino et al. (2022) analyzed key features that have effects on ergonomic risks in the car assembly line. It considered heterogeneous workers in a real case study and showed the key features of ergonomic risks in a production system. Rathore et al. (2022) focused on workers 'health and safety. This study believed that the mentioned concepts were ignored in previous studies. It developed a tool that integrated ergonomic and lean to enhance the health and safety of workers, along with productivity rate. To read more about ergonomic issues in the manufacturing line literature, you could read Brito et al. (2019); Neag et al. (2020); Mgbemena et al. (2020).

2.2. Assembly line

Now, assembly line literature will be reviewed. (Özcan et al. 2010) focused on designing a parallel two-sided assembly line balance, and (Kucukkoc and Zhang 2014) added stochastic process times to a parallel two-sided assembly line. Then, the parallel U-shaped assembly line was introduced by (Kucukkoc and Zhang 2015), and it showed parallel U-shaped assembly lines could decrease the number of workers. Kucukkoc et al. (2018) offered an underground station in the MIP model, and Rabbani et al. (2016) developed a metaheuristic algorithm to solve the assembly line balance problem. (Periera et al. 2018), (Dong et al. 2018), and (Foroughi et al. 2018) presented the different metaheuristic algorithms like G.A., PSO, and S.A. to solve assembly line balance problems. Cantos Lopes et al. (2019) focused on a mixed-integer linear model to introduce one balancing task station in which sequencing or scheduling of heterogeneous products in different cycle times was analyzed. Özcan (2019) focused on the optimization and balancing in parallel assembly lines with sequence-dependent setup times. A simulated annealing algorithm was introduced as the solution method in the investigation. One binary linear mathematical programming model was presented to solve different test problems. In another investigation, the multi-objective schedule problem was presented in that way to balance the assembly line by considering uncertainty in the cost and limited resources (Behnamian and Rahimi 2020). In the mentioned investigation, a robust optimization approach was applied as a solution method to solve the different test problems. Hematian et al. (2020) is one of the papers that focus on allocating the human workforce in one system to project activities simultaneously. The human workforce was considered heterogeneous based on their skill level. One multi-objective optimization model was designed to answer multi-project scheduling and multi-skilled human resource assignment problems. Zhang et al. (2021) considered preventing maintenance (PM) for the U-shaped assembly line. The offered algorithm in that study presented JAYA algorithm to deploy PM in the U-shaped assembly line. Also, the mentioned algorithm was deployed in a real case study. Li et al. (2021) used an enhanced beam search heuristic to solve two types of U-shaped assembly line problems (UALBP-1 and UALBP-2). Extensive numerical test problems were evaluated to show the mentioned solution method's efficiency. Simonetto and Sgarbossa (2021) evaluated the concept of industry 4.0 in one straight line and one U-shaped assembly line balance. Khorram et al. (2022) used a meta-heuristic algorithm in a U-shaped assembly line balancing problem to allocate equipment and workers optimally. One multi-objective model was presented to solve the problem, and the classical algorithms like variable neighborhood search, simulated annealing, and classical genetic algorithm with a novel encoding/decoding scheme were used. To read more about U-shaped assembly line literature, you can read Chutima and Suchanun, 2019 ; Zhang and Xu, 2020; Yılmaz,2020.

2.3. Research gaps and contributions

Based on the investigation papers, it can be concluded that considering ergonomic risks and system's costs when two different types of workers (humans and robots) are assumed is added to the U-shaped assembly line's literature. Moreover, it should be noted human workers are divided into normal and disabled workers, and the GOA was developed to solve U-shaped assembly line big-sized problems as the solution method. According to mentioned research gaps, we consider a U-shaped assembly line with different stations and tasks. Management has two options to allocate different tasks to workers: Human workers and Robot workers. By consideration of ergonomic risks and the system's cost. The innovation of our study could be listed as: 1) consideration of ergonomic risks and system's cost. 2) Usage of robots and human workers simultaneously. 3) Government tax benefits are offered to use disabled workers. 4) Presenting one metaheuristic algorithm (GOA) efficiency in U-shaped assembly line problems.

3. Problem description

The problem study of this paper is considering a U-shaped assembly line in which all tasks have to be assigned to the assembly line's stations and workers. Each task's operation time is uncertain and different for each worker based on their skills. Two types of workers are available in the U-shaped assembly line (humans and robot workers), and human workers are divided into normal and disabled workers. Disabled workers are hired to enable tax benefits from the government. The mentioned motivation encourages the U-shaped assembly line management to collaborate simultaneously with normal and disabled workers. This study focuses on two main objectives (Costs and Ergonomic Risks). The following assumptions for constraint modeling are considered:

- More than one task could be assigned to each station in a cycle time.
- All tasks assigned to each station must be completed in a cycle time.
- Several tasks (more than one) may be assigned to workers (humans or robots) in a cycle time.
- All workers are not allowed to work more than the maximum workers 'time in a cycle time.

- Each task has to be done by one specific worker at one specific station.
- The cost of opening and operating each station is different from the other.
- The types of equipment and their features are already known.
- Prerequisite relationships between assembly tasks are determined.
- Tasks cannot be broken down into smaller elements.
- Each task can be performed at an assembly line station, provided that the type of equipment assigned to the station can perform this task and follow the prerequisite relationships.

The developed model presents how to allocate workers to each station to do a specific task, determine normal and hard duties, and minimize ergonomic risks and system costs while the system has limited stations, tasks, and workers with a specific cycle time.

3. 1. Mathematical Modelling

In this section, firstly, the sets, parameters, and decision variables are introduced, then the constraint programming model is developed:

Sets	
I	Set of tasks ($i, p, q \in I$)
J	Set of stations ($j \in J$)
H	Set of human workers ($Hn \cup Hd = H$)($h \in H$)
R	Set of robot workers ($r \in R$)
W	Set of all workers ($H \cup R = W$)
Hn	Set of normal human workers ($hn \in Hn$)
Hd	Set of all disabled human workers ($hd \in Hd$)

Parameters	
n	Total number of tasks
m	The upper limit of the number of stations
W	Total number of workers
CT	Cycle Time
WCT	Maximum allowed worker cycle time
ψ	A big number
μt_i^w	Mean of time that worker $w \in W$ will be done task $i \in I$
j	Indicator for stations
C_j	Cost of preparing and using of station $j \in J$
C_i^w	Cost of doing task $i \in I$ by worker $w \in W$
α	Fatigue rate of human worker for normal duty
β	Fatigue rate of human worker for hard duty
p_i	Task $i \in I$'s pressure

T	Criteria for distinguishing hard duty from normal duty
TB	Tax benefit

Decision variables	
Z_j	If station $j \in J$ is used 1, and 0 otherwise
a_{ij}^{w}	If task $i \in I$ is assigned to station $j \in J$ and worker $w \in W$ 1, and 0 otherwise
u_i^{w}	If task $i \in I$ is assigned to output side of assembly line and worker $w \in W$ 1, and 0 otherwise
x_{ij}^{w}	If task $i \in I$ is assigned to input side of station j and worker $w \in W$ 1, and 0 otherwise
y_{ij}^{w}	If task $i \in I$ is assigned to output side of station $j \in J$ and worker $w \in W$ 1, and 0 otherwise
ht_i^{h}	If task $i \in I$ that is assigned to worker $h \in H$ is hard

Now all sets, variables, and parameters are presented, the following part develops the constraint programming model:

$$Min\ Z_1 = \sum_{j=1}^{m} z_j \,.\, C_j + \sum_{j=1}^{m}\sum_{i=1}^{n}\sum_{w=1}^{W} a_{ij}^{w}.\, C_i^{w} - TB.\sum_{hd=1}^{Hd} a_{ij}^{hd} \quad (1)$$

$$Min\ Z_2 = \beta.\sum_{i=1}^{n}\sum_{h=1}^{H} ht_i^{h} + \alpha \sum_{i=1}^{n}\sum_{h=1}^{H}(1 - ht_i^{h}) \quad (2)$$

$$\sum_{j=1}^{m}\sum_{w=1}^{W} a_{ij}^{w} = 1 \qquad \forall\, i = 1, \dots, n \quad (3)$$

$$\sum_{i=1}^{n}\sum_{w=1}^{W} \mu t_i^{w}.\, a_{ij}^{w} \le CT \qquad \forall\, j = 1, \dots, m \quad (4)$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} \mu t_i^{w}.\, a_{ij}^{w} \le WCT \qquad \forall\, w = 1, \dots, W \quad (5)$$

$$\sum_{j=1}^{m}\sum_{w=1}^{W} \mathrm{j}.\,(a_{pj}^{w} - a_{qj}^{w}) \le \psi\,.\sum_{w=1}^{W} u_q^{w} \qquad \forall (p, q) \in I \quad (6)$$

$$\sum_{j=1}^{m}\sum_{w=1}^{W} \mathrm{j}.\,(a_{qj}^{w} - a_{pj}^{w}) \le \psi.\ (1 - \sum_{w=1}^{W} u_p^{w}) \quad \forall (p, q) \in I \quad (7)$$

$$\sum_{i=1}^{n}\sum_{w=1}^{W} \mathrm{j}.\, a_{ij}^{w} \le \psi\,.\, z_j \qquad \forall\, j = 1, \dots, m \quad (8)$$

$$\sum_{j=1}^{m}\sum_{w=1}^{W} \mathrm{j}.\, a_{pj}^{w} - \sum_{j=1}^{m}\sum_{w=1}^{W} \mathrm{j}.\, a_{qj}^{w} \le m.\,(1 + \sum_{w=1}^{W} u_p^{w} - 2.\sum_{w=1}^{W} u_q^{w}) \ \ \forall (p, q) \in \mathrm{I} \quad (9)$$

$$\sum_{j=1}^{m}\sum_{w=1}^{W} \mathrm{j}.\, a_{qj}^{w} - \sum_{j=1}^{m}\sum_{w=1}^{W} \mathrm{j}.\, a_{pj}^{w} \le m.\sum_{w=1}^{W} u_p^{w} \quad \forall (p, q) \in \mathrm{I} \quad (10)$$

$$(\mu t_i^{h}.\, p_i) - T \le (1 - (\sum_{j=1}^{m} a_{ij}^{h}) + ht_i^{h}).\psi \qquad \forall h \in H, i \in I \quad (11)$$

$$Z_j, a_{ij}^w, u_i^w, ht_i^h \in \{0,1\} \tag{12}$$

The first objective (1) is to minimize the total cost of a U-shaped assembly line. The objective function (2) minimizes the human workers' fatigue and ergonomic risks. Equation (3) ensures that all tasks are assigned to one worker and station. Constraint (4) indicates that all tasks' time that is assigned to one station does not exceed the cycle time, and constraint (5) does not allow each worker's time to exceed the maximum allowed worker time. Constraint (6) indicates that task q can be assigned when all of its previous activities have been assigned, while constraint (7) ensures that task p can be assigned if all of its subsequent activities have been assigned. Equation (8) shows that the station will be used if one task is assigned to one station. Equations (9) and (10) ensure that each task should be assigned to the input side of the assembly line or output side. The constraint (11) shows whether each task belongs to hard or normal tasks, and (12) defines the binary variables.

Inspired by (Urban and Chiang 2006), a_{ij}^w could be replaced by $x_{ij}^w + y_{ij}^w$. As mentioned in decision variables, x_{ij}^w and y_{ij}^w are binary decision variables that determine which task should be assigned to input or output side of the allocated station. Therefore, the proposed model can also be modeled as follows:

$$Min\ Z_1 = \sum_{j=1}^{m} z_j . C_j + \sum_{j=1}^{m}\sum_{i=1}^{n}\sum_{w=1}^{W} (x_{ij}^w + y_{ij}^w). C_i^w - TB. \sum_{hd=1}^{Hd} (x_{ij}^{hd} + y_{ij}^{hd}) \tag{13}$$

$$Min\ Z_2 = \beta. \sum_{i=1}^{n}\sum_{h=1}^{H} ht_i^h + \alpha \sum_{i=1}^{n}\sum_{h=1}^{H} (1 - ht_i^h) \tag{14}$$

$$\sum_{j=1}^{m}\sum_{w=1}^{W} (x_{ij}^w + y_{ij}^w) = 1 \qquad \forall\, i = 1, \dots, n \tag{15}$$

$$\sum_{i=1}^{n}\sum_{w=1}^{W} \mu t_i^w. (x_{ij}^w + y_{ij}^w) \le CT \qquad \forall\, j = 1, \dots, m \tag{16}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} \mu t_i^w. (x_{ij}^w + y_{ij}^w) \le WCT \qquad \forall\, w = 1, \dots, W \tag{17}$$

$$\sum_{j=1}^{m}\sum_{w=1}^{W} \text{j}. ((x_{pj}^w + y_{pj}^w) - (x_{qj}^w + y_{qj}^w)) \le \psi . \sum_{w=1}^{W} u_q^w \qquad \forall (p,q) \in \tag{18}$$

$$\sum_{j=1}^{m}\sum_{w=1}^{W} \text{j}. (x_{qj}^w + y_{qj}^w) - (x_{pj}^w + y_{pj}^w)) \le \psi.\ (1 - \sum_{w=1}^{W} u_p^w) \quad \forall (p,q) \in \tag{19}$$

$$\sum_{i=1}^{n}\sum_{w=1}^{W} \text{j}. (x_{ij}^w + y_{ij}^w) \le \psi . z_j \qquad \forall\, j = 1, \dots, m \tag{20}$$

$$\sum_{j=1}^{m}\sum_{w=1}^{W} \text{j}. (x_{pj}^w + y_{pj}^w) - \sum_{j=1}^{m}\sum_{w=1}^{W} \text{j}. (x_{qj}^w + y_{qj}^w) \le m. (1 + \sum_{w=1}^{W} u_p^w - 2. \sum_{w=1}^{W} u_q^w)\ \forall (p,q) \in \text{I} \tag{21}$$

$$\sum_{j=1}^{m}\sum_{w=1}^{W} \text{j}. (x_{qj}^w + y_{qj}^w) - \sum_{j=1}^{m}\sum_{w=1}^{W} \text{j}. (x_{pj}^w + y_{pj}^w) \le m. \sum_{w=1}^{W} u_p^w \quad \forall (p,q) \in \text{I} \tag{22}$$

$$(\mu t_i^h . p_i) - T \le (1 - (\sum_{j=1}^{m} (x_{ij}^h + y_{ij}^h)) + ht_i^h). \psi \qquad \forall h \in H, i \in I \tag{23}$$

$$Z_j, x_{ij}^w, y_{ij}^w, u_i^w, ht_i^h \in \{0,1\} \tag{24}$$

Now the model is presented. The problem definition is about considering one U-shaped assembly line and the management of the assembly line's goal is to assign different tasks to different stations and workers by considering costs and ergonomic issues. Workers are divided into two groups (Human and Robot). Moreover, the government offers tax benefits to use disabled workers.

4. Solution methods

The LP-metric method is used in the GAMS software to solve the presented multi-objective model. It should be mentioned that the ANTIGONE solver is used to solve small and medium-size test problems in GAMS. The LP-metric method is one of the solutions in which the deviation of each objective function from its optimal points has been minimized (lasaloo and Paydar, 2019). The objective function of the LP-metric method is defined as follows:

$$\min z = \sum W_i \left(\frac{Z_i^* - Z_i}{Z_i^*}\right) \tag{25}$$

Because increasing the dimensions of the problem causes the time to solve the problem by the exact software of GAMS to increase exponentially, in this section, it is suggested to use the GOA to solve the problems at the appropriate time with a little solution gap. Therefore, to solve the big-sized problem, GOA is developed. It is a metaheuristic algorithm that helps us to find an appropriate solution. It could work better than other metaheuristic algorithms for solving the large-scale and real-world problems with uncertain search space and it has a higher ability to obtain optimal solutions (Mirjalili et al., 2018; Zeng et al., 2021; Malekkhouyan et al., 2021). GOA is inspired by the grasshopper swarms' behavior in nature and the repulsion among the grasshoppers is mimicked in this algorithm. Grasshoppers are considered a pest because they often hurt agricultural crops, and this fact has a deep impact on people's beliefs. Sometimes the grasshopper is seen individually but usually; grasshoppers become a member of vast swarms among all world animals. The main reason for gathering grasshoppers together is that they looking for finding a food source, this kind of search is unique. GOA uses the grasshoppers' swarms feature to find the optimal answer (Saremi et al., 2017). In addition to its simplicity, this algorithm could solve various optimization problems in complex situations and constructively find optimal solutions for complicated problems (Aljarah et al., 2018, 2020; Rezaei et al., 2021). Therefore, appropriate and acceptable answers can be obtained by using GOA as an advanced optimization algorithm (Abualigah, L. and Diabat). Examining the literature on the GOA, we can refer to (Abazari et al. 2021), and (Momeni et al. 2019), which have solved their large size problems with efficiency by using the mentioned algorithm. Both GAMS and GOA were run on an intel i7-4702 M.Q. laptop with 6 GB of Ram.

5. Numerical examples

5. 1. Deterministic Method

In this section, small and medium-sized problems are solved. Four test problems are presented in table 1. Table 1 has one column that is shown by $i \times j \times w \times h \times r$, that shows in order the number of tasks, number of stations, number of workers, and number of human and robot workers in each test problem. Then, two objective function's results are presented for each test problem. As it mentioned before, small and medium-sized problems are solved by GAMS software and the ANTIGONE algorithm. 30 test problems are solved by the GAMS software and the ANTIGONE solver. To find the test problems' results, please see Appendix A.

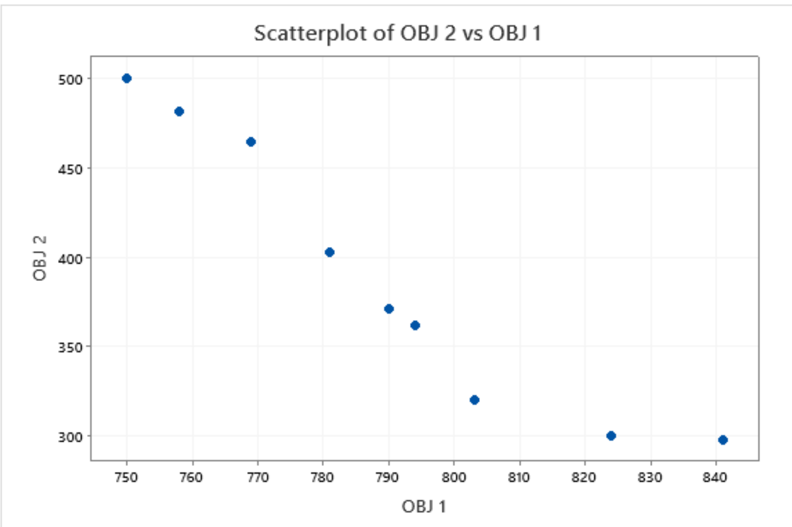

Figure 1. Pareto diagram of test problem 15

Figure 1 presents the Pareto results of test problem 15 for both objectives. The best result for the first objective is 750 (for this result, the second objective result becomes 500), and the best result for the second objective is 298 (for this result, the first objective result becomes 841).

5. 2. Meta-heuristic Method and Parameters Tuning

In this section, big-sized test problems are solved by GOA. But, the efficiency of GOA should be proved by comparing the results of GAMS and GOA in small and medium-sized problems. Table 2 shows the comparison of exact and GOA to prove the GOA efficiency. Before solving the test problems, the Taguchi method in MINITAB software is used to adjust the GOA parameters like the number of iterations (Iter) and the number of population (npop).

Table 1. The sets examined in the Taguchi test

Number of Iteration	Number of populations
220	90
175	80
190	100

As you see in figure 2, the best Iter is 190, and the best npop is 80.

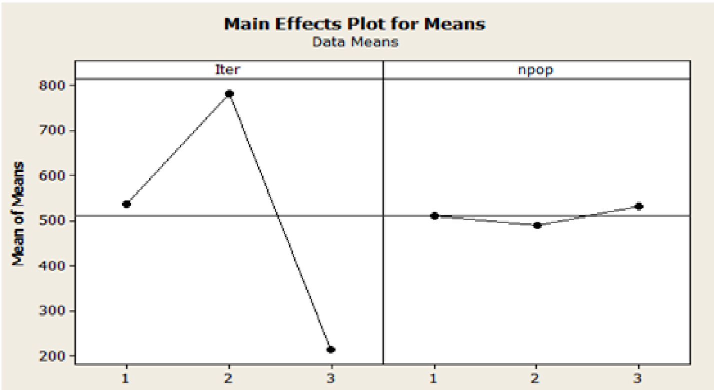

Figure 2. Taguchi method

Table 2 presented as follows:

Table 2. The Comparison of exact and GOA

Test problem	GOA		Gap%		Average gap
	Obj1	Obj2	Obj1	Obj2	
1	226	194	0	0	0
2	341	302	1.18	1.3	1.24
3	362	231	2.2	2.2	2.35
4	454	327	0.8	2.1	1.45
5	370	248	1.6	2.9	2.25
6	402	265	1.2	1.5	1.35
7	415	301	0.5	1.3	0.9
8	342	300	1.4	0.67	2.07
9	345	307	1.1	1.6	1.35
10	419	326	2.1	1.5	1.8
11	436	319	2.8	2.2	2.5
12	461	374	1.7	2.7	2.2
13	429	352	3.6	1.4	1.4
14	481	377	2.1	1.9	2

15	762	506	1.6	4	2.8
16	778	520	1.8	1.5	1.65
17	791	531	2.7	1.3	2
18	789	579	2.6	1.5	2.05
19	784	579	1.8	3.2	2.5
20	916	623	2.8	1.7	2.25
21	911	625	2.2	2.2	2.2
22	911	595	3	1.3	2.15
23	867	580	3.5	3.6	3.55
24	874	579	3	0.8	1.9
25	892	614	3	1.5	2.25
26	882	559	3.1	2.1	2.6
27	979	661	3.3	2.6	2.95
28	1003	680	3	1.3	2.15
29	1020	701	2.2	1.4	2
30	1015	704	3.1	1.8	2.45
	Average		2.16	1.845	2.0025

According to table 2, the average gap between obj1, obj2, and the total average in order are about 2.16, 1.845, and 2.0025. It should be noticed all results have not been illustrated. Thus, it could be concluded that GOA could be fit to solve big-sized problems. In the rest of section 5.2. Figures 3 and 4 show the GOA's result for the first and second objectives of test problem 15.

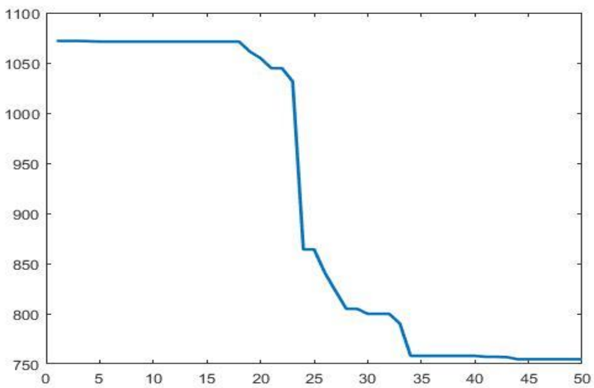

Figure 3. The GOA's result of the first objective of test problem 15

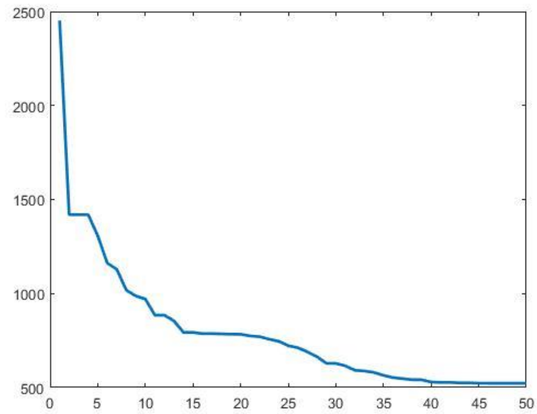

Figure 4. The GOA's result of the second objective of test problem 15

6. Sensitivity analysis

In this section, three parameters are analyzed to find their impact on the results' behavior (objective functions). Figure 5 represents the impact of cycle time changes on the two objective functions. As can be seen, by the increasing cycle time, the first objective (Costs) is plunged, and the second objective (Ergonomic risks) is enhanced. The reason for the mentioned pattern would be that increasing cycle time allows the model to assign robot worker tasks with the high cost and low mean time of doing tasks to human workers with low cost and high mean time of doing tasks. Also, figure 6 shows the impact of fatigue rate changes. As shown in figure 6, increasing the fatigue rates cause the first objective to boom due to using robot workers instead of human workers. Meanwhile, the ergonomic objective causes the using human workers to decrease by increasing the fatigue rates. The impact of Tax benefits is evaluated in Figure 7. It could be conducted that if the tax benefit is plunged, the usage of disabled human workers will be decreased. Therefore, the model chooses the normal human or robot workers to do tasks and causes the first objective to increase due to the high cost of robots and normal workers, and the second objective to reduce.

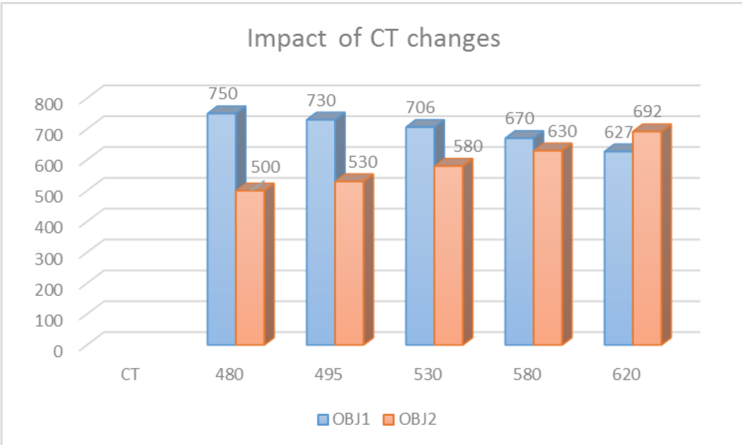

Figure 5. The impact of Cycle Time on Objective Functions

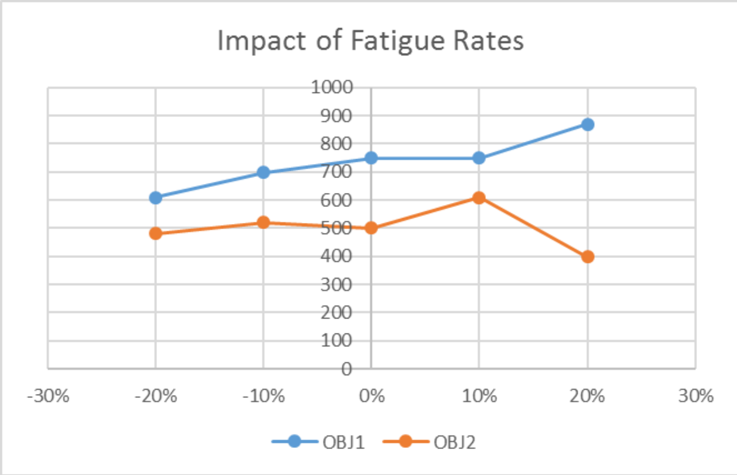

Figure 6. The impact of Fatigue Rates on Objective Functions

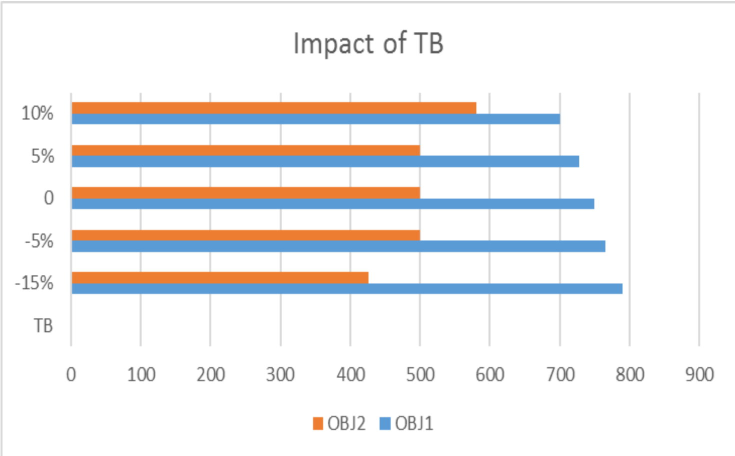

Figure 7. The impact of Tax benefit on Objective Functions

7. Managerial insights

This investigation focuses on considering costs and ergonomic issues in the U-shaped assembly line while the workers are divided into humans and robots, also, the government offers the tax benefit to the system when tasks are assigned to disabled workers. The consideration of ergonomic risks is inspired by Mokhtarzadeh et al. (2021), but in our paper, unlike that. we consider robot and human workers simultaneously. Moreover, using disabled workers to enable tax benefits is inspired by Chutima and Khotsaenlee (2022), and we use ergonomic risk concepts to enrich the problem set.

By using a sensitive analysis of section 6, we offer some managerial insights. First, it is conducted in section 6, the cycle time has a serious impact on the system costs. Thus, management could determine the appropriate cycle time for each period (neither long nor short work time) based on its historical data to prevent spending money (using robots with high costs due to short cycle time) and to increase ergonomic risks (using human workers for all tasks due to long cycle time). The other managerial insight is the about correct understanding of the workload of all assembly system tasks on normal and disabled workers. As seen in Section 6, if the fatigue rate of any of the hard and normal tasks changes, the system changes tasks differently. Therefore, it can be perceived that the management's misunderstanding about the working pressure of each of the tasks of the assembly system can cause incorrect inputs to the model and cause excessive fatigue of workers or not fully utilizing their capabilities. The last one is about the consideration of tax benefits. Management should evaluate the situation whether using disabled workers could decrease the system costs or not. As shown in section 6, the tax benefits could play the main role in assigning tasks to each worker.

8. Conclusions and future research

In this investigation, the main contribution is to evaluate the impact of consideration of human and robot workers in the U-shaped assembly line. A two-objective model was presented to achieve the mentioned focus, which minimized the system costs and ergonomic risks. Moreover, by using disabled human workers, the system's costs could be decreased by enabling offered tax benefits. In the solution method section, it was shown the efficiency of the GOA by the comparison of the exact solution (GAMS's results). Thus, the GOA could be used to solve big-sized problems, and it can find the solution with a deviation of 2.0025. To reach the mentioned gap, 30 test problems were solved via GAMS and GOA, then their results were compared together. Next, the cycle time, fatigue rates, and tax benefit parameters were evaluated in section 6. All three parameters have direct effect on cost and ergonomic objectives. The production cycle time has a critical effect on selection of workers, the fatigue rate could determine the system task allocation to human workers, and the tax benefit could affect on usage of disabled workers. In section 7, some managerial insights are suggested for the U-shaped assembly line balance. For future research, the concept of preventive maintenance (PM) can be deployed in the model. In multi-period systems, it is possible the stations or equipment do not work with high efficiency or do not work completely. The PM could play a critical role in reducing the mentioned problem probability. Using limited work hours for human workers could be used to decrease ergonomic risks in multi-period production systems. Also, consideration of parallel and straight assembly lines in which robots and human workers are available could be added to the literature. Different assembly lines exist in giant production systems due to the high volume of orders. Consideration of parallel U-shaped or one straight and one U-shaped assembly line could be interesting work for the future. The last suggestion is about the solution method. The exact and other metaheuristic algorithms could be used to solve U-shaped assembly line problems, and their average deviation could be compared with the existing solution (GOA). By adopting this approach, the best algorithm to solve a U-shaped assembly line could be found.

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Appendix A

In this section all test problems are shown in Table A.1. Table A.1 has one column that is shown by $i \times j \times w \times h \times r$, that shows in order the number of tasks, number of stations, number of workers, and number of human and robot workers in each test problem. As it mentioned in section 5.1, two objective function's results are presented for each test problem and small and medium-sized problems are solved by GAMS software and the ANTIGONE algorithm.

Table A.1. The objective results of small and medium-sized problems

Test problem	$i \times j \times w \times h \times r$	Objective functions	
		Obj1	Obj2
1	$3 \times 3 \times 5 \times 3 \times 2$	226	194
2	$3 \times 3 \times 5 \times 3 \times 2$	321	205
3	$3 \times 4 \times 7 \times 4 \times 3$	354	226
4	$3 \times 4 \times 7 \times 4 \times 3$	450	320
5	$5 \times 3 \times 9 \times 4 \times 5$	364	241
6	$5 \times 6 \times 9 \times 4 \times 5$	397	261
7	$6 \times 3 \times 10 \times 7 \times 3$	409	297
2	$6 \times 9 \times 10 \times 8 \times 2$	337	298
9	$6 \times 10 \times 10 \times 8 \times 2$	341	302
10	$6 \times 9 \times 12 \times 10 \times 2$	410	321
11	$7 \times 12 \times 13 \times 8 \times 5$	424	312
12	$8 \times 10 \times 16 \times 8 \times 8$	453	364
13	$9 \times 9 \times 12 \times 8 \times 4$	414	347
14	$10 \times 10 \times 10 \times 8 \times 2$	471	370
15	$12 \times 15 \times 13 \times 6 \times 7$	750	500
16	$12 \times 15 \times 18 \times 11 \times 7$	764	512
17	$13 \times 15 \times 14 \times 6 \times 8$	770	524
18	$13 \times 17 \times 13 \times 6 \times 7$	781	570
19	$13 \times 17 \times 15 \times 6 \times 9$	770	561
20	$14 \times 15 \times 18 \times 10 \times 8$	891	612
21	$14 \times 15 \times 19 \times 10 \times 9$	891	612
22	$14 \times 16 \times 20 \times 11 \times 9$	887	587
23	$14 \times 16 \times 18 \times 10 \times 8$	847	574
24	$14 \times 17 \times 19 \times 11 \times 8$	866	574
25	$14 \times 17 \times 19 \times 11 \times 8$	866	597
26	$14 \times 17 \times 21 \times 12 \times 9$	857	547
27	$15 \times 15 \times 20 \times 12 \times 8$	947	644
28	$15 \times 15 \times 18 \times 10 \times 8$	974	671
29	$16 \times 15 \times 20 \times 12 \times 8$	998	697
30	$16 \times 15 \times 18 \times 10 \times 8$	984	691

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