Collaborative Robots' Assembly System in the Manufacturing Area Considering the Safety Issue, Assembly System 4.0

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Collaborative Robots' Assembly System in the Manufacturing Area Considering the Safety Issue, Assembly System 4.0

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Abstract

This paper aims to study allocating tasks problem in a single-station collaborative robot assembly system 4.0 considering the ISO standard. Two products with identical demands are run in a system simultaneously in mixed mode to reduce the idle time and improve the system utilization. The idle time occurs due to balancing difficulties and particularly in this case restrictions in the task vs. robot-worker feasibility matrix. It is not allowed for the resources to assemble a same product simultaneously to avoid any direct contact between resources. Thus, the products are swapped between resources as needed to complete the assembly tasks. Two approaches, a novel mathematical model and the shortest processing time (SPT) rule, are propounded in this study to reduce the cycle and idle times, and enhance the production rate of an assembly system. The two proposed methods rely on dividing the timeline of a station into unknown stages with unknown lengths. The performance of the proposed mathematical model and SPT rule are evaluated by two performance measures: the total number of stations and the % average station utilization. The obtained results are compared to the results of the modified COMSOAL heuristic. The findings revealed that the novel mathematical model dominated results. It guaranteed minimizing the cycle time and maximizing the production rate compared to the SPT rule and modified COMSOAL heuristic. However, many companies value a one-second reduction in cycle time as valuable. This directly relates to the reduction of direct resources costs and the total number of stations.

Keywords: Assembly system 4.0; ISO Standard; Mathematical Model; Shortest Processing Time Rule.

1. Introduction

Manufacturing systems design and control has attracted both practitioners and academicians over the last decades. Recently, the manufacturing of information technology and materials witness several developments that were accompanied by the emergence of different concepts, such as industry 4.0, Accessible Automation, Mobile Robotics, Artificial Intelligence & Machine Learning. Besides, other concepts have appeared to support these developments including but not limited to Universal Connectability, Enterprise Resource Planning, Internet of Things (IoT), Additive Manufacturing, Collaborative Robots (Cobots), *etc*. This paper studies collaborative robots within manufacturing systems, particularly, in assembly operations (assembly system 4.0). Basically, this work focuses on solving allocating tasks problem in a single-station collaborative robot assembly as it dramatically impacts the efficiency and profitability of the entire manufacturing system.

The assembly system problem is part of the NP-hard problem (nondeterministic polynomial) as it follows the class of intensively studied combinatorial optimization problems [1,2,3]. The first identified formulation for the assembly system problem was in 1955 by Salveson [4]. Salveson assumed that a set of tasks is assigned to a series of workstations, and the cycle time for each workstation is known. The relations order among tasks for each product are determined by the precedence graph [2,5,6], as depicted in Figure 1. Typically, the assembly system problem is divided into two types [7,8]. Type I focuses on the minimization of the number of stations given that the assembly tasks and precedence requirements are known. Unlike, Type II which has a fixed number of stations. In Type II, the performance measures optimize the cycle time, makespan, productivity, etc. [1,9,10]. In Type II, the task allocation and scheduling at feasible stations are determined based on the assembly times of tasks and the time available at each station. Thus, type II of the assembly system problem falls into the class of sequencing and scheduling problems [7,11]. Several studies tackled the two types of assembly system problem using different solution methods. For example, Özcan, and Toklu, [12] provided a heuristic approach to solve the simple straight and U-shape assembly systems. Their proposed heuristic focused on two performance measurements. The first performance is the maximization of the system efficiency by reducing the number of workstations. The second performance measure is the equalization of workloads among stations. It is worth clarifying that type II of the assembly system problem was studied in their paper.

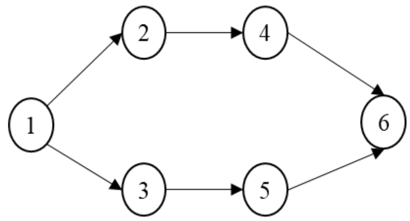

Figure 1. Product Precedence Graph.

Recently, a shift toward human-robot collaboration in the assembly field has been witnessed and resulted in a new concept in the assembly system, which is assembly system 4.0 [13]. In the collaborative robots' assembly system, the robots perform assembly tasks alongside a human in the station(s) based on their capabilities, as depicted in Figure 2. Allowing worker(s) and robot(s) to work in the same workstation guarantees more flexibility in production processes [14, 15]. Therefore, collaborative robots' assembly system has gained recently significant practical relevance. For example, Bogner et. al, [16] studied task' scheduling and allocation of printed circuit boards assembly using an integer linear programming model, and heuristic approaches to minimize the makespan. They assumed that the worker and robot can assemble a product at the station simultaneously. The obtained results illustrated the efficiency of the heuristic approach for reducing the overall makespan. Weckenborg et al. [17] proposed mixed-integer programming and metaheuristic (Hybrid Genetic Algorithm) for task allocation and scheduling in a collaborative robots' assembly system. The objective of their model was to minimize the cycle time of the station, while a single robot can move from one station to another. The results show the importance of using collaborative robots in manual assembly lines to improve productivity. Casalino et al. [18] developed a scheduling method to minimize the idle time in the station when the worker and robot were assigned to assemble the tasks in a station considering the variation in the processing time during the runtime. The authors observed the ability of the propounded method in minimizing idle time. Further, Wang et al. [19] modeled task allocation and scheduling for four types of tasks in the assembly system to optimize the trade-offs between ergonomic and cycle time. The first task type is H, and it is completed by the human worker only. The second task type is R and it is processed by a robot. The third type is H/R, and it is assembled by either a human worker or a robot. The fourth type is H+R, it is completed by a human worker and robot collaboratively.

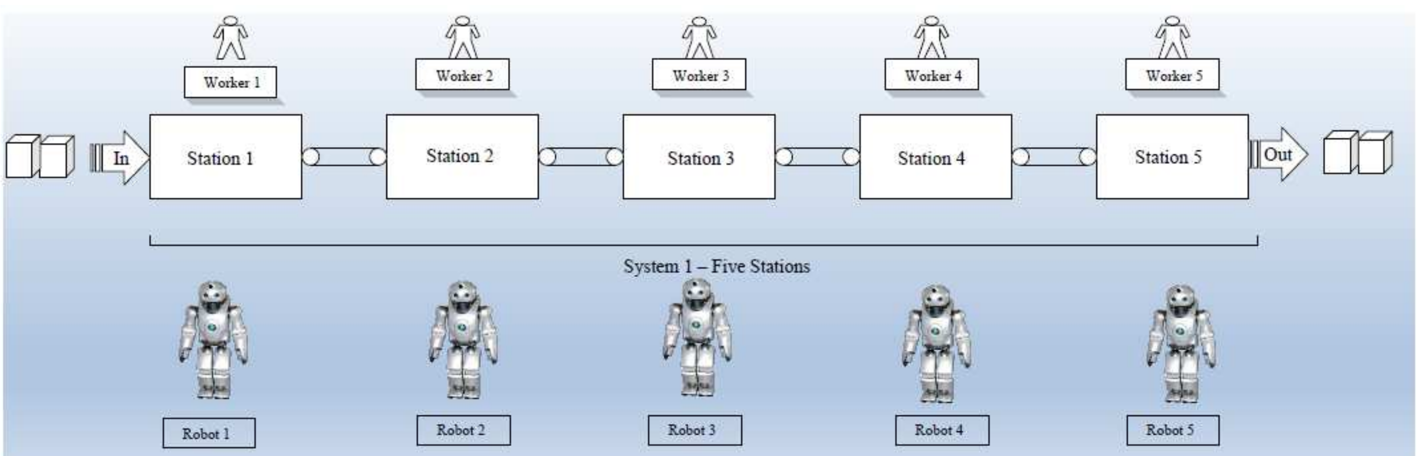

Figure 2. Collaborative Robots Assembly System.

Allowing workers and robots to work in the same workplace increases the interaction between them, and it does not comply with the safety condition (ISO 10218) [13,18,20]. Many studies have shown the state of the art in collaborative robots and interactions recently taking into account the safety issue [21,22,23,24,25,26,27,28]. Thus, to maintain worker safety in this study, it is not allowed for the resources (worker and robot) to perform the same product simultaneously.

However, this work will focus on the task allocation decisions in the single station collaborative robots' assembly system. We are proposing working on two products simultaneously to increase the efficiency of both the robot and the worker and thus lower the cycle time. Obviously, this is equivalent to an increase in output rate. On the other hand, this approach has some restrictions in terms of the product sizes because it may be impractical, if products are too large, to fit them both into the workspace in a station simultaneously. Another obstacle is that if products are too heavy and big, it may be so inconvenient to move them between robot and worker many times. However, the concepts developed herein can be implemented in many industries without much difficulty. Any efficient improvement in assembly systems is considered significant in terms of lowering costs. It is not uncommon that many companies value a one-second reduction in cycle time as valuable. This directly leads to reducing the investment costs including the resources stations costs, and the total number of stations needed to meet the demand. Therefore, a novel mathematical model and SPT rule are propounded to schedule and determine the sequencing of the tasks of products in a single station collaborative robot assembly system 4.0.

The remaining sections of this paper are organized as follows. Section 2 describes the problem statement of this work. Section 3 presents the technical details of the methodology. Section 4 illustrates the experimentation and results. The last section gives the conclusion and future works.

2. Problem Statement

This research is proposed to study the task allocation problem to robot and assembly worker in type II collaborative robot assembly system 4.0. We consider the problem where the worker and robot cannot work on the same product in a workstation simultaneously to maintain worker safety.

We proposed that the station layout is split into 5 regions. In the input region (*Region A*), items needed to create both products are entered into the station by a conveyor belt with a known input rate, as illustrated in Figure 3. Once the arrived items reach the end of *Region A*, one of the resources picks them up and places them in *Region D*. Then, the resources start assembling the products using the required tools from *Regions B* and *C*. *Region B* represents the reachable area by the first resource (Robot), and it includes all tools that can be used by a resource. *Region C* includes the tools that the second resource (Worker) required to implement the tasks. One of the main assumptions in this study is that direct contact between the resources is prohibited; thus, it is not allowed for the resources to work on the same product simultaneously.

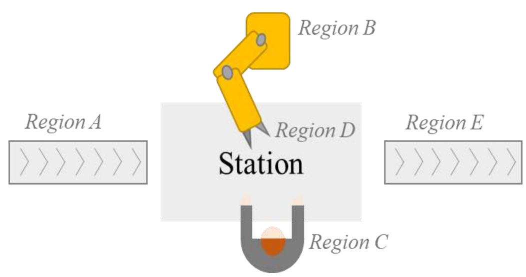

Figure 3. The Propounded Single-Station Collaborative Robots Assembly System Layout.

The timeline of a station is divided into T stages ($h = 1 \ldots T$), where $T \geq \sum_{i=1}^{n} m_i - 1$ to guarantee that the two resources are occupied, as given in Figure 4. Where a m_i is number of tasks per product *"i"* The length of each stage is unknown and nonpredetermined, and it is equal to S_h. It depends on the assembly times of the tasks assigned to be performed in a stage. In each stage, it is not allowed for a resource to assemble two products simultaneously; thus, each resource is dedicated to one product to avoid any direct contact between resources. A new stage is formed once the products are switched between the resources. The swapped time is negligible. When a given task has more than one immediate predecessor, all must be finished before the task can begin assembling.

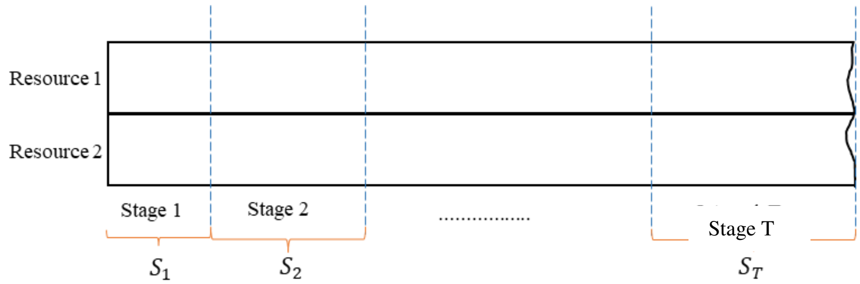

Figure 4. The Timeline of a Station.

3. Methodology

The overall objective of the paper is to develop a procedure and model to minimize cycle time and hence maximize the output rate taking into consideration the safety issue, without violating task feasibility restrictions. Thus, two approaches are propounded: mathematical modeling and the shortest processing time rule (SPT rule). Mathematical modeling is a powerful problem-solving tool; however, these optimal solutions are only attainable within a tolerable time for simple or small-scale problems. As the problem complexity and/or size increases, as in real-life scenarios, the problem is no longer optimally solved in polynomial time. Figure 5 illustrates the structure of the paper.

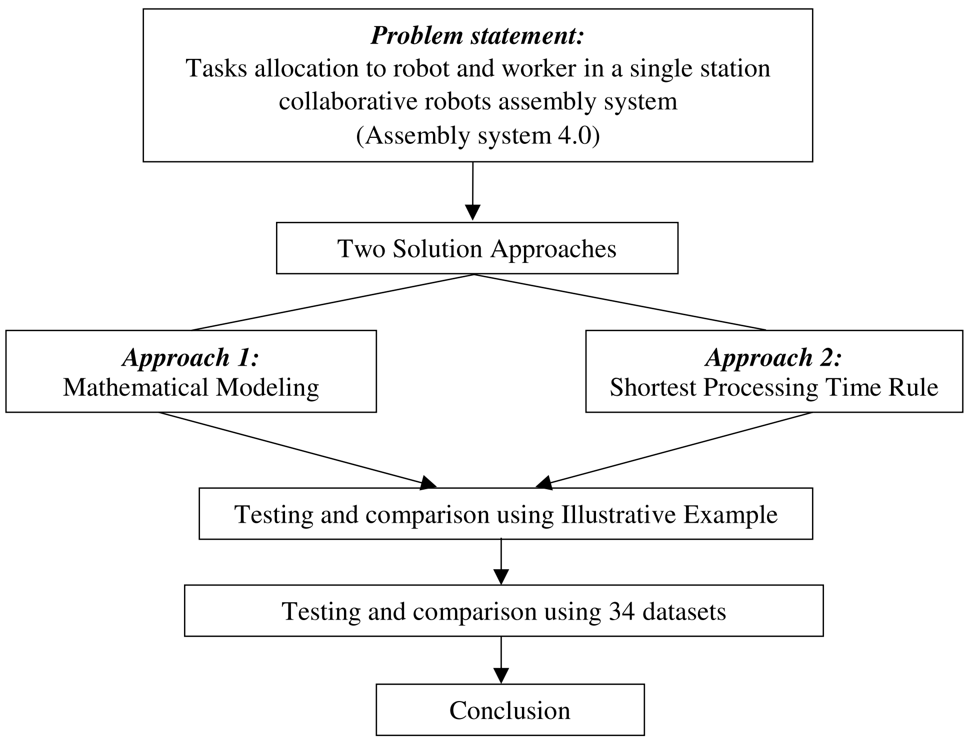

Figure 5.The Structure of This Study.

3.1 Mathematical Model

The objective function of the proposed mathematical model, Equation 1, minimizes the maximum completion time (cycle time) for the tasks in a station. Equation 2 determines the maximum completion time for each stage in a station. Equation 3 guarantees the execution of each task in one stage by a single resource (either a worker or a robot). Equation 4 ensures coherence among the tasks per stage and the number of products per stage. Equation 5 assigns the resource to the stage where a single resource can assemble only one product in a stage. Equation 6 warrants that the product can be assembled by only one resource at a time. Equation 7 guarantees that the completion time for the task per stage is less than the total lengths of created stages including the current stage, *so far*. Equation 8 calculates the length for each stage. The length of a stage is equal to the maximum completion time for either the worker or the robot. Equation 9 handles the unidirectional flow of tasks per product. Equation 10 computes the completion time for the precedented tasks of products at the first stage, where $S_0 = 0$. Equation 11 calculates the completion time for the precedented tasks of products at other stages. Equation 12 calculates the completion time for the precedence tasks of products at a stage. Equations 13 and 14 define the completion time for the disjunctive tasks of products. Equation 15 defines the variable domains, where the s is a set of resources (worker and robot) that is incapable of assembling the task.

Objective Function

$$Minimize \quad CT \tag{1}$$

Subject to

$$CT \geq C_{khij} \qquad \forall \mathrm{j} \in \mathrm{m}_i \ \forall \mathrm{i} \in \mathrm{n} \ \ \forall \mathrm{h} \in \mathrm{T} \ \forall \mathrm{k} \in \mathrm{W} \tag{2}$$

$$\sum_{k=1}^{W} \sum_{h=1}^{T} X_{khij} = 1 \qquad \forall \mathrm{j} \in \mathrm{m}_i \ \ \forall \mathrm{i} \in \mathrm{n} \tag{3}$$

$$X_{khij} \leq Y_{khi} \qquad \forall \mathrm{j} \in \mathrm{m}_i \ \forall \mathrm{i} \in \mathrm{n} \ \ \forall \mathrm{h} \in \mathrm{T} \ \forall \mathrm{k} \in \mathrm{W} \tag{4}$$

$$\sum_{k=1}^{W} Y_{khi} \leq 1 \qquad \forall \mathrm{i} \in \mathrm{n} \ \ \forall \mathrm{h} \in \mathrm{T} \tag{5}$$

$$\sum_{i=1}^{n} Y_{khi} \leq 1 \qquad \forall \mathrm{k} \in \mathrm{W} \ \ \forall \mathrm{h} \in \mathrm{T} \tag{6}$$

$$\sum_{l=1}^{h} S_l \geq C_{khij} \qquad \forall \mathrm{j} \in \mathrm{m}_i \ \forall \mathrm{i} \in \mathrm{n} \ \ \forall \mathrm{h} \in \mathrm{T} \ \forall \mathrm{k} \in \mathrm{W} \tag{7}$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m_i} PT_{kij} * X_{khij} \leq S_h \qquad \forall \mathrm{k} \in \mathrm{W} \ \ \forall \mathrm{h} \in \mathrm{T} \tag{8}$$

$$\sum_{h}^{T} X_{khij} \leq \sum_{l=1}^{h} \sum_{k}^{T} X_{klir} \qquad \forall r \in pred\ j \ \ \forall \mathrm{j} \in \mathrm{m}_i \ \forall \mathrm{i} \in \mathrm{n} \tag{9}$$

$$C_{k1ij} \geq S_0 + PT_{kij} * X_{k1ij} \qquad S_0 = 0 \ \forall r \in pred\ j \ \ \forall \mathrm{j} \in \mathrm{m}_i \ \forall \mathrm{i} \in \mathrm{n} \ \forall \mathrm{k} \in \mathrm{W} \tag{10}$$

$$C_{khij} \geq \textstyle\sum_{l=1}^{h-1} S_l + PT_{kij} * X_{khij} \qquad \forall r \in pred\ j \ \ \forall \mathrm{j} \in \mathrm{m}_i \ \forall \mathrm{i} \in \mathrm{n} \ \forall \mathrm{k} \in \mathrm{W} \ \forall \mathrm{h} \in \mathrm{T} \tag{11}$$

$$C_{khij} \geq C_{khir} + PT_{kij} * X_{khij} \qquad \forall r \in pred\ j \ \ \forall \mathrm{j} \in \mathrm{m}_i \ \forall \mathrm{i} \in \mathrm{n} \ \forall \mathrm{k} \in \mathrm{W} \ \forall \mathrm{h} \in \mathrm{T} \tag{12}$$

$$C_{khit} + PT_{kij} * X_{khij} \leq C_{k1ij} + M * \left(1 - Z_{khitj}\right) \quad \forall \mathrm{h} \in \mathrm{T} \ \forall \mathrm{k} \in \mathrm{W} \ \forall \mathrm{i} \in \mathrm{n} \ \ \text{t\&j disjunctive tasks} \tag{13}$$

$$C_{khij} + PT_{kit} * X_{khit} \leq C_{k1it} + M * Z_{khitj} \tag{14}$$

$$X_{shij} = 0 \qquad s \notin \mathrm{k} \ \ \mathrm{j} \in \mathrm{m}_i \ \ \mathrm{i} \in \mathrm{n} \ \ \mathrm{h} \in \mathrm{T} \tag{15}$$

Indices:

j	*Task Index*
i	*Product Index*
k	*Resource Index (Worker and Robot)*
h	*Stage Index*

Parameters:

n	*Number of Products*
T	*Number of Stages in a Station*
W	*Number of Resources*
PT_{kij}	*Assembling Time for Task j of Product i by the Resource k*
CT	*Completion Time (Cycle Time)*
M	*Large Number*

Decision Variables:

X_{khij}	*1, if Task j of Product i is Assigned to be Assembled by Resource k at Stage h* *0, Otherwise*
Y_{khi}	*1, if Product i is Assigned to be Assembled by Resource k at Stage h* *0, Otherwise*
Z_{khitj}	*1, if Task j Precedes Task t of Product i when Resource k Assembles the Tasks (j & t) at Stage h* *0, Otherwise*
C_{khij}	*Completion Time (Cycle Time) for task j of Product i when the Resource k is assigned to Stage h*

Typically, the production rate increases as the cycle time decrease. Once the completion time (cycle time) of a station is calculated, the production rate of product i (PR_i) is computed using Equation 16:

$$PR_i = \frac{1}{CT} \tag{16}$$

Having determined the production rate, Equation 17 is used to determine the number of stations needed to meet the demand for products.

$$Number\ of\ Stations\ = \left\lceil \frac{Demand}{Production\ Rate} \right\rceil \tag{17}$$

3.2 Shortest Processing Time Rule (SPT)

SPT was utilized to assign the tasks of two products into a station to be assembled by two resources (worker and robot) in mixed mode. This was to maximize the output rate by reducing the station cycle time and hence improving the station utilization. Several steps are utilized, as follows:

1. Order all feasible tasks in the increasing order of the processing times for the two resources.
2. Assign feasible tasks starting from the top of the list as long as precedence relations are not violated.
3. The tasks with the shortest assembly time of the two resources are selected to be assembled by either the robot or worker.
4. In case the available tasks in a stage have the same assembly time, the task that belongs to the current product assembled in a stage by the same resource is selected to reduce the number of stages formed.
5. Once the products are swapped between the resources, a new stage is formed, then the length of a stage is determined based on the maximum total assembly time of tasks for both resources.
6. The Completion time is equal to the total lengths of the created stages, and it calculates using Equation 18:

$$CT = \sum_{h=1}^{T} S_h \tag{18}$$

7. The station completion time and idle time are computed.
8. The production rate is defined, and then the number of stations required to meet the demand is computed.

3.3 *Illustrative Example*

Two products are assigned to be assembled in a single-station collaborative robots assembly system 4.0 by two resources (worker and robot). Each product has several tasks to be implemented, as presented in Figure 6. The assembly times for tasks are known and deterministic, as shown in Table 1. For example, worker and robot can perform tasks (2, 5, 6, and 9). Tasks 3, 7, and 8 can be assembled by the worker, while Tasks (1, 4, and 10) can be assembled by the Robot. Depending on the precedence relations, Task 1 should be completed first, and then it is allowed to start assembling Tasks 2 and 3. Additionally, Tasks 1 and 6 do not need to wait for any other tasks. Task 6 must be completed before starting to assemble Tasks 7, 8, and 9. Tasks 5 and 10 have more than one immediate predecessor, all must be finished before they can be assembled. The monthly demand for two products is identical and equal to 548 units for each product. Considering 8-hr shift and 20 days/month.

Table 1. Task Feasibility Matrix (Minute).

Products	1					2				
Task	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Assembly time (Worker)	-	6	13	-	6	12	4	9	5	-
Assembly time (Robot)	5	3	-	3	3	7	-	-	3	4

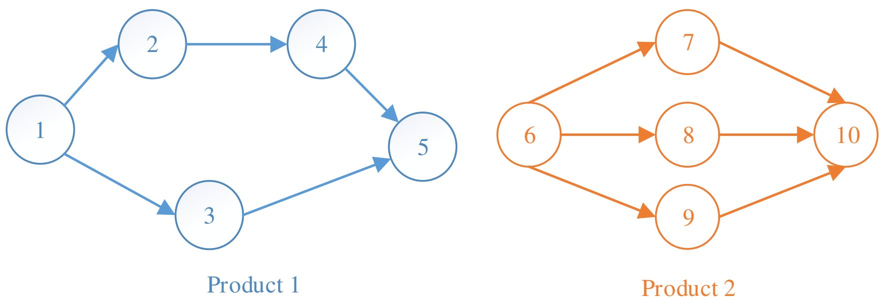

Figure 6. Products 1 and 2 Precedence Relations.

3.3.1. Results of Mathematical Model for the illustrative example

CPLEX software has been utilized to solve the proposed mathematical model for the example presented earlier. Gantt chart shows the tasks scheduled in the assembly system (Figure 7). The results show that the idle and completion times for a worker and a robot are 9 and 7, and 31 and 35 minutes, respectively; thus, the cycle time of the station is 35 minutes. The output of the assembly system is 1 unit of product 1 and 1 unit of product 2 every 35 minutes. In addition, four stages are formed. In stage 1, the worker is idle, while the robot assembled task 1 of product 1. Afterward, the products are swapped between the resources, which created Stage 2. T3 of P1 is assembled by the worker, and T6 and T9 of P2 are performed by the robot, and *so on*. The lengths of stages 1, 2, 3, and 4 are not equal, as they last for 5, 13, 13, and 4 minutes, respectively. For a single station, the production rate of each product is 1.71 units per hour and 274.28 units of each product every month; thus, two stations are needed to meet the demand for two products.

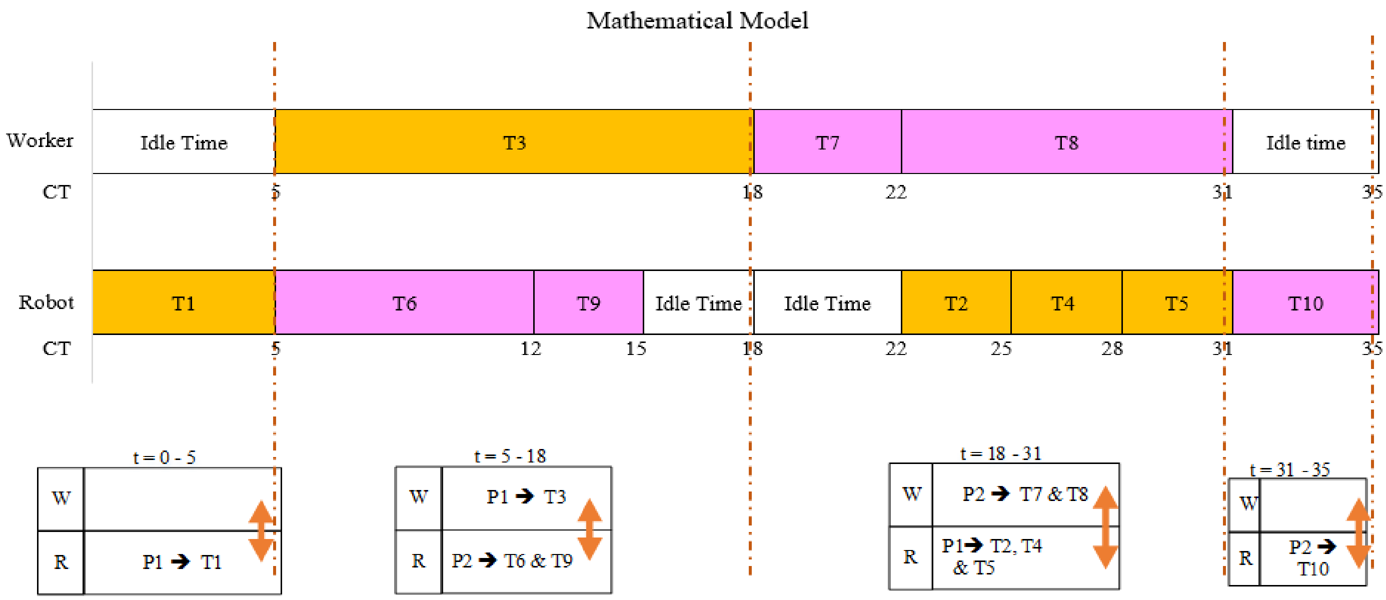

Figure 7. The Tasks Scheduling in a Single-Station Collaborative Robot Assembly System based on the Results of Mathematical Model.

3.3.2 Results of Shortest Processing Time Rule (SPT) for the illustrative example

Figure 8 illustrates the decision on allocating the tasks for the two resources in a single-station collaborative robot's assembly system. At time Zero, two tasks, T1 & T6, are available to be assembled in a station. Considering the SPT rule, T1 is assigned to be performed by the Robot, since the worker is not able to process it. Thus, T6 is assigned to be assembled by the worker to reduce the waiting time. At time 5, T2 & T3 are available to be assembled in a system. The worker is still working on T6 of P2, in other words, the status of worker is busy. Therefore, the robot begins assembly of T2 where the robot is not able to execute T3 based on the task feasibility matrix given in Table 1, and *so on*.

t_{now} =	0		t_{now} =	5		t_{now} =	8		t_{now} =	11		t_{now} =	12	
AT**	***W***	***R***	***AT***	***W***	***R***	***AT***	***W***	***R***	***AT***	***W***	***R***	***AT***	***W***	***R***
T1	--	5	T2	6	3	T3	13	--	T3	13	--	T3	13	--
T6	12	7	T3	13	--	T4	--	3				T7	4	--
												T8	9	--
												T9	5	3
Current Status	W	T6	Current Status	W	Busy/T6	Current Status	W	Busy/T6	Current Status	W	Busy/T6	Current Status	W	T3
	R	T1		R	T2		R	T4		R	Idle		R	T9
t_{now} =	15		t_{now} =	25		t_{now} =	28		t_{now} =	29		t_{now} =	38	
AT	***W***	***R***	***AT***	***W***	***R***	***AT***	***W***	***R***	***AT***	***W***	***R***	***AT***	***W***	***R***
T7	4	--	T7	4	--	T8	9	--	T8	9	--	T10	--	4
T8	9	--	T8	9	--									
			T5	6	3									
Current Status	W	Busy/T3	Current Status	W	T7	Current Status	W	Busy/T7	Current Status	W	T8	Current Status	W	Idle
	R	Idle		R	T5		R	Idle		R	Idle		R	T10

AT** Task Available to be assembled in a system

Figure 8. The Task Allocation Decision in A Single-Station Collaborative Robot's Assembly System.

The results depicted in Figure9 show that the completion time (cycle time) of a station is 42 minutes based on the results of the SPT rule. The idle times of worker and robot are 4 and 21 minutes, respectively, which affect negatively the %station utilization (station efficiency). Four stages are created with non-identical lengths. The length of stages 1, ,2, 3 and 4 are 12, 13, 13, and 4 minutes, respectively. In stage 1 ($0 \leq t \leq 12$), the worker performs T6 of P2, while the robot assembles T1, T2, and T4 of P1. In stage 2 ($12 \leq t \leq 25$), the products are swapped between the resources, where the worker performs T3 of P1 and the robot assembles T9 of P2. At the end of this stage, the resources exchange the products, and they continue performing tasks until t = 38, and *so on*. The production rate of each product is 228.57 units per month of each product; therefore, three stations are required to meet the monthly demand for two products.

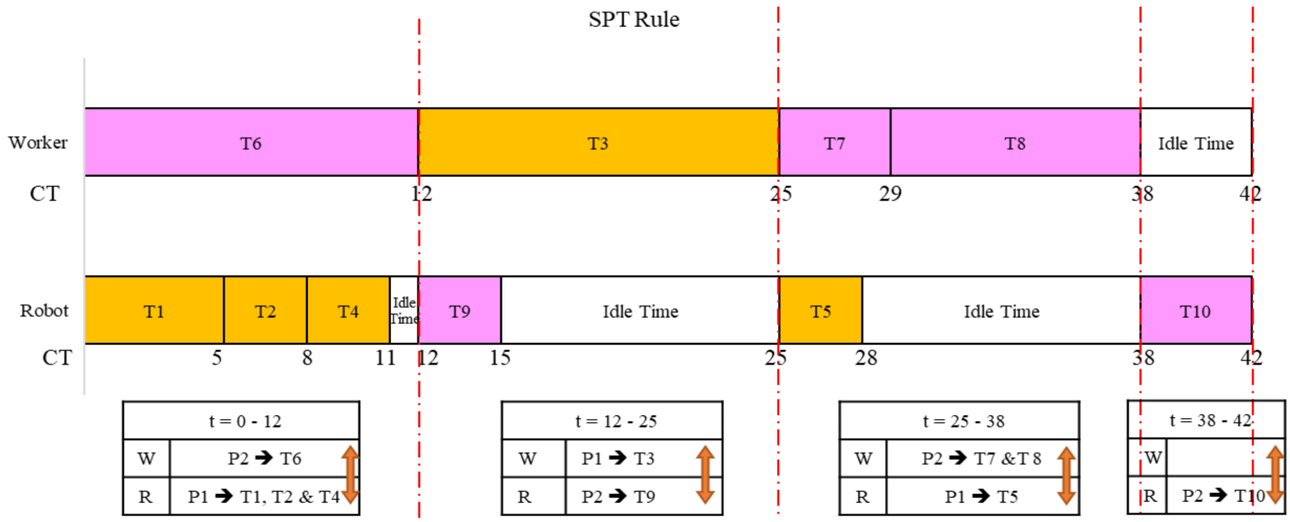

Figure 9. The Tasks Scheduling in a Single-Station Collaborative Robot Assembly System based on the Results of SPT Rule.

4 Experimentation and Results

The performance of the proposed mathematical model and SPT rule were evaluated using thirty-four datasets with different sizes. The comparison was made in terms of the station cycle time, the number of stations needed to cover the monthly demand, and % the average stations utilization. In each example, the demand for two products was identical. The assembly times of tasks were unknown and deterministic, as given in Table 2. However, the behavior of the proposed mathematical model and SPT rule were compared to the modified COMSOAL heuristic. The modified COMSOAL heuristic used in the literature to minimize the makespan in a mixed-mode single station, where the worker and robot work side by side [29].

Table 2.The Size of Dataset and the Monthly Demand Tested in the Experimentation.

S. No.	Size of Dataset	Monthly Demand	*S. No.*	Size of Dataset	Monthly Demand
1	9 × 9	948	18	16 × 16	241
2	11 × 11	315	19	16 × 16	436
3	7 × 7	791	20	17 × 17	968
4	7 × 7	682	21	17 × 17	937
5	8 × 8	537	22	18 × 18	128
6	8 × 8	538	23	18 × 18	764
7	11 × 11	518	24	18 × 18	789
8	14 × 14	524	25	18 × 18	562
9	14 × 14	124	26	19 × 19	760
10	14 × 14	594	27	19 × 19	311
11	13 × 13	439	28	20 × 20	511
12	7 × 7	859	29	20 × 20	359
13	14 × 14	185	30	12 × 12	407
14	15 × 15	473	31	14 × 14	138
15	15 × 15	151	32	14 × 14	825

16	18 × 18	550	33	10 × 10	869
17	16 × 16	645	34	20 × 20	626

4.1 The comparison in terms of the cycle time of the station

The cycle time and monthly production rate of each product are given in Table 3. The obtained results illustrate the ability of the proposed mathematical model to reduce cycle time, which leads to maximizing the monthly production rate compared to the proposed SPT rule and modified COMOSAL heuristic. In most cases, the mathematical model dominates the results, where it could obtain the minimum cycle time. In datasets 17, 19, and 26, the SPT rule could duplicate the results of the mathematical model. Meanwhile, COMSOAL duplicates the result of the mathematical model in dataset 29. It is also worth mentioning that the running time of the mathematical model increases as the size of the dataset increases and the assembly times of tasks get tighter, and *vice versa*.

Table 3. Summary of Obtained Results in terms of the Cycle Time and Monthly Production Rate.

S. No.	*Cycle Time*			*Monthly Production Rate of Each Product*		
	Mathematical Model	*SPT*	*COMSOAL*	*Mathematical Model*	*SPT*	*COMSOAL*
1	<u>89.000</u>	92.000	90.000	107.86	104.34	106.66
2	<u>91.520</u>	92.312	93.271	104.89	103.99	102.92
3	<u>108.400</u>	109.800	109.100	88.56	87.43	87.99
4	<u>65.203</u>	65.247	65.489	147.23	147.13	146.58
5	<u>46.000</u>	73.000	78.000	208.69	131.5	123.07
6	<u>87.791</u>	93.866	89.424	109.35	102.27	102.27
7	<u>107.000</u>	108.000	109.000	89.71	88.88	88.07
8	<u>157.000</u>	159.000	158.000	61.14	60.37	60.75
9	<u>151.691</u>	170.437	181.545	63.28	56.32	52.87
10	<u>116.000</u>	118.000	124.000	82.75	81.35	77.41
11	<u>193.000</u>	199.000	198.000	49.74	48.24	48.48
12	<u>67.000</u>	69.000	70.000	143.28	139.13	137.14
13	<u>73.544</u>	73.644	73.710	130.53	130.35	130.24
14	<u>114.062</u>	114.762	260.463	84.16	83.65	36.85
15	<u>149.193</u>	149.681	149.534	64.34	64.13	64.19
16	<u>257.000</u>	261.000	266.000	37.35	36.78	36.09
17	<u>91.663</u>	<u>91.663</u>	94.579	104.73	104.73	101.5
18	<u>78.528</u>	79.184	79.972	122.24	121.23	120.04
19	<u>177.000</u>	<u>177.000</u>	185.000	54.23	54.23	51.89
20	<u>91.028</u>	92.720	93.725	105.46	103.53	102.42
21	<u>132.616</u>	132.846	134.666	72.38	72.26	71.28
22	<u>288.345</u>	289.508	304.301	33.29	33.15	31.54
23	<u>199.055</u>	199.584	203.934	48.22	48.10	47.07
24	<u>370.538</u>	373.514	371.951	25.90	25.70	25.80
25	<u>170.562</u>	170.608	171.081	56.28	56.26	56.11
26	<u>184.188</u>	<u>184.188</u>	184.684	52.12	52.12	51.98
27	<u>336.138</u>	339.564	339.691	28.55	28.27	28.26
28	<u>243.918</u>	249.111	246.000	39.35	38.53	39.02
29	<u>240.707</u>	240.987	<u>240.707</u>	39.88	39.83	39.88
30	<u>211.693</u>	212.567	211.773	45.34	45.16	45.33
31	<u>237.734</u>	238.225	238.085	40.38	40.29	40.32
32	<u>197.343</u>	199.548	200.360	48.64	48.10	47.91
33	<u>135.535</u>	136.807	136.584	70.83	70.17	70.28
34	<u>394.578</u>	401.068	397.775	24.32	23.93	24.13

4.2 The compression in terms of the number of Stations and % Average Stations Utilization

Two performance measures, number of stations and % average stations utilization, were utilized to evaluate the performance of the propounded mathematical model and SPT rule. The obtained results were compared to the modified COMSOAL heuristic. Equation 19 calculates the %Average Stations Utilization based on the demand for products, production rate, and the number of stations. In Table 4, the obtained results are summarized.

$$\%\text{Average Stations Utilization} = \frac{Monthly\ Demand\ of\ Either\ Product\ 1\ or\ Product\ 2}{Monthly\ Production\ Rate\ \times Number\ of\ Station} \times 100\% \qquad (19)$$

Table 4. The Number of Stations and %Average Stations Utilization.

S. No.	*Number of Stations*			*%Average Stations Utilization*		
	Mathematical Model	SPT	*COMSOAL*	Mathematical Model	SPT	*COMSOAL*
1	***9***	10	***9***	97.7%	90.9%	***98.8%***
2	4	4	4	75.1%	75.7%	***76.5%***
3	***9***	10	***9***	99.2%	90.5%	***99.9%***
4	5	5	5	92.6%	92.7%	***93.1%***
5	***3***	5	5	85.8%	81.7%	***87.3%***
6	***5***	6	6	***98.4%***	87.7%	87.7%
7	6	6	6	96.2%	97.1%	***98.0%***
8	9	9	9	95.2%	***96.4%***	95.8%
9	***2***	3	3	***98.0%***	73.4%	78.2%
10	8	8	8	89.7%	91.3%	***95.9%***
11	***9***	10	10	***98.1%***	91.0%	90.6%
12	***6***	7	7	***99.9%***	88.2%	89.5%
13	2	2	2	70.9%	***71.0%***	***71.0%***
14	***6***	***6***	13	93.7%	94.2%	***98.7%***
15	3	3	3	78.2%	***78.5%***	78.4%
16	***15***	***15***	16	98.2%	***99.7%***	95.2%
17	7	7	7	88.0%	88.0%	***90.8%***
18	***2***	***2***	3	98.6%	***99.4%***	66.9%
19	9	9	9	89.3%	89.3%	***93.4%***
20	10	10	10	91.8%	93.5%	***94.5%***
21	***13***	***13***	14	99.6%	***99.7%***	93.9%
22	***4***	***4***	5	96.1%	***96.5%***	81.2%
23	***16***	***16***	17	99.0%	***99.3%***	95.5%
24	31	31	31	98.3%	***99.0%***	98.6%
25	***10***	***10***	11	***99.9%***	***99.9%***	91.1%
26	15	15	15	97.2%	97.2%	***97.5%***
27	***11***	12	12	***99.0%***	91.7%	91.7%
28	***13***	14	14	***99.9%***	94.7%	93.5%
29	10	10	10	90.0%	90.0%	***90.1%***
30	***9***	***9***	10	99.7%	***99.8%***	90.1%
31	4	4	4	85.4%	***85.6%***	***85.6%***
32	***17***	18	18	***99.8%***	95.3%	95.7%
33	13	13	13	94.4%	***95.3%***	95.1%
34	***26***	27	***26***	99.0%	96.9%	***99.8%***

Considering the tabulated results, it can be observed that in most cases the mathematical model could acquire the minimum number of stations, in other cases SPT rule could duplicate the results of the mathematical model, while in other cases the COMOSAL heuristic could duplicate the results of the mathematical model. Meanwhile, the number of stations required to meet the monthly demand for products is identical in some datasets based on the results of the mathematical model, SPT rule, and modified COMSOAL heuristic. On the other hand, we can easily conclude that the increase in the number of stations does not always lead to improving the

%Average Stations Utilization because of the changes in the production rate of stations based on the approach used to allocate the tasks in a station. For example, in dataset 5, the results illustrate that the number of stations needs to meet the demand for two products are 3, 5, and 5 based on the results of the mathematical model, SPT rule, and modified COMSOAL heuristic, respectively. Considering this, it is expected that the maximum %average stations utilization should occur when the mathematical model is utilized to determine the number of stations. Meanwhile, the results showed that the maximum %average stations utilization was obtained by the COMOSAL heuristic because of the low level of the station's monthly productivity compared to other approach utilized, as given in Table 3.

5 Conclusion

In this paper, a novel mathematical model and SPT rule are proposed for allocating tasks to the collaborative robots' assembly system 4.0, where two resources (worker and robot) are utilized to assemble the tasks of two products in the system (Mixed-model assembly system). The timelines of the two resources were divided into stages of unknown length for the propounded mathematical model and SPT rule. Afterward, the tasks are allocated to resources. The stages are formed when the products are swapped between the resources. The results show the ability of the mathematical model to minimize the cycle time of stations, which leads to maximizing the production rate; thus, the number of stations required to meet the demand for product decreases. Further, The SPT rule duplicated the results of a mathematical model in some datasets, as well as the modified COMSOAL heuristic.

It worth mentioning that the complexity of the proposed approaches increases as the size of the problem and the gap among the assembly times of tasks increase, and *vice versa*. To handle this issue, meta-heuristics, heuristics, and mathematical models should be considered in future research for solving the large sizes of problems, considering the task allocation in the assembly system with the different number of stations, improving the resource utilizations, and minimizing the idle times for the resources in the system.

Declarations

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References

[1] Hwang, R. K., Katayama, H., & Gen, M. (2008). U-shaped assembly line balancing problem with genetic algorithm. International Journal of Production Research, 46(16), 4637–4649.

[2] Zhang, W., Xu, W., & Gen, M. (2014). Hybrid multiobjective evolutionary algorithm for assembly line balancing problem with stochastic processing time. Procedia Computer Science, 36, 587-592.

[3] Bratcu, A. I., & Dolgui, A. (2003). Synergy, collaboration and self-balancing in production systems-the Bucket brigades. IFAC Proceedings Volumes, 36(23), 61-66.

[4] Salveson, M., 1955. The assembly line balancing problem. Journal of Industrial Engineering 6 (3), 18–25.

[5] Zhang, W., Lin, L., & Gen, M. (2008). Using multi-objective genetic algorithm with fuzzy logic controller for assembly line balancing problem with worker allocation. Int J Inf Syst Logist Manag, 3(2), 79-88.

[6] Boysen, N., Fliedner, M., & Scholl, A. (2007). A classification of assembly line balancing problems. European journal of operational research, 183(2), 674-693.

[7] Öztürk, C., Tunalı, S., Hnich, B., & Örnek, A. (2013). Balancing and scheduling of flexible mixed model assembly lines with parallel stations. The International Journal of Advanced Manufacturing Technology, 67(9-12), 2577-2591.

[8] Hackman, S. T., Magazine, M. J., & Wee, T. S. (1989). Fast, effective algorithms for simple assembly line balancing problems. Operations Research, 37(6), 916-924.

[9] Gen, M., Tsujimura, Y., & Li, Y. (1996). Fuzzy assembly line balancing using genetic algorithms. Computers & Industrial Engineering, 31(3-4), 631-634.

[10] Bautista, J., & Pereira, J. (2009). A dynamic programming based heuristic for the assembly line balancing problem. European Journal of Operational Research, 194(3), 787-794.

[11] Baker, K. R. (1974). Introduction to sequencing and scheduling. John Wiley & Sons.

[12] Özcan, U., & Toklu, B. (2009). A new hybrid improvement heuristic approach to simple straight and U-type assembly line balancing problems. Journal of Intelligent Manufacturing, 20(1), 123.

[13] Bortolini, M., Ferrari, E., Gamberi, M., Pilati, F., & Faccio, M. (2017). Assembly system design in the Industry 4.0 era: a general framework. IFAC-PapersOnLine, 50(1), 5700-5705.

[14] Casalino, A., Zanchettin, A. M., Piroddi, L., & Rocco, P. (2019). Optimal Scheduling of Human-Robot Collaborative Assembly Operations With Time Petri Nets. IEEE Transactions on Automation Science and Engineering.

[15] Faccio, M., Minto, R., Rosati, G., & Bottin, M. (2019). The influence of the product characteristics on human-robot collaboration: a model for the performance of collaborative robotic assembly. The International Journal of Advanced Manufacturing Technology, 1-15.

[16] Bogner, K., Pferschy, U., Unterberger, R., & Zeiner, H. (2018). Optimised scheduling in human–robot collaboration–a use case in the assembly of printed circuit boards. International Journal of Production Research, 56(16), 5522-5540.

[17] Weckenborg, C., Kieckhäfer, K., Müller, C., Grunewald, M., & Spengler, T. S. (2019). Balancing of assembly lines with collaborative robots. Business Research, 1-40.

[18] Fryman, J., & Matthias, B. (2012, May). Safety of industrial robots: From conventional to collaborative applications. In ROBOTIK 2012; 7th German Conference on Robotics (pp. 1-5). VDE.

[19] Wang, W., Bandaru, S., & TORROBA, A. S. D. O. (2019, August). Improved Humanobot Collaboration hrough Simulation-Based Optimization. In Advances in Manufacturing Technology XXXIII: Proceedings of the 17th International Conference on Manufacturing Research, incorporating the 34th National Conference on Manufacturing Research, 10-12 September 2019, Queen's University, Belfast (Vol. 9, p. 153). IOS Press.

[20] Vasic, M., & Billard, A. (2013, May). Safety issues in human-robot interactions. In 2013 IEEE international conference on robotics and automation (pp. 197-204). IEEE.

[21] Argall, B. D., & Billard, A. G. (2010). A survey of tactile human–robot interactions. Robotics and autonomous systems, 58(10), 1159-1176.

[22] Cherubini, A., Passama, R., Crosnier, A., Lasnier, A., & Fraisse, P. (2016). Collaborative manufacturing with physical human-robot interaction. Robotics and Computer-Integrated Manufacturing, 40, 1-13.

[23] De Santis, A., Siciliano, B., De Luca, A., & Bicchi, A. (2008). An atlas of physical human–robot interaction. Mechanism and Machine Theory, 43(3), 253-270.

[24] Tadele, T. S., de Vries, T., & Stramigioli, S. (2014). The safety of domestic robotics: A survey of various safety-related publications. IEEE robotics & automation magazine, 21(3), 134-142.

[25] Guiochet, J., Machin, M., & Waeselynck, H. (2017). Safety-critical advanced robots: A survey. Robotics and Autonomous Systems, 94, 43-52.

[26] Luckcuck, M., Farrell, M., Dennis, L. A., Dixon, C., & Fisher, M. (2019). Formal specification and verification of autonomous robotic systems: A survey. ACM Computing Surveys (CSUR), 52(5), 1-41.

[27] Dragan, A. D., Bauman, S., Forlizzi, J., & Srinivasa, S. S. (2015). Effects of robot motion on human-robot collaboration. In 2015 10th ACM/IEEE International Conference on Human-Robot Interaction (HRI) (pp. 51-58). IEEE.

[28] Johannsmeier, L., & Haddadin, S. (2016). A hierarchical human-robot interaction-planning framework for task allocation in collaborative industrial assembly processes. IEEE Robotics and Automation Letters, 2(1), 41-48.
[29] Suer, G. A., Almasarwah, N., Pagan, J., & You, Y. (2021). Assembly System 4.0: Human-Robot Collaboration in Assembly Operations. In IFIP International Conference on Advances in Production Management Systems (pp. 551-560). Springer, Cham.