Assembly System 4.0: Human-Robot Collaboration in Assembly Operations

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Abstract. This study focuses on allocation of assembly tasks to the robot(s) and assembly worker(s) in human-robot collaboration assembly systems 4.0. A new method is proposed to allocate tasks of products to a robot and a worker (resources) to minimize the cycle time and hence maximize the output, the single workstation, where the safety issues are considered. Thus, it is not allowed for the worker and robot to process the same product simultaneously to avoid any direct contact between the resources. The proposed method starts with dividing the cycle time for a station into intervals with unknown and unequal lengths. Afterward, a COMSOAL heuristic is utilized to task allocation to resources. The results obtained illustrate the ability of the proposed method to minimize the workstation cycle time and improve productivity.

Keywords: Assembly System 4.0, Assembly line, Safety Issues, COMSOAL.

1 Introduction

Manufacturing systems are going through rapid transformation in recent years as a result of various developments in the manufacturing processes, materials, and information technology and also as a result of increased globalization. Several new concepts have been used to capture these developments as advanced manufacturing, industry 4.0, smart manufacturing, cyber manufacturing among others. Most of these systems involve the Internet of Things (IoT), 3D printing, Wearable Robots, Human-Robot Collaboration, etc.

Cellular manufacturing is a manufacturing system, where dissimilar machines are grouped to process raw materials. The Assembly line is an integral part of most cellular manufacturing systems. It consists of various workstations in which the resources (e.g., robot(s), and or human worker(s)) use usually simple tools to assemble the products.

1.1 Assembly Line

Depending on the number of products assembled in the assembly lines, they can be categorized into single-model, mixed model and multi-model assembly lines [1,2], as depicted in Figure 1. A single product is assembled in the single-model assembly line. More than one product can be assembled in the mixed-model assembly line simultaneously [3,4]. In this category, similar products are grouped, where the setup times, the changeover times between products, are negligible. Meanwhile, dissimilar products are assembled in the multi-model assembly line at different times based on the demand and processing times of tasks. In this study, two products are assembled in the line simultaneously (mixed-model assembly line).

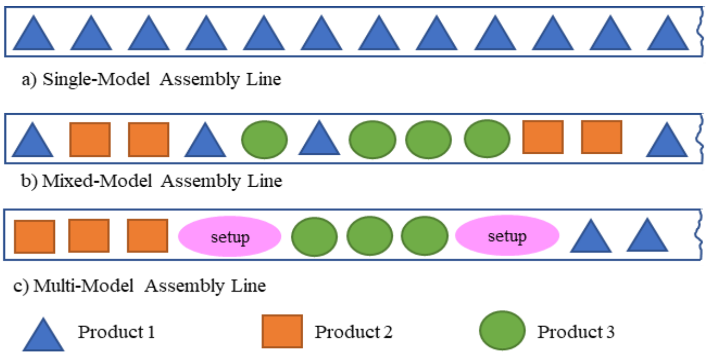


Figure 1. Categories of assembly line based on the number of products on assembly line.

Typically, there are two essential problems in mixed-model assembly lines, which are balancing and scheduling [5]. Assembly line balancing problem is one of the main active research areas, where several methods have been emerged in the literature to assign the tasks into consecutive workstations depending on a sequential manner. It is divided into two types of problems. The first type (type I) aims to minimize the number of workstations since the cycle times, assembly tasks, and precedence requirements are known. The second type (type II) has a fixed number of workstations, and the performance measures are minimizing the cycle time, maximizing output rate, etc. The second problem is assembly line scheduling. This problem studies the starting and completion times of products and defines the sequence of products in the line [3]. On the other hand, different types of material handling equipment can be used to move the products among the workstations, such as a conveyor belt, forklift, *etc*.

1.2 Human-Robot Collaboration

Human-robot collaboration is studied in this paper, where a set $P = \{P_1, P_2, .. P_n\}$ of n products with different tasks is assigned to be assembled in a single station. In this case, resources work together to run the products in the workstation. Depending on the resources' skills, some tasks can be assembled by the worker(s), other tasks can be run by the robot(s), while other tasks can be assembled by either the worker(s) or robot(s). Furthermore, the task times vary based on the resources used to implement the task. However, it is assumed that the processing times of tasks by worker and robot are known in advance and constant.

The human-robot collaboration assembly line problems are theoretically attractive combinatorial optimization problems since they are NP-complete, i.e., no procedure can solve each problem instance in polynomial time. Over the years, different solution approaches to these problems have been developed. These approaches can be divided into two groups: exact and heuristic methods. Specific methods, which are mostly based on linear programming or enumeration approaches such as branch-and-bound or dynamic programming, can quickly become inefficient to solve the problem when the number of variables increases. Heuristic and metaheuristic procedures, on the other hand, are fast but do not guarantee convergence to an optimal solution. They produce well enough solutions or near-optimal solutions at a reasonable computational cost and time.

In this paper, COMSOAL heuristic propounded by [6] is modified to schedule the products in a station in mixed mode to minimize the cycle time and hence improve productivity, to determine the task allocation to resources (worker(s), and robot(s)) where the worker(s) and robot(s) are working side by side in the workstation. The strong motivation for the proposed method is to avoid any direct contact between the resources to preserve the resources' safety. Another motivation for the method is the use of human and robotic skills in combination simultaneously. Typically, people contribute dexterity and can react very flexibly to new situations, while robots are not. Furthermore, this method allows the implementation of partially automated manufacturing solutions, which would improve flexibility in face of small lot sizes, such as electrical circuits, *etc*.

This paper is organized as follows. Section 2 reviews the related works on assembly line balancing and scheduling. Section 3 describes the problem statement. Section 4 describes the methodology proposed. Section 5 briefly discusses the results. Finally, the paper is concluded, and future research possibilities are stated in Section 6.

2 Related Literature

The concept of the assembly line arose in the literature at the beginning of the 20th century by Henry Ford [7]. In each assembly line, a series of workstations processes a repetitive set of tasks of products. Each workstation in the line is responsible for certain tasks, these tasks can be done by robot(s), and or human worker(s) using simple equipment. Thus, lines can be labeled as manual, robotic, and human-robot collaboration assembly lines. Typically, the manual assembly line is classified by high labor cost, where the skilled worker(s) work/s in the line to perform the operations consecutively [8]. In some cases, at least one worker should be assigned to a workstation, where the worker is responsible to complete the tasks at a workstation [9]. In other cases, the worker should move from the workstation to others in the assembly line in order to complete the assembly process (*Seru*) [10,11]. The flexibility and changeability of the assembly process in the manual assembly line are high [8]. Meanwhile, the robotic assembly line is used for faster assembly rates with high line efficiency, where certain tools, grippers are required to perform the tasks in the workstations by the robot(s). The variation between the established workplace and task performance is negligible; therefore, any breakdown that takes a place in workstation(s) reduces the line efficiency [12, 13, 14].

In the human-robot collaboration assembly line, the robots perform assembly tasks alongside a human in the workstation(s) based on their ability [15]. Allowing worker(s) and robot(s) to work in the same workstation guarantees more flexibility in production processes [16]. More importantly, the human-robot collaboration in the assembly field results in a new concept in an assembly line, which is assembly system 4.0 [17]. Several studies have covered the area of human-robot collaboration assembly line. For example, Bogner, Pferschy, Unterberger, and Zeiner, [18] studied scheduling and task allocation of printed circuit board assembly using integer linear programming model, and heuristic approaches to minimize the makespan. They assumed that the workers and robots are working together in a station to assemble the products.

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) [17, 19]. However, this research is proposed to study the optimal task allocation and scheduling in type II mixed-model assembly line balancing problem considering human-robot collaboration, where the worker and robot cannot perform assembly tasks on the same workstation simultaneously to maintain worker safety.

3. Problem Description

The layout of the workstation in this study is divided into five zones (Figure 2). In *Zone A*, the materials required to build products 1 and 2 are moved from the inventory area at a predetermined feed rate to the end of Zone A by using a conveyor belt. Once the materials get close to *Zone D*, the worker or robot move them to *Zone D.* The next step involves assembling the products in *Zone D* by worker and robot using the required parts from *Zone B* and *Zone C*. *Zone B* shows the storage area of the robot and it has all parts needed by the robot. *Zone C* presents the worker's storage area, where all parts needed by the worker are found. Considering the safety issues, it is not allowed to the resources to work on the same product simultaneously. Thus, the conveyor belt is utilized in *Zone D* to move the products from the worker side to the robot side, and *vice versa*, until the desired products are assembled. Finally, a material handling system like a conveyor belt in *Zone E* moves the products to the finished product containers.

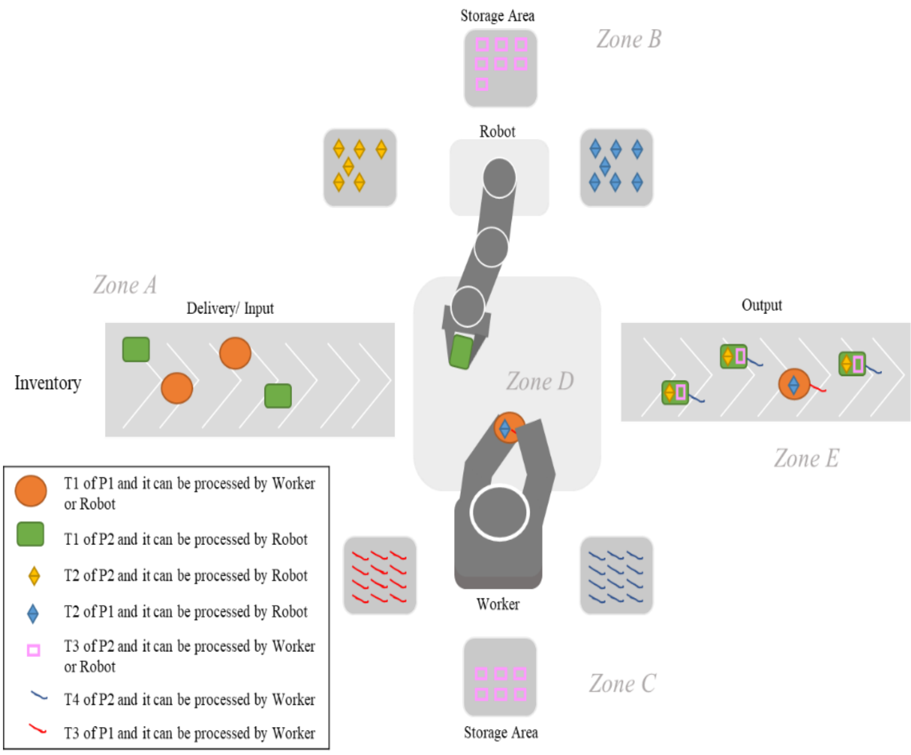
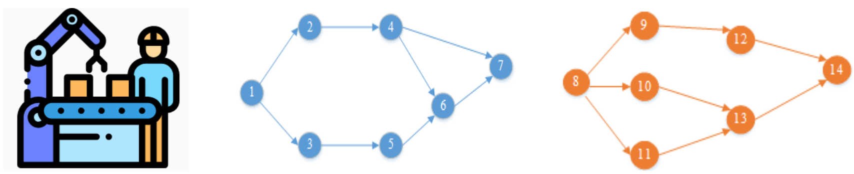


Figure 2. The proposed assembly line.

The problem considered in this study consists of two products that are assigned to be assembled in a single station. Their precedence relations are given in Figure 3. Product 1 has tasks 1-7 and Product 2 has tasks 8-14. There is only one robot and one worker in the station. The task feasibility matrix with processing times is given in Table 1. Some tasks can only be performed by the assembly worker (tasks 3,7,8, and 12) while some others can only be performed by the robot (tasks 1,4,10, and 14) and the remaining tasks can be performed by either the robot or the worker (tasks 2,5,6,9,11, and 13). It is easy to notice that the robot can finish its tasks in a shorter time compared to the worker.



a) Single workstation

b) Precedence relation for Product 1

c) Precedence relation for Product 2

Figure 3. An example.

Table 1. Task feasibility matrix with processing times (minutes).

Product	1							2						
Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Processing Time (Worker)	-	6	13	-	6	12	4	9	5	-	4	6	7	-
Processing Time (Robot)	5	3	-	3	3	7	-	-	3	4	2	-	5	9

4. Methodology

This study assumes that ($i = 1..m$) tasks of products are assigned to be assembled on a single workstation by the resources (worker and robot). The cycle time of the station is divided into $m - 1$ intervals with unknown lengths, as depicted in Figure 4. L_j is the length of interval#j. The lengths of intervals might be equal, or might not. It depends on the processing times of the tasks and the idle times at each interval. Each resource is dedicated to processing a single product in an interval, where it is not allowed for a resource to process the same product in two consecutive intervals. The first interval is created when the products are assigned to resources. Once the products are swapped between the resources the second interval is created, and *so on*.

The *COMSOAL* heuristic, the random sequence generation, is utilized to allocate tasks to the resources in a station to minimize the cycle time and improve productivity, where several steps have to be implemented as follows:

1. Identify all unassigned tasks, S_A
2. Identify all tasks from a set S_A, whose all immediate predecessors have been assigned,S_B.
3. Identify all operations from set S_B, that can be assembled by the worker S_W, the robot S_R, and worker or robot $S_{W\&R}$
4. Assign the task to be assembled by either the worker or robot based on random sequence generation, where each resource is dedicated to a single product in an interval.
5. Continue to process the unassigned tasks in interval#1 by either the worker or robot considering the random sequence generation. Start to schedule the products in interval#2, if the products are swapped between the resources.
6. Go to step 1 and continue until all tasks for two products are allocated.
7. Calculate the cycle time of the station by adding the lengths of all generated intervals (Equation 1).

$$Cycle\ time = \sum_{j=1}^{m-1} L_j \qquad (1)$$

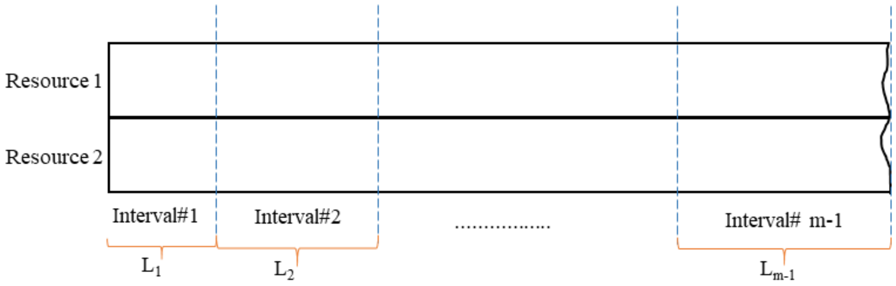


Figure 4. Task allocations to two resources (robot & worker) in the station.

A possible solution to the given example is illustrated in Figure 5. In the interval of $0 \leq t \leq 13$, the robot assembles product 1, while the worker runs Product 2. At time 9, three tasks, T_3, T_9 & T_{11}, are available to be assembled in a station by a worker. Considering the COMSOAL heuristic, three periods are generated for scheduling purposes. The length of each period is 0.333, which equals 1 divided by the number of tasks available $\left(\frac{1}{3}\right)$. The first period is (0-0.333), and it is corresponding to T_3. The second period is (0.334 – 0.666), it is corresponding to T_9, and *so on*.

T_3	0 – 0.333
T_9	0.334 – 0.666
T_{11}	0.667 – 1.000

Having determined the number of periods, length of each period, and their corresponding tasks, the first random number (RN#1) is created. In this case, it is 0.823, and it is within the fourth period (0.667 – 1.00). Thus, T_{11} is assigned to be performed by the worker in the first interval because it belongs to product 2.

RN#1: 0.823

	T_3	0 – 0.250	
	T_9	0.251-0.500	
0.823 ➔	T_{11}	0.751 – 1.00	∴ T_{11} is assigned to be assembled after T_8 by the worker

By the same token, two tasks, T_9 & T_{10}, are available to be assembled by the robot at time 11. These tasks belong to product 2. In this case, it is not allowed for the robot to perform any of them because product 2 is assembled by the worker. Therefore, the robot should stay idle till the worker finishes its current task (T_{11}). At time 13, two tasks, T_3 & T_9, are available to be performed by the worker; thus, two periods are created. The first period is (0 – 0.50), and it is corresponding to T_3. The second period is (0.501 – 1.000) and is corresponding to T_9. The generated random number is 0.231. Considering this, the products are swapped between the robot and the worker and they continue performing tasks until t = 26 minutes in the second interval when they swapped products again and *so on*.

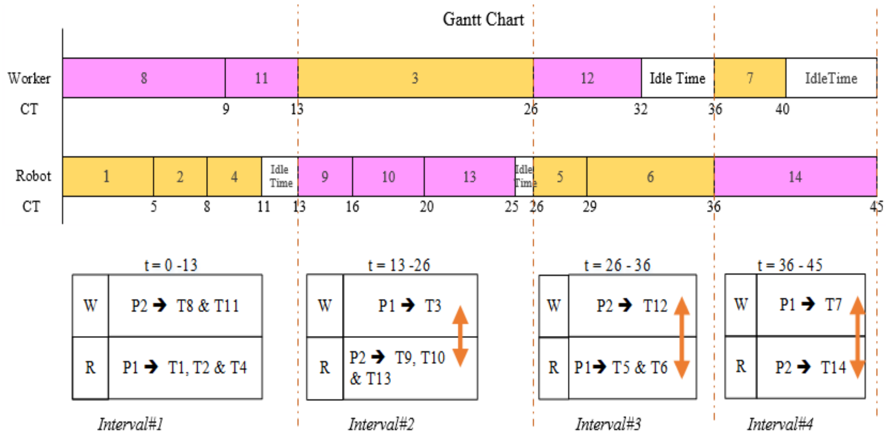


Figure 5. Gantt chart: scheduling tasks in the workstation using COMSOAL procedure.

The results obtained show that four intervals with different lengths are created. The length of the first two intervals is identical and equals 13 minutes, and the lengths of the third and fourth intervals are 10 and 9 minutes, respectively. The completion times of the worker and robot are 40 and 45 minutes, respectively. Therefore, the cycle time of the workstation is 45 minutes. The idle times for the worker and robot are 9, and 3 minutes, respectively.

5. Analysis and Results

Three problems are developed to test the performance of the proposed method. In each problem, two products are assigned to be assembled in a station by either robot or worker. The number of tasks in problems 1, 2, and 3 is 10, 12, and 8, respectively. The processing times are constant and known in advance.

In Table 2, the results obtained are summarized. The minimum idle times in three problems are acquired by the worker, and equal 4, 0, and 10.02 minutes, respectively. Meanwhile, the idle times for the robot are 21, 19.97, and 9 minutes in problems 1, 2, and 3, respectively. The completion time for the worker and robot in problem 1 is identical and equals 42 minutes; thus, the cycle time for a workstation is 42 minutes. In problem 2, the completion times for worker and robot are 69.19, and 49.22 minutes, respectively. Therefore, the cycle time for a workstation is 69.19 minutes based on the maximum completion time in a workstation. Whereas, the completion times for the worker and robot in problem 3 are 37, and 32 minutes, respectively; thus, the cycle time for a workstation is 37 minutes. The cycle time for the workstation is determined based on the completion time for the worker. Based on the results found, the number of intervals and the lengths of them are different from one problem to another and they depend on the number of tasks and processing times of tasks and the resources' skills.

Table 2. The results for three problems.

	Problem 1		Problem 2		Problem 3	
	Idle time	Completion time	Idle time	Completion time	Idle time	Completion time
Worker	4	42	10.02	69.19	0	37
Robot	21	42	19.97	49.22	9	32

6. Conclusion

This paper introduced a new method for task allocations to the robot(s) and worker(s) in a single workstation to minimize the cycle time and hence maximize the output with known and constant processing times. This method depends on dividing the cycle time of the station into intervals with unknown lengths. Afterward, the COMSOAL heuristic is utilized to allocate tasks at each interval. Each resource is dedicated to processing a single product in an interval to avoid any direct contact between the resources. Any direct contact could lead to creating an unsafe work environment. The completion time (cycle time) for the station is calculated based on the maximum completion time of both resources. The results obtained illustrate that the number of products and their tasks, and the processing times of tasks affect the number of intervals created and their lengths and idle times of the resources.

Human-robot collaboration is one of the main research areas, where it plays a vital role in manufacturing systems, and it introduces to the industry 4.0. Even so, the human-robot collaboration leads to reduce to use of the workers in the system, which increases the unemployment rate.

Several issues should be taken into account for future research, such as developing meta-heuristics, heuristics, and mathematical models for solving different sizes of problems, considering the task allocation in the assembly line with the different number of workstations, and minimizing the idle times for the resources in the system.

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