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The Development of Human-Robot Collaborative Assembly Line Model by Considering Availability of Robots, Tools, and Setup Time

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Abstract. *This research develops a design model of a human-robot collaboration assembly line by taking into account the number of robots, tools, and setup time. The objective function of the proposed mixed integer linear programming model is to minimize cycle time. The results of model testing utilizing various scenarios reveal that the number of available robots, tools, and setup time can all have an impact on the assignment of assembly tasks at workstations. In other words, the suggested model takes into account the practical constraints of human-robot collaboration assembly line design. Further research will be conducted to build efficient algorithms for identifying solutions that take into account the assembly line in companies with a significant number of assembly tasks.*

Keywords: *assembly line balancing, human-robot collaboration, cycle time*

I. INTRODUCTION

The assembly line has enabled mass manufacturing in the industry. Assembly line designs are broadly classified into two groups. Type I involves combining numerous assembly tasks into a workstation with a specific cycle time as the primary goal, whereas Type II includes grouping several assembly tasks into a limited number of workstations (Boysen et al., 2007).

For both Type I and Type II assembly lines, an analytical model or heuristic algorithm is used to solve the allocation of assembly tasks in each workstation. Walter (2021), for example, created an analytical model to balance a load of a Type I assembly line using a combination of branch and bound and dynamic programming, whereas Michels (2020) employed decomposition techniques for a Type II assembly line. These analytical models indicate that the assembly line design problem is an NP-hard problem, which means that the solution space grows exponentially with the number of assembly tasks. As a result, for both Types I and II, the assembly line design is likewise carried out using a heuristic method for a high number of assembly tasks (Baskar & Anthony Xavior, 2020; Lalaoui & el Afia, 2019). Another method of designing assembly lines is to undergo a process of enhancing work procedures to increase assembly line performance (Dias et al., 2019; Larasari et al., 2020; Parvez et al., 2017). Methods for improving assembly line efficiency essentially identify non-add values to streamline the cycle time of each workstation.

Production trends show a shift away from mass production and toward mass customization. The implication of the mass customization trend, there are more product varieties and shorter product life cycles. As a result, the assembly line must be adaptable to product variations and must be simple to reconfigure once a new model is placed into production. Using Collaborative Robots (Cobot) on the assembly line is one strategy for dealing with the frequency of changes on the assembly line (Olivares-Alarcos et al., 2022).

A cobot is a robot that can operate independently or together with humans safely (Djuric et al., 2016). This is possible because the

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cobot has a safety feature to detect if the movement of the cobot will collide with the operator or an object (Hanna et al., 2022). Thus, the cobot will move or stop the movement automatically to fulfill safety conditions in real-time mode. In addition, cobots are easier to program through various multi-modal so there is no need for a detailed coding process found in conventional robots (Wang et al., 2019). Other advantageous usages of cobots in collaboration with humans increase the flexibility of the assembly line (Knudsen & Kaivo-oja, 2020; Land et al., 2020). For example, using cobots to tighten bolts and nuts is faster and consistently tightens for the required torque. In other cases, human is more flexible in some assembly operations, such as orienting and mating two or more assembly parts. Aside from these various assembly operations, there is the possibility of assembly collaboration, in which the cobot acts as a jig to hold the workpiece and the human executes the assembly process on the product. In this case, the human and cobot are collaborating to complete an assembly task. Taking into account these various alternatives to using humans, robots, or human-robot collaboration will have varying effects on assembly time and assembly operational costs (Weckenborg & Spengler, 2019).

This study focuses on the design of assembly lines that use humans, robots, and human-robot collaboration as alternative resources to perform assembly tasks. The fundamental distinction between the human-robot collaboration assembly line (ALHRC) design and the Type I and Type II assembly line models is the requirement for task sequencing. Task sequencing not only fulfills the precedence constraint but also fulfills the possibilities of two conditions: 1) human and cobot may undertake two separate assembly tasks at the same time, and 2) human-robot collaboration can take place if both human and cobot are idle at the start of an assembly operation.

ALHRC is often designed by modifying the Type I or Type II model by including additional decisions, restrictions, or/and optimization targets. In the case of ALHRC, technologies that aid the cobot's operation should be considered when deciding the best strategy. One technological characteristic explored in this research is the cobot's capacity to do numerous assembly operations using various appropriate tools. The cobot will exchange the appropriate tool to execute a certain task.

To date, research that analyzes collaboration between human and robot such as Ranz (2017), Dalle (2019), and Weckenborg (2020), has not included the change of tools in the assembly process. However, using cobots on the assembly line necessitates the employment of several tools for specific jobs (Aaltonen et al., 2018; Universal Robots, 2022). The term "tools" in this study refers to any equipment affixed to the end of a robot arm. For example, if a welding job is assigned, the end of the robot arm is hooked to a welding torch.

Weckenborg (2020) proposed an assembly line design model to minimize cycle time. As parameters, the model includes the upper bound cycle time and the maximum number of robots. Nugraha (2021) has improved on Weckenborg's model by considering the number of tools accessible to execute various assembly tasks. The Nugraha model's objective function is to decrease ALHRC's operating costs, which is appropriate for reasonably long-run production because the suggested model allows for investment in additional cobots or tools. Yaphiar (2020) expanded on the Nugraha paradigm by having the ALHRC assemble several product mixes on a single assembly line. The suggested model also serves as an analytical model for reducing assembly line operational expenses.

The use of cobots on the assembly line allows for greater flexibility because a single cobot can perform multiple jobs by changing tools. Tool changes can be performed automatically, however, this tool change takes time. In other words, changing the tools on the cobot will cause the setup time to be triggered. Aghajani (2014) created a robot-based assembly line design model that takes setup time into account, but the model is not on the human-robot collaboration track. Setup time is triggered by conventional setup activities found in the application of conventional robots.

Based on the previous studies, as well as discussions with engineers from industries that use cobots, ALHRC implementation is frequently found to 1) the goal of reducing cycle time, 2) the number of robots and tools are limited, and 3) the setup time for tools should be addressed. As a result, the purpose of this research is to develop a human-robot collaboration assembly line design model to minimize cycle time while taking into account practical constraints such as the number of robots available, the number of tools accessible, and the setup time between tool change. The next chapter will go into the research methods as well as the scenarios created to put the suggested model to the test. The numerical results of the assembly line design based on various scenarios will be described in Chapter III, and the benefits of the suggested model will be analyzed. This paper will conclude with closing remarks and future research goals.

II. Research Method

This study used the Weckenborg model as the primary reference model development (Weckenborg et al., 2020). Furthermore, the constraints related to the number of tools and setup time are a combination and modification of the Cahyadi model (2021) and the Alghajani model (2014). Other assembly line design parameters included in the model are the number of assembly tasks and assembly precedence requirements.

The notation used in the model is as follows.

I	Set of task
K	Set of workstation
P	Set of alternative resources
E	Set of precedence diagram
G	Set of *tools* for task *i*
$\bar{c}$	Maximum cycle time
Q	Number of available robots
t_i	Operation time to conduct task *i*
γ_g	Tool type *g*
N	Number of available tools
ς	Setup time
ς_{0ip}	Setup times for the first operation
ς_{ijp}	Setup times between task i and task j
x_{ikp} ={	1, if task *i* is assigned at workstation *k* using resource *p* 0, otherwise
r_k ={	1, if a robot is assigned at workstation *k* 0, otherwise
y_{ij} ={	1, if task *i* is conducted prior to task *j* 0, otherwise
z_i	Workstation which task *i* is assigned
s_i	Starting time of task *i*
c	Cycle time

The model provided in this work has 18 constraints, 15 of which are from Weckenborg (2020), one from Nugraha et al. (2021), and two constraints from Alghajani (2014). The developed model can be explained below. Equation (1) represents the model's objective function, which is to minimize the cycle time of each workstation that executes a series of assembly tasks using a specific resource (ex: human, robot, or human-robot collaboration). Equation (2)-(4) is the determinant of the decision variable and ensures that each job is only performed at one specific workstation utilizing one specific resource while minimizing the cycle time. If the task is conducted using a robot or human-robot collaboration, Equations (3) is modified to account for the setup time if a tool change is required. The precedence restriction in the assembly process is ensured by Equations (5)-(6). The sequencing procedure is represented by Equations (7)-(11). Human and robot can be assigned to do different tasks independently at the same time. If both the human and the cobot are idle, they can be assigned to collaborate on a certain task. Equation (12) ensures that the human-robot collaboration could only be assigned if the robot is available at the designated workstation. Equation (13) represents the robot's tool restriction which was adopted from the Nugraha (2021) model. The equation is further modified to account for setup time if different tools are used between tasks. Equation (14) represents the number of available robots. Equation (15) is a sequencing procedure within a workstation that guarantees no tasks are done using the same resources at the same time. Decision variables

$$\boldsymbol{Minimize\ \ c} \tag{1}$$

Subject to:

$$\sum_{k\,\epsilon\,K}\sum_{p\,\epsilon\,P} x_{ikp} = 1 \ \ ; \ \ \forall i\,\epsilon\,I, \tag{2}$$

$$s_i + \sum_{k\,\in K}\sum_{p\,\in P}(t_{ip} + \varsigma_{0ip} + \varsigma_{ijp}).\,x_{ikp} \le c \ \ ; \ \ \forall i\,\epsilon\,I, \tag{3}$$

$$\sum_{k\,\epsilon\,K}\sum_{p\,\epsilon\,P} k \cdot x_{ikp} = z_i \ \ ; \ \ \forall i\,\epsilon\,I, \tag{4}$$

$$s_i + \sum_{k\epsilon K}\sum_{p\epsilon P} t_{ip} \cdot x_{ikp} \le s_j + \bar{c}(z_j - z_i) \ ; \ \forall(i,j)\,\epsilon\,E, p\epsilon\{p^H\} \tag{5}$$

$$s_i + \sum_{k\epsilon K}\sum_{p\epsilon P}(t_{ip} + \varsigma_{ijp}) \cdot x_{ikp} \le s_j + \bar{c}(z_j - z_i); \ \forall(i,j)\epsilon\,E, p\epsilon\{p^R, p^C\} \tag{6}$$

$$s_i + t_{ip^C} \cdot x_{ikp^C} \le s_j + \bar{c}\left(1 - \textstyle\sum_{p\epsilon P} x_{jkp}\right) + \bar{c}\left(1 - x_{ikp^C}\right) + \ \bar{c}\left(1 - y_{ij}\right); \tag{7}$$
$$\forall i, j\ \epsilon\ I, k\epsilon K,$$

$$s_i + \sum_{p\in P} t_{ip^H} \cdot x_{ikp^H} \le s_j + \bar{c}\left(1 - x_{jkp^C}\right) + \bar{c}\left(1 - y_{ij}\right) \ \ ; \ \forall i,j\ \epsilon\ I, k\epsilon K \tag{8}$$

$$s_i + \sum_{p\in P}(t_{ip^R} + \varsigma_{ijp}) \cdot x_{ikpR} \le s_j + \bar{c}\left(1 - x_{jkp^C}\right) + \bar{c}\left(1 - y_{ij}\right); \ \ \forall i,j\ \epsilon\ I, k\epsilon K, \tag{9}$$

$$s_i + t_{ip} \cdot x_{ikp} \le s_j + \bar{c}\left(1 - x_{ikp}\right) + \bar{c}\left(1 - x_{jkp}\right) + \bar{c}\left(1 - y_{ij}\right); \ \forall i,j\ \epsilon\ I, k\epsilon K, p\epsilon\{p^H\}, \tag{10}$$

$$s_i + (t_{ip} + \varsigma_{ijp} \cdot x_{ikp} \le s_j + \bar{c}\left(1 - x_{ikp}\right) + \bar{c}\left(1 - x_{jkp}\right) + \bar{c}\left(1 - y_{ij}\right); \tag{11}$$
$$\forall i,j\ \epsilon\ I, k\epsilon K, p\epsilon\{p^R\},$$

$$x_{ikp} \le r_k \quad \forall i\ \epsilon\ I, k \in K, p \in \{p^R, p^C\} \tag{12}$$

$$\sum\sum_{g\epsilon G}((\gamma_{gijkp^R}.\,x_{ikp^R}) + (\gamma_{gikp^C}.\,x_{ikp^C}) \le N\ ; \quad \forall i,j\ \epsilon\ I,\ k \in K, p\epsilon\{p^H, p^R\} \tag{13}$$

$$\sum_{k\in K} r_k \le q, \tag{14}$$

$$y_{ij} = 1 - y_{ji}\ ; \ \ \forall i,j\ \epsilon\ I, i < j \tag{15}$$

$$x_{ikp} \in \{0,1\} \ ; \ \forall i\ \epsilon\ I, k \in K, p \in P \tag{16}$$

$$s_i, z_i \ge 0\ ; \ \ \forall i\epsilon\ I, \tag{17}$$

$$r_k \ge \{0,1\} \ \ \forall k \in K, \tag{18}$$

$$y_{ij} \in \{0,1\} \ \ \forall i,j \in I, i \ne j. \tag{19}$$

and non-negative variables are defined by Equations (16) - (19).

Table 1. Parameter setting.

Parameter	Value
No. of workstation (K)	3
Max. no. of robot (q)	1
Max. cycle time ($\bar{c}$)	M

The numerical data for the experiment are gathered from Weckenborg to validate the model construction and analysis (Weckenborg et al., 2020). As indicated in Table 1, the data covers the maximum number of workstations, the number of available robots, and the maximum cycle time. Table 2 and Figure 1 show the assembly task data, which includes the operating time data for each resource used, as well as the precedence diagram.

The number M appears in Table 1 and Table 2, indicating a large number. The value M indicates that a job cannot be completed using the associated resource.

Table 2. Processing Time.

Task	Human (H)	Robot (R)	H-R Collaboration
1	8	M	6
2	7	10	5
3	6	M	M
4	4	M	3
5	5	11	4
6	6	M	M
7	5	11	4
8	4	M	M
9	7	M	5
10	5	11	4

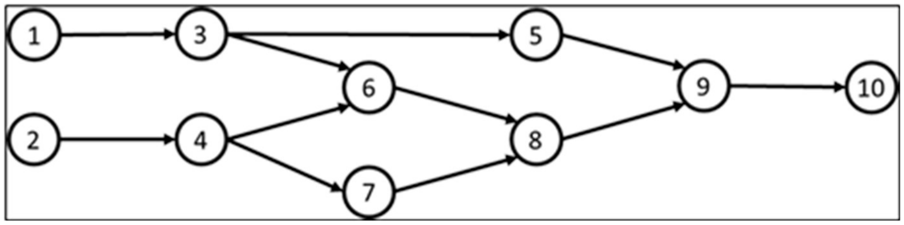

Figure 1. Precedence diagram

In this study, three scenarios will be carried out. Scenario 1 examines the impact of the number of tools accessible. In situations 1a and 1b, the number of tools accessible is two and one, respectively. Scenario 2 examines the impact of setup time. In situations 2a and 2b, the setup time is a one-time unit and two-time unit, respectively. Scenario 3 examines the impact of the number of robots accessible. The number of robots in situations 3a and 3b is two and three, respectively.

III. RESULTS AND DISCUSSION

Additional data is utilized to test the established model, in addition to the hypothetical data provided in the previous chapter. Table 3 shows the tools that the cobot utilized to do specific tasks. For example, if task 7 is performed by a robot, tool number 4 will be used, while tool number 3 will be used if task 7 is performed by human-robot collaboration.

CPLEX Studio solver is used to compute the proposed scenarios. An example of the computation result is shown in Figure 2. The result from the solver consists of three decision variables: 1) assignment of task 2) allocation of robots and 3) assembly task sequences. Verification of the model is conducted by checking the decision variables are valid to each constraint in the proposed model. The following subsection will go through numerical calculations and discussions of each scenario.

Scenario 1

Scenario 1a set the number of accessible tools to two. The optimum cycle time is 17-time units and a robot is assigned at workstation 1 as shown in Figure 2. Task 1 uses tool no 1 and task 4 is carried out using human-robot collaboration. Therefore, in the optimal solution, the robot has a time slack of 4 units of time to wait for the availability of the human.

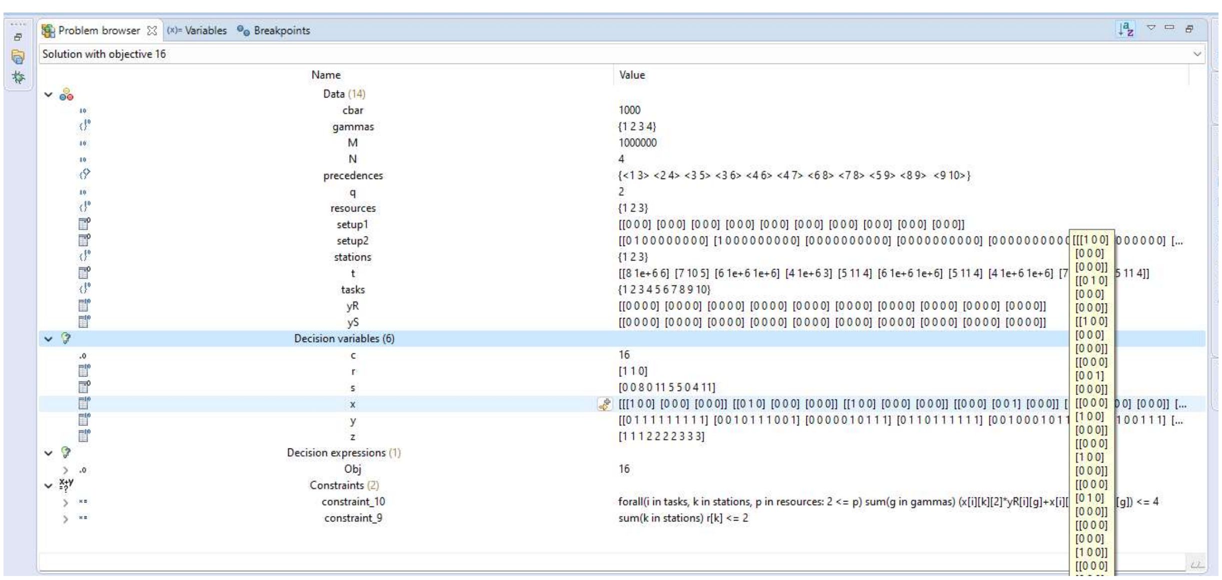

Figure 2. Computational output example

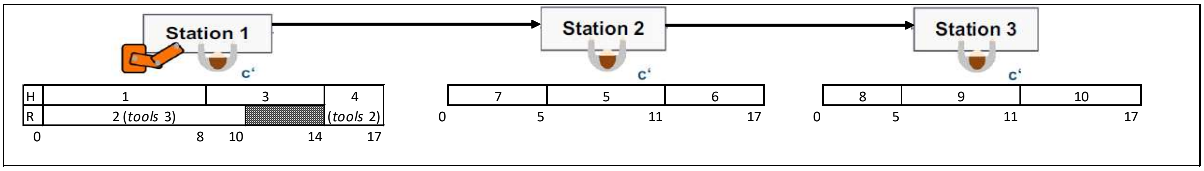

Figure 3. Scenario 1a: number of available tool = 2.

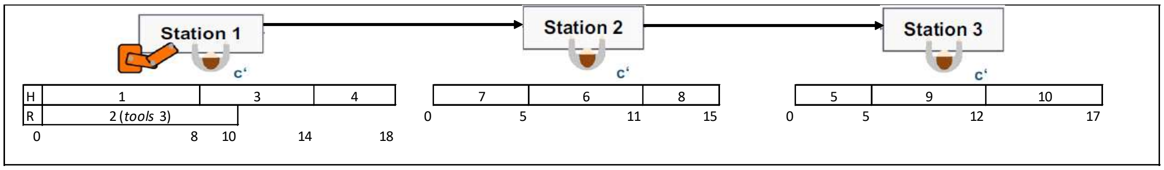

Figure 4. Scenario 1b: number of available tool = 1.

Table 3. Usable tools

Task No.	Tool No. for Robot				Tool No for Human-Robot			
	1	2	3	4	1	2	3	4
1					√			
2							√	
3			√					
4						√		
5		√						
6								
7				√			√	
8								
9								√
10	√					√		

Scenario 1b set the number of tools to one. The optimum cycle time is 18-time units, and workstation 1 is assigned one cobot, as shown in Figure 4. By restricting the number of tools to one, the cycle duration increases, and the efficiency of line balancing between stations decreases. As a result, the amount of accessible tools influences ALHRC design. As an example of a realistic application, a robot with two distinct tools is assigned to carry out two distinct assembly tasks. For example, the screwing and picking processes require separate instruments. The first tool is an end-effector that holds an electric screwdriver, and the second tool is a gripper that holds a specific part assembly.

Scenario 2

Scenario 2 is configured to test the impact of setup time between tool changes in ALHRC design. In Scenario 2a, the setup time is set to one unit of time. The optimum cycle time is 17 unit times, as shown in Figure 5. Tool number 3 has been allocated to Task 2. The overall operating time includes one unit of setup time. Scenario 2b increased the setup time to two units

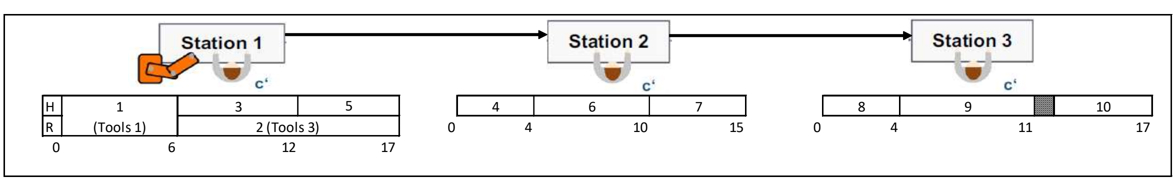

Figure 5. Scenario 2a: Setup time = 1.

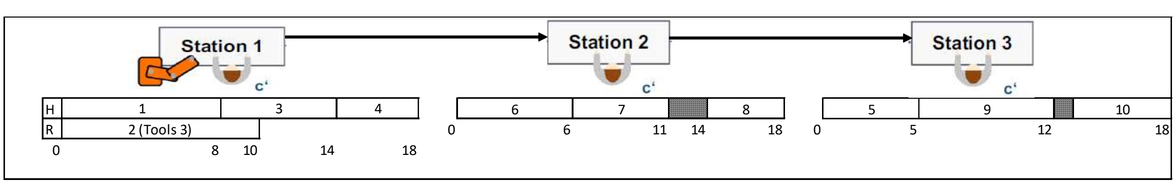

Figure 6. Scenario 2b: setup time = 2.

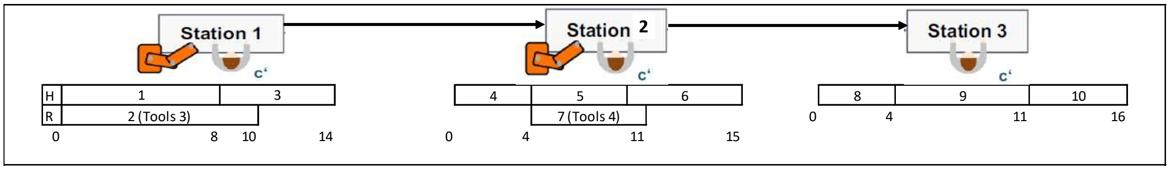

Figure 7. Scenario 3a: number of available tool = 2 units.

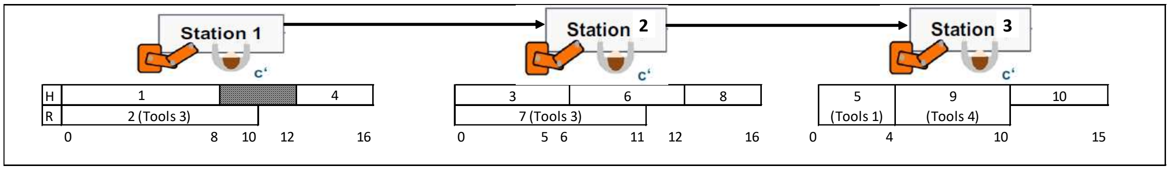

Figure 8. Scenario 3b: number of available tool = 3 units.

of time. The optimum cycle time is 18 units of time, as shown in Figure 6. With the rise in setup time, there has been a shift in work assignments. Task 1 was allocated using human-robot collaboration in scenario 2a, however, the task is assigned to humans.

Based on the outcomes of scenarios 2a and 2b, it is demonstrated that setup time can have an impact on the assembly line design solution. Tool changes take time in the industrial use of cobots. As a result, setup time must be factored into the assembly line design.

Scenario 3

Scenario 3 considers the impact of the assembly line's maximum number of robots. This component is significant since a specific number of robots have been invested in industrial applications.

Scenario 3a limits the number of robots by two. The optimal cycle time achieved with the task allocation given in Figure 7 is 16 units of time. Scenario 3b restricts the number of robots owned to three. The optimal cycle time achieved with the task allocation given in Figure 8 is 16 units of time.

When the outcomes of scenarios 3a and 3b are compared, the same cycle time, 16 units of time, is attained, but with different human-robot assignment arrangements. To put it another way, adding more cobots does not always result in a shorter cycle time but may imply different task assignments.

Implication of the proposed model

In the previous section, numerical examples of three scenarios were performed. The numerical examples are utilized to validate the advantages by considering practical limitations such as the number of robots available, the number of tools accessible, and the setup time between tool changes. If the number of tools is limited to one and setup time is set to zero, the proposed model will result in an identical optimal solution as Weckenborg's model.

The model proposed in this study is a mixed integer programming model with NP-hard properties. Previous experiments attempt to compute ALHRC having assembly tasks more than 25. The computational time required surpassed 24 hours, and no optimal solution was found. As a result, an efficient heuristic algorithm must be developed for the suggested model to be applied in the industry.

IV. CONCLUSION

This study developed a model for human-robot collaboration assembly lines that takes into account the number of robots available, the number of tools accessible, and the setup time. The model's output is in the form of allocating tasks to stations and determining the resources needed to execute each work using humans, robots, or human-robot collaboration. Furthermore, the model defines the sequencing task in each station. Model testing reveals that the number of robots, tools, and setup time are all practical constraints that impact the ALHRC design solution. Further research will be conducted to design a heuristic method to solve ALHRC with a high number of assembly tasks.

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