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2-Stage Design for a Hybrid Assembly Line with Humans and Robots Considering Automation Difficulty Level: Case Study of the Electrical Equipment Assembly Line

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Abstract

Labor force in the manufacturing industry has declined with an aging society, and from a labor-saving perspective, automation using robots is expected for assembly lines. However, there are many tasks on an assembly line; while some such tasks can become easily automated using robots, others are hard to automate due to different automation difficulty levels. Therefore, with the automation difficulty level in mind, a line design is required to configure both human and robot contributions. This study applies a 2-stage design to an actual case in an electrical equipment assembly line and analyzes a hybrid assembly line design with humans and robots that considers automation difficulties from manual work. In the first stage, all tasks are selected as either human or robot tasks, based on the automation difficulty level and the automation rate of the line, using 0-1 integer programming. In the second stage, a line balancing problem is calculated by 0-1 integer programming to minimize the numbers of stations. Subsequently, numerical experiments are solved on the actual electrical product manufacturing line with a commercial solver. As a result, a line design is obtained with a short idle time and a small fluctuation for the time among assembly stations.
Keywords: Cyber physical systems, Task selection, Line balancing, Human–Robot integrations, 0-1 integer programming

1 Introduction

In the manufacturing industry, businesses are competing intensely over product quality amidst accelerating technological innovation. The available numbers of employees have been decreasing due to an aging society, especially in Japan. The use of automated machines and robots has been increasingly expected to solve the issue of labor shortages [1]. Under such circumstances, the rational introduction of industrial robots and manufacturing equipment has been proposed, and utilization in actual factory sites has been implemented [2].

With regards to the assembly line in particular, automation has not progressed and manual work still remains. One reason for this is that automation investment requires a large facility installation cost, and the return on investment is a significant concern [3]. The primary goal of promoting automation is reducing production costs by means of labor savings, and thus if labor

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cost savings are not clear, automation planning does not progress from a managerial perspective. Therefore, it is necessary to design an assembly line by considering the automation cost effectiveness; an economical hybrid assembly line is required, where both humans and robots are assigned to assembly tasks simultaneously.

In actual automation planning, production and equipment engineers often proposes a line design plan based on their experience. For this reason, in many cases, line design procedure and the proposal levels are not systematic and person-dependent. Thus, one of line design issues is difficulty to communicate to related organizations.

There are previous studies on the design methods of automated assembly lines; Izumi [3] presented basic ideas for promoting the automation concept. Additionally, numerous studies have been developed for solving the economical design in assembly lines as a line balancing problem [4], which are methods to balance the workloads among workstations in a manufacturing line. Pinto, Dannenbring and Khumawala [5] proposed a method to minimize the total cost, including both equipment and labor costs. Hazira, Delorrneh and Dolgui [6] presented a review paper that solved the assembly and transfer line balancing problems in terms of cost and profitability. Çil, Mete and Agpak [7] studied the robotic assembly line balancing (RALB) problem assuming that only robots could perform a task at each station. With regards to an actual line design work, there are some cases where it is difficult to automate some of the manual work by using a robot, owing to automation technological and cost difficulties. Thus, another design issue is that there may be cases wherein information on equipment introduction costs cannot be obtained in advance. Furthermore, Lopes et al. [8] treated a line balancing problem of spot welding manufacturing lines using robots and solved a case in a real-world car factory. However, the case study assigning multiple tasks to robots only were already laid out, and it did not provide a method for assigning tasks to both humans and robots.

In order to resolve these issues, Miyauchi and Yamada [9] proposed a hybrid assembly line design procedure considering the automation difficulty level. However, they did not formulate the design procedure with mathematical programming; thus, optimal solutions could not be found. Furthermore, line design based on engineer's experience that is not formulated, could lead to different solutions by different planners. To solve this problem, Miyauchi and Yamada [10] proposed a design method for a hybrid assembly line with the objectives for minimizing the sum of automation difficulty level and the total assembly time. In the first stage, all tasks are selected as human or robot task based on the automation difficulty level and total assembly time. In the second stage, a line balancing problem is solved by integer programming to minimize the number of stations. The reason why the minimizing the total assembly time is that reducing the total assembly time brings more alternatives for assigning tasks for a given cycle time constraint.

On the other hand, at actual manufacturing sites, it is expected to automate more tasks not only to reduce costs through labor-saving, but also to stabilize production quantity and quality, reduce painful tasks for workers, ensure safety, and promote factory IoT. Therefore, as actually designing a hybrid assembly line, it is required to avoid automation of difficult tasks and to automate more tasks simultaneously [2][3]. Focusing on these requirements, Miyauchi, Yamada and Sugi [11] proposed a 2-stage design method for a hybrid assembly line considering the automation difficulty level and the automation rate of the line.

This study applies the 2-stage assembly line design method with humans and robots considering the difficulty of work automation [11] to a case study in which a manual assembly line was already in operation. The design method consists of two stages. In Stage 1, each task is selected as either a human or robot task considering the automation difficulty level and the automation rate of the line. In Stage 2, line balancing is carried out to minimize the numbers of stations based on task selection in Stage 1. The respective stage is solved using integer programming (0-1 IP) [12].

The remainder of this paper is organized as follows. Section 2 shows an overview of 2-stage assembly design method and defines notation and assumptions. In Section 3, the design problem at each stage is formulated as 0-1 IP. Section 4 prepares an actual case for electrical product manufacturing line with 42 tasks as a case study. In Section 5, a commercial solver is used for the numerical experiments, and resulted designs are discussed. Finally, Section 6 concludes this study and mentions future works.

2 2-stage Assembly Design Method Considering the Automation Difficulty Level

2.1 Overview of 2-stage assembly design method

This section explains a 2-stage method for a hybrid system with humans and robots considering the automation difficulty level, as shown in Figure 1 [11]. The 2-stage design method for assembly lines were proposed and analyzed in previous studies [13][14]. Moreover, the 2-stage design method was also adopted to disassembly lines [15][16][17][18]. The 2-stage assembly design method in this study is to solve the assembly line balancing using 0-1 IP after all tasks are selected as a human or robot task at Stage 1.

In Stage 1, all tasks are selected as either human or robot tasks in three steps. First, the assembly time and automation difficulty level of each task are surveyed [9]. Next, each task is selected as either a human or robot task by 0-1 IP with ε constraint [19] method for maximizing the automation rate for the line and for minimizing the automation difficulty level. The bi-objective functions in Stage 1 are to maximize the automation rate for the line and to minimize the sum of the automation difficulty level when each task is selected as either a human or a robot task. The reason for maximizing the automation rate for the line is that it is expected to automate more tasks from the perspective of reducing costs by saving manpower and relaxing hard manual work, stabilizing production quantity and quality, and ensuring workers' safety and IoT in manufacturing [1]. The definition of the automation rate is different across companies and processes. Fujimoto [20] classified the definitions of automation rate into four categories: machine-based definition, worker-based definition, material-based definition and process-step-base definition. Since this study focuses on the automation of each task, the process-step-based definition is referred to. Thus, in this study, the automation rate for the line is defined as the rate of the numbers of automated tasks to the total numbers of tasks in the assembly line.

Moreover, humans and robots have different assembly times for each task, and therefore, selecting each task as either a human or a robot task also affects the total assembly time. Further, the reason for minimizing the total automation difficulty level is to avoid high automation costs and failure risks. Finally, assembly precedence relationship diagrams are developed using the results of task selection.

In Stage 2, the assembly line balancing problem is defined to minimize the numbers of stations. Next, the assembly line balancing problem is solved using 0-1 IP with the given cycle time, and finally, the result of the line design is evaluated.

It is noted that the robot in this study refers to a system that can work on assembly tasks performed by humans. Specifically, a system integrating originally industrial robots is introduced with some devices such as end effectors and parts supply units [21].

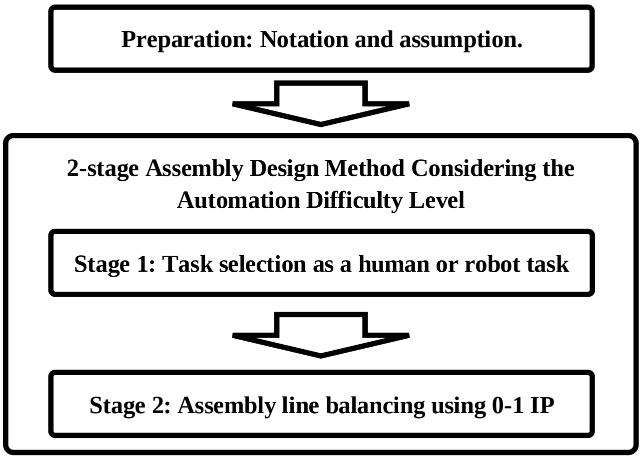


Figure 1: Overview of 2-stage assembly design method [11].

2.2 Notation and assumptions

A summary of the notations used in this study is shown below:

・Sets and indices

J : Set of tasks
J_{human} : Set of tasks selected as human task at Stage 1
J_{robot} : Set of tasks selected as robot task at Stage 1
P_j : Set of tasks that immediately precede task j

・Parameters

i : Index for the predecessors of task j
j : Index of tasks (j =1, 2,…, N.)

<< Stage 1: Task selection as a human or robot task >>

ad_j : Automation difficulty level of task j
$TD_{\max}$: Maximal total automation difficulty level for assembly
ε_{TD} : Constraint of total automation difficulty level for assembly

TT_{h} : Total assembly time of human tasks
TT_{r} : Total assembly time of robot tasks
K_0 : Total numbers of necessary stations without allocating human or robot stations
$K_{0\mathrm{h}}$: Total numbers of necessary human stations
$K_{0\mathrm{r}}$: Total numbers of necessary robot stations
$K_{0\mathrm{L}}$: Sum of necessary stations (= $K_{0\mathrm{h}}$ + $K_{0\mathrm{r}}$)

<< Stage 2: Assembly line balancing using 0-1 IP >>

k : Index of stations (k = 1, 2, 3, …, K.)
CT : Cycle time
$t_{\mathrm{robot}\ j}$: Assembly time of task j by a robot
$t_{\mathrm{human}\ j}$: Assembly time of task j by a human
st_k : Binary value; 1 if station k is a robot station, otherwise 0
$t_{\max}$: Maximal total assembly time among all stations
t_k : Total assembly time at station k

・Decision variables

<< Stage 1: Task selection as a human or robot task >>

x_j : Binary value; 1 if task j is selected as a robot task, otherwise 0

<< Stage 2: Assembly line balancing using 0-1 IP >>

y_{kj} : Binary value; 1 if task j is assigned to station k, otherwise 0

・Evaluation indices

TA : Automation rate for the line
TD : Total automation difficulty level
TT : Total assembly time (= TT_{h} + TT_{r})
K : Total numbers of assembly stations
BL : Balance loss
SI : Smoothness index

Assumptions for the formulation in this study are shown below:

- All tasks are selected for either human or robot task.
- All stations are set up as either robot or human.
- All human tasks must be assigned to human stations, and all robot tasks must be assigned to robot stations.
- Any task is not assigned to more than one station.
- If there is a precedence relation between tasks j and i, task i must not be assigned to a station earlier than the station that is to perform task j.

- The total assembly time of any stations do not exceed a given cycle time.

3 Formulations

3.1 Stage 1: Task selection as a human or robot task

Based on [11], the bi-objective functions in Stage 1 are set to maximize the automation rate for the line and to minimize the total automation difficulty level when each task is selected as either a human or a robot task. The following 2-stage formulation for assembly lines are based on the previous studies on disassembly line design [15][16][17][18].

In Stage 1 the automation difficulty levels are firstly introduced to evaluate the automation difficulty for each manual work task. Secondly the task is selected by 0-1 IP for either the human or the robot. The automation difficulty level [9] is defined as the necessity for the development of elemental technologies and the system development man-hours required using elemental technologies.

The objective functions for maximizing the automation rate in the line and for minimizing the sum of automation difficulty levels are set as Equations (1) and (2), respectively.

$$TA = \sum_{j=1}^{|J|} \frac{x_j}{|J|} \rightarrow Max \tag{1}$$

$$TD = \sum_{j=1}^{|J|} ad_j x_j \rightarrow Min \tag{2}$$

s.t.

$$TD \leq \varepsilon_{\mathrm{TD}} \tag{3}$$

$$TD_{\max} = \sum_{j=1}^{|J|} ad_j \tag{4}$$

$$x_j = \{0,1\} \qquad j \in J \tag{5}$$

This bi-objective optimization is calculated by changing the value of $\varepsilon_{\mathrm{TD}}$ using the ε constraint method [19]. After calculating the whole constraint value of $\varepsilon_{\mathrm{TD}}$, the Pareto optimal solutions are obtained. Thus, Inequality (3) represents the ε constraint to minimize the total automation difficulty level for assembly TD. Therefore, the automation rate for the line TA is regarded as only one objective function by using the ε constraint method. Equation (4) expresses the maximal automation difficulty level $TD_{\max}$. Equation (5) indicates that all tasks are selected as either human or robot tasks.

In Stage 1, all tasks are selected as either human or robot tasks. Therefore, human and robot tasks are set as Equation (6).

$$J = \{J_{\mathrm{robot}} \cup J_{\mathrm{human}}\}$$
$$where \quad J_{\mathrm{robot}} \cap J_{\mathrm{human}} = \Phi \tag{6}$$

Additionally, the total assembly time of human tasks TT_{h} and the total assembly time of human tasks TT_{r} are set as Equations (7) and (8), respectively. Hence, the total assembly time TT is the sum of TT_{h} and TT_{r} and set as Equation (9).

$$TT_{\mathrm{h}} = \sum_{j=1}^{|J|} t_{\mathrm{human}\ j}\,(1 - x_j) \tag{7}$$

$$TT_{\mathrm{r}} = \sum_{j=1}^{|J|} t_{\mathrm{robot}\ j}\, x_j \tag{8}$$

$$TT = TT_{\mathrm{h}} + TT_{\mathrm{r}} \tag{9}$$

Furthermore, the total numbers of necessary human stations $K_{0\mathrm{h}}$ are calculated by dividing TT_{h} by CT and rounded to the nearest minimal integer above, as Equation (10). Similarly, the total numbers of necessary robot stations $K_{0\mathrm{r}}$ are obtained using Equation (11). Hence, the sum of necessary stations $K_{0\mathrm{L}}$ are the sum of $K_{0\mathrm{h}}$ and $K_{0\mathrm{r}}$, and is set as Equation (12). For comparison to the conventional line balancing problem, K_0 is set as Equation (13). K_0 is the total numbers of necessary stations calculated from CT and TT without considering allocated as human or robot stations [4].

$$K_{0\mathrm{h}} = \left\lceil \frac{TT_{\mathrm{h}}}{CT} \right\rceil \tag{10}$$

$$K_{0\mathrm{r}} = \left\lceil \frac{TT_{\mathrm{r}}}{CT} \right\rceil \tag{11}$$

$$K_{0\mathrm{L}} = K_{0\mathrm{h}} + K_{0\mathrm{r}} \tag{12}$$

$$K_0 = \left\lceil \frac{TT}{CT} \right\rceil \tag{13}$$

3.2 Stage 2: Assembly line balancing using 0-1 IP

Line balancing is a traditional formulation of the assembly system design problem [4]. In assembly line balancing at Stage 2, the objective function is set as Equation (14) in order to minimize the total numbers of assembly stations with a given cycle time.

$$K = \sum_{k=K_{0L}+1}^{K} k y_{k\,|J_{\mathrm{robot}} \cup J_{\mathrm{human}}|} \quad \rightarrow Min \tag{14}$$

s.t.

$$\sum_{k=1}^{K} y_{kj} = 1 \quad j \in \{J_{\mathrm{robot}} \cup J_{\mathrm{human}}\} \tag{15}$$

$$\sum_{k=1}^{K} k y_{ki} - \sum_{k=1}^{K} k y_{kj} \leq 0 \qquad i \in P_j, \quad j \in \{J_{\mathrm{robot}} \cup J_{\mathrm{human}}\} \tag{16}$$

$$\sum_{j \in J_{\mathrm{robot}}} t_{\mathrm{robot}\,j}\, y_{kj} \leq CT \quad k = 1, \cdot \cdot \cdot, K \tag{17}$$

$$\sum_{j \in J_{\mathrm{human}}} t_{\mathrm{human}\,j}\, y_{kj} \leq CT \quad k = 1, \cdot \cdot \cdot, K \tag{18}$$

$$\sum_{j \in J_{\mathrm{robot}}} y_{kj} \leq st_k \times |J_{\mathrm{robot}}| \qquad k = 1, \cdot \cdot \cdot, K \tag{19}$$

$$\sum_{j \in J_{\mathrm{human}}} y_{kj} \leq (1 - st_k) \times |J_{\mathrm{human}}| \qquad k = 1, \cdot \cdot \cdot, K \tag{20}$$

$$y_{kj} = \{0,1\} \qquad k = 1, \cdot \cdot \cdot, K, \quad j \in \{J_{\mathrm{robot}} \cup J_{\mathrm{human}}\} \tag{21}$$

$$st_k = \{0,1\} \qquad k = 1, \cdot \cdot \cdot, K \tag{22}$$

To balance the assembly line, Constraint (15) requires that each task be assigned to exactly one station. The precedence constraint is set as Constraint (16); this constraint implies that if $i \in P_j$, task i cannot be assigned to a station that precedes task j. The cycle time constraint of the robot station is set as Constraint (17), which indicates that the total assembly time of the robot station does not exceed the cycle time. Similarly, the cycle time constraint of the human station is set as Constraint (18). Constraint (19) shows the results of task selection as a robot task in Stage 1. Similar to Constraint (19), Constraint (20) shows the results of task selection as human task in Stage 1. Constraint (21) does not allow a task to be assigned to more than one station. Lastly, Constraint (22) indicates that all stations are either a robot or a human station.

3.3 Evaluation of the line design results using balance loss and smoothing index

The balance loss BL indicates the percentage of total idle time to product of CT and K, while the smoothness index SI shows a variation of the total assembly task time among assembly stations [22]. Both indices are used for line evaluations. The balance loss BL is calculated in Equation (23), and the smoothness index SI is obtained as Equation (24).

$$BL = \frac{K \times CT - TT}{K \times CT} \tag{23}$$

$$SI = \sqrt{\sum_{k=1}^{K} (t_{\max} - t_k)^2} \tag{24}$$

4 Design Problem

In this section, a design problem is prepared to evaluate the formulation in Section 3. An actual electronic equipment manufacturing line, which was already in manual operation, is used as an example. The factory staff developed this line plan to automate it by using robots; however, the staff pursued a reasonable automation strategy because automating all tasks also entail higher costs and machine failure.

4.1 Assumptions for the design problem

The following assumptions are made to apply the formulation in this study to the design problem.

- Assumptions for the production requirements;

- ●The target line is already running in manual operation. The factory staff plan to automate it by using robots.
- ●The type of product models is one.
- ●A cycle time is given based on the requirements of the demand quantity for a given planning horizon production.

- Assumptions for tasks;

- ●Automation difficulty levels of each task are known.
- ●Assembly time of each task by robot and human is constant and known. Additionally, the assembly time of same task varies by human or robot.
- ●Precedence relationships are known and combined into a single precedence diagram.

4.2 Introduction of automation difficulty levels

In order to manage automating the assembly line, it is effective to distinguish automation difficulty and know easy tasks by means of automation difficulty levels. Table 1 shows examples of various automation difficulty levels for tasks associated with each level [9]. In this case, the automation level of each task is divided into three groups: A, B, and C, in an order of increasing technical difficulty level.

For example, "A1: Simple transporting" and "A2: Simple assembling" use established technologies that can be realized relatively easily and can be purchased and introduced. Therefore, their difficulty levels are set as the automation difficulty level A. Next, "B1: Transporting complex shaped parts" and "B2: Assembling complex shaped parts" include complex tasks that cannot be handled by linear movements and are thus classified into difficulty level B. Finally, difficulty level C represents tasks which are the most difficult to replace humans with robots. This is because basic elemental technologies are needed to proceed and to automate these tasks. Therefore, "C1: Picking up bulk parts" and "C2: Connector connection" are classified into the difficulty level C.

Furthermore, in order to treat them by 0-1 IP, the automation difficulty levels A, B, and C in Table 1 correspond to automation difficulty levels ad_j = 0, 1, and 2, respectively.

Table 1: Examples of Automation Difficulty Levels [9]

Automation difficulty level		Task	
Symbol	Parameter	Symbol	Task description
A	0	A1	Simple transporting
		A2	Simple assembling
		A3	Lamination/ pasting
		A4	A type packing
		A5	Dispensing/Painting
		A6	Mixing and stirring
		A7	Screw tightening
		A8	Soldering
		A9	Measurement type inspection
		A10	Others
B	1	B1	Transporting complex shaped parts
		B2	Assembling complex shaped parts
		B3	Brazing/ welding
		B4	Pasting to uneven surface
		B5	Screw tightening in narrow areas
		B6	Assembling and processing with multiple degrees of freedom
		B7	Others
C	2	C1	Picking up bulk parts
		C2	Connector connection
		C3	Wiring routing
		C4	Multi-degree of freedom assembling of flexible objects
		C5	Sensory type inspection
		C6	Others

4.3 Actual example of precedence relationships among assembly tasks

Figure 2 shows the developed precedence relationships with an actual electronic equipment assembly line. It is assumed that the automation difficulty level and assembly time for each task are already surveyed and known, and that the assembly time for each task is different for humans and robots. It is noted that the assembly time for each operation is omitted at the request of the target company in Figure 2.

Regarding the setting of the automation difficulty level, tasks #6, #18, #29, #31 #32 and #36 have automation difficulty level C—the highest difficulty level to automate. Moreover, tasks #17 and #37 have the level B, which implies the second highest difficulty level, and other tasks have the level A, where automation by the robots is not difficult.

From a production requirement, a cycle time CT was set as 60 sec. The results of the assembly system design in this example are shown in the next section.

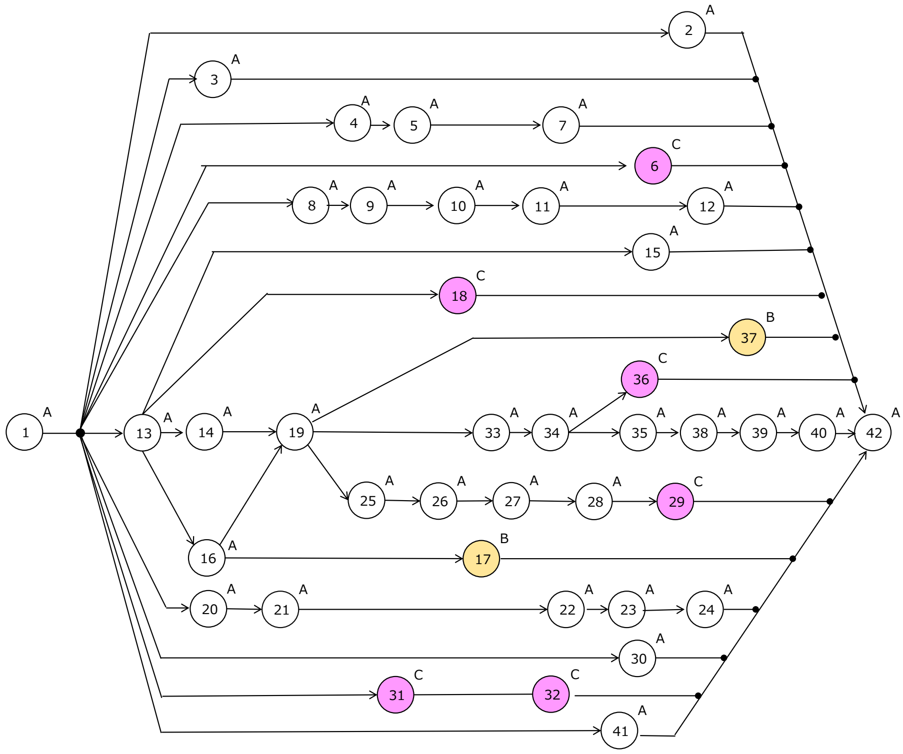


Figure 2: Assembly precedence relationships: An actual electronic equipment assembly line

5 Results of Case Study

In this section, the assembly system design example is evaluated. In Stage 1, each task is selected as either a human task or robot task by 0-1 IP [12], in order to maximize the automation rate for the line and minimize the total automation difficulty level. In Stage 2, the assembly line is designed using the line balancing method with 0-1 IP [12] by minimizing the total numbers of stations based on the result of task selection in Stage 1.

A commercial solver ILOG® CPLEX® application [23] is used for the numerical experiments. The problems in Stage 1 and Stage 2 are firstly programmed using the modeling language GNU MathProg [24]. Next, they are converted to CPLEX LP file format [25] using GLPK [26]. Then, the programs are solved by ILOG CPLEX.

5.1 Results of Stage 1: Task selection as human or robot

Firstly, the maximal total automation difficulty level for assembly $TD_{\max}$= 14 is calculated in Equation (4). To obtain a solution in the bi-objective problem for TA and TD, the constraint of the total automation difficulty level for assembly $\varepsilon_{\mathrm{TD}}$ is constraint Inequality (3), method [19], and it is changed to $\varepsilon_{\mathrm{TD}}$ = 0, 1, 2, …, 14, respectively. By changing $\varepsilon_{\mathrm{TD}}$, a solution that maximizes the TA is obtained. It is noted that the automation difficulty constraint $\varepsilon_{\mathrm{TD}}$ = 0 implies that all tasks with high automation difficulty level are selected as only human ones. Meanwhile, $\varepsilon_{\mathrm{TD}}$ = $TD_{\max}$ (= 14) implies that all tasks can be selected as robot ones.

Table 2 shows the results of task selection as a human or robot task in Stage 1 when $\varepsilon_{\mathrm{TD}}$ is changed to 0, 1, 2,…, 14, respectively. In the case of the lowest robot priority $\varepsilon_{\mathrm{TD}}$ = 0, eight high difficulty tasks are selected as human ones. Meanwhile, in the case of $\varepsilon_{\mathrm{TD}}$ = 14, which means that the robot priority is the highest, no task is selected as the human priority. In addition, total automation difficulty level TD, automation rate for the line TA, the total assembly time and the necessary numbers of stations are also noted.

As shown in Table 2, in the case of $\varepsilon_{\mathrm{TD}}$ = 0, since the total assembly time of human tasks TT_{h} is 82 sec and cycle time CT = 60 sec, the total numbers of necessary human stations $K_{0\mathrm{h}}$ are calculated as two using Equation (10). If $\varepsilon_{\mathrm{TD}}$ is increased from 0, TT_{h} is decreased. In the case of $\varepsilon_{\mathrm{TD}}$ = 6, TT_{h} is 60 sec and $K_{0\mathrm{h}}$ become one. Contrary to the case of $K_{0\mathrm{h}}$, the total numbers of necessary robot stations $K_{0\mathrm{r}}$ increase with an increase in $\varepsilon_{\mathrm{TD}}$. Thus, $K_{0\mathrm{r}}$ become three when $\varepsilon_{\mathrm{TD}}$ is from 0 to 6. When $\varepsilon_{\mathrm{TD}}$ is from 7 to 12 and from 13 to 14, $K_{0\mathrm{r}}$ become four and five, respectively. From the above two results, $K_{0\mathrm{L}}$ is four in the case of $\varepsilon_{\mathrm{TD}}$ = 6, $K_{0\mathrm{L}}$ is six in the case of $\varepsilon_{\mathrm{TD}}$ = 13, and $K_{0\mathrm{L}}$ is five in the other cases. Accordingly, it is shown that $K_{0\mathrm{L}}$ varies depending on the results of task selection as a human or robot task. Furthermore, total numbers of necessary stations without allocating human or robot stations K_0 is equal to or less than $K_{0\mathrm{L}}$. This result indicates that $K_{0\mathrm{L}}$ are increased with the task selection as a human or robot task. In Section 5.2, these results are compared with those in Stage 2 by considering the given precedence constraints.

Figure 3 shows the resulted relationship between TD and TA. As $\varepsilon_{\mathrm{TD}}$ is increased, both TD and TA are also increased. Thus, there is a trade-off between the total automation difficulty TD and the automation rate for the line TA. However, in some local results, even if $\varepsilon_{\mathrm{TD}}$ is increased, TA remains unchanged. For example, if $\varepsilon_{\mathrm{TD}}$ is increased from 2 to 3, the automation rate TA remains the same at 85.7%. Similar results are observed when $\varepsilon_{\mathrm{TD}}$ is increased from 4 to 5, from 6 to 7, from 8 to 9, and from 10 to 11. The reason for these results is that even if $\varepsilon_{\mathrm{TD}}$ is increased by 1, there are no human tasks with an automation difficulty level ad_j =1. In the example of $\varepsilon_{\mathrm{TD}}$ =2, because all tasks with ad_j =1, that is, j = 17 and 37, are selected as robot tasks, even if $\varepsilon_{\mathrm{TD}}$ is increased by 1, no tasks are added as robot selections.

As the above discussion, it is observed that there is a trade-off between TD and TA; however, if TD is increased, TA is not increased in some cases. On the other hand, $K_{0\mathrm{L}}$ depends on the results of task selection as a human or robot task.

Table 2: Results of task selection as a human or robot task in Stage 1

Senario	Index of tasks j: 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	Automation rate for the line TA	Total automation difficulty level of assembly TD	Total assembly time: Total assembly time of human task TT_h (sec)	Total assembly time of robot task TT_r (sec)	Total assembly time TT (sec)	Necessary numbers of stations: Total numbers of necessary human stations K_{0h}	Total numbers of necessary robot stations K_{0r}	Sum of necessary stations K_{0L}	Total numbers of necessary stations without allocating human or robot stations K_0
Automation difficulty level (A, B and C)	A	A	A	A	A	C	A	A	A	A	A	A	A	A	A	A	B	C	A	A	A	A	A	A	A	A	A	A	C	A	C	C	A	A	A	C	B	A	A	A	A	A									
Robots priority lowest; $\varepsilon_{TD} = 0$	R	R	R	R	R	H	R	R	R	R	R	R	R	R	R	R	H	H	R	R	R	R	R	R	R	R	R	R	H	R	H	H	R	R	R	H	H	R	R	R	R	R	81.0%	0	82	149	231	2	3	5	4
$\varepsilon_{TD} = 1$	R	R	R	R	R	H	R	R	R	R	R	R	R	R	R	R	R	H	R	R	R	R	R	R	R	R	R	R	H	R	H	H	R	R	R	H	H	R	R	R	R	R	83.3%	1	74	157	231	2	3	5	4
$\varepsilon_{TD} = 2$	R	R	R	R	R	H	R	R	R	R	R	R	R	R	R	R	R	H	R	R	R	R	R	R	R	R	R	R	H	R	H	H	R	R	R	H	R	R	R	R	R	R	85.7%	2	73	158	231	2	3	5	4
$\varepsilon_{TD} = 3$	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	H	R	R	R	R	R	R	R	R	R	R	H	R	H	H	R	R	R	H	H	R	R	R	R	R	85.7%	3	71	163	234	2	3	5	4
$\varepsilon_{TD} = 4$	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	H	R	R	R	R	R	R	R	R	R	R	H	R	H	H	R	R	R	H	R	R	R	R	R	R	88.1%	4	70	164	234	2	3	5	4
$\varepsilon_{TD} = 5$	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	H	R	H	H	R	R	R	H	H	R	R	R	R	R	88.1%	5	61	175	236	2	3	5	4
$\varepsilon_{TD} = 6$	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	H	R	H	H	R	R	R	H	R	R	R	R	R	R	90.5%	6	60	176	236	1	3	4	4
$\varepsilon_{TD} = 7$	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	H	R	R	H	R	R	R	H	H	R	R	R	R	R	90.5%	7	51	190	241	1	4	5	5
$\varepsilon_{TD} = 8$	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	H	R	R	H	R	R	R	H	R	R	R	R	R	R	92.9%	8	50	191	241	1	4	5	5
$\varepsilon_{TD} = 9$	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	H	R	R	R	R	R	R	H	H	R	R	R	R	R	92.9%	9	46	200	246	1	4	5	5
$\varepsilon_{TD} = 10$	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	H	R	R	R	R	R	R	H	R	R	R	R	R	R	95.2%	10	45	201	246	1	4	5	5
$\varepsilon_{TD} = 11$	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	H	R	R	R	R	R	R	R	H	R	R	R	R	R	95.2%	11	36	208	244	1	4	5	5
$\varepsilon_{TD} = 12$	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	H	R	R	R	R	R	R	R	R	R	R	R	R	R	97.6%	12	35	209	244	1	4	5	5
$\varepsilon_{TD} = 13$	R	R	R	R	R	H	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	97.6%	12	3	253	256	1	5	6	5
Robots priority highest; $\varepsilon_{TD} = 14$	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	100.0%	14	0	259	259	0	5	5	5

Note: "R" means robot task, while "H" means human task.

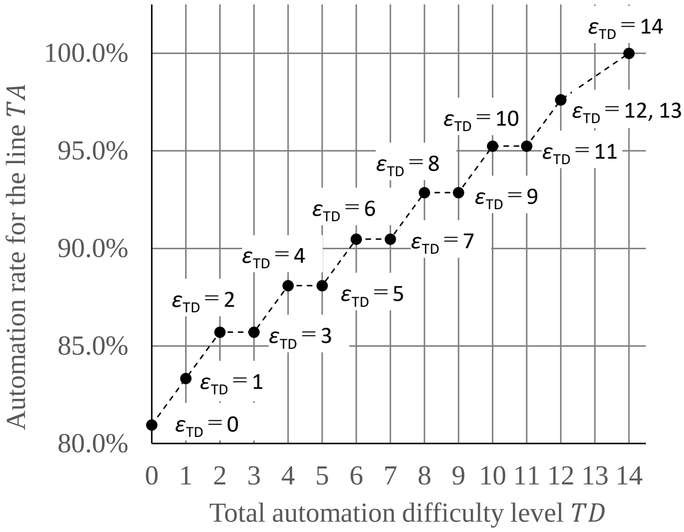


Figure 3: Resulted relationship between total automation difficulty level TD and automation rate for the line TA.

5.2 Results of Stage 2: Assembly line balancing using 0-1 IP

In Stage 2, the assembly line balancing problem for minimizing the numbers of stations are solved using the results of Stage 1.

Table 3 shows the results of the station assignments in Stage 2. In any scenario, the total numbers of stations K are the same as the sum of necessary stations K_{0L}. This result means that the precedence constraint is satisfied without increasing the total numbers of stations from K_{0L} to K. In scenario ε_{TD}=6, K becomes 4, which is the smallest value in any scenario. Furthermore, in scenario ε_{TD}=13, K is the largest value of 6. Comparing the values of balance loss BL and smoothness index SI, when ε_{TD}=6, both indices are the lowest (BL = 0.02 and SI = 2.45) in any scenario. They are the highest (BL = 0.29 and SI = 62.24) when ε_{TD}=13. In general, a smaller BL represents less idle time, and a smaller SI implies a smaller assembly time fluctuation among the stations. Thus, in scenario ε_{TD}=6, both the idle time while the assembly time fluctuation among the stations is smallest. In contrast, in scenario ε_{TD}=13, both the idle time and the assembly time fluctuation among the stations became largest.

Figure 4 respectively shows the pitch diagrams in scenarios ε_{TD}= 6 and ε_{TD}=13. In Figure 4 (a) scenario ε_{TD}= 6, all human tasks are assigned to one human station 3, and all robot tasks are assigned to three robot stations 1, 2, and 4. Thus, the total assembly time at each station in 1 to 4 is 59, 58, 60, and 59 sec, respectively. Hence, the idle time at each station is only 1, 2, 0, and 1 sec respectively, which is very short compared to cycle time CT = 60 sec. Thus, it is considered that K, BL and SI become small in scenario ε_{TD}= 6 because the idle time of all stations become short. Meanwhile, in Figure 4 (b) scenario ε_{TD}= 13, the total assembly time at station 5 is short as 3 sec. However, that at station 6 is 35 sec, and each idle time is 57 sec at station 5 and 25 sec at station 6, respectively. Therefore, it is observed that this longer idle time brought largest K in scenario ε_{TD} = 13.

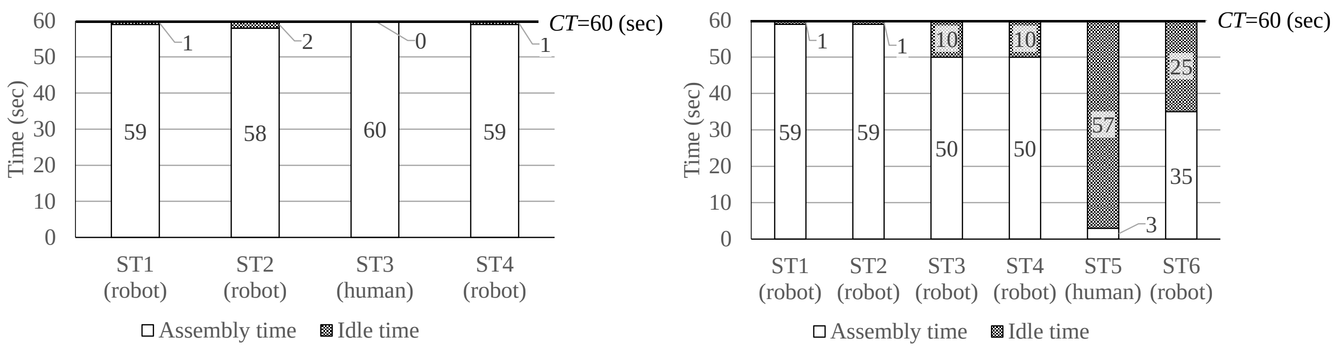
Figure 5 shows the results of station assignment on assembly precedence relationships in scenarios ε_{TD}= 6 and ε_{TD}= 13. In Figure 5 (a) scenario ε_{TD}= 6, for both human and robot tasks, the stations are assigned with little idle time, while satisfying the precedence constraint. In contrast, as shown in Figure 5 (b) scenario $\varepsilon_{TD} = 13$, the station 5 has only 1 task which brings longer idle time. It seems that the numbers of stations should be reduced by merging station 5 and 6 since the total assembly time at station 5 and 6 is only 3 sec and 25 sec, respectively. However, these stations cannot be merged in Stage 2, because there is a limitation in this study due to the constraints of human and robot task selection in Stage 1.

In the experiment, the line balancing problem was solved using the results of the task selection at Stage 1. As a result, the total numbers of stations K are the same as the sum of necessary stations K_{0L} in Stage1. Thus, in this example, the precedence constraint is satisfied without increasing the numbers of stations. Meanwhile, it is considered that the idle time caused by the results of the task selection at Stage 1 influences the difference in the total numbers of stations K among scenarios. Therefore, to solve this problem, another objective or constraint to reduce the idle time should be considered in future studies.

Table 3: Results of station assignments in Stage 2

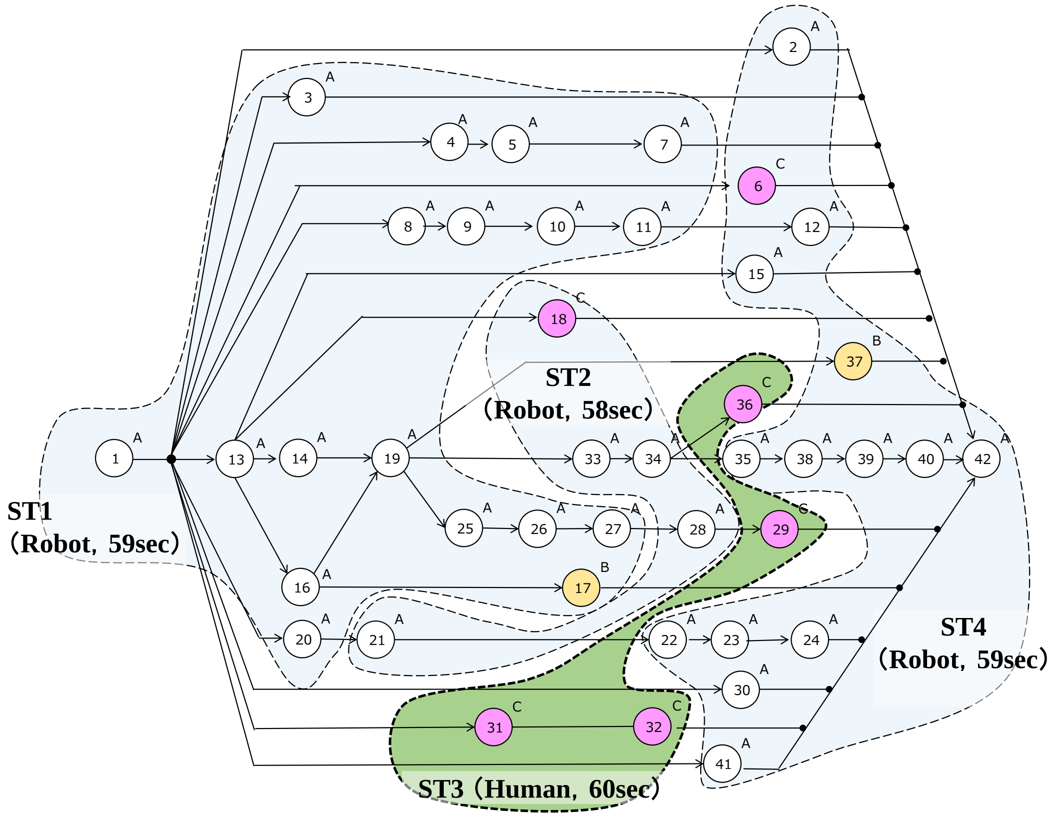
Senario	Results of Stage 1								Results of Stage 2										
	Automation rate for the line *TA*	Total automation difficulty level of assembly *TD*	Total assembly time			Necessary numbers of stations			Station									Balance loss *BL*	Smooth-ness index *SI*
			Total assembly time of human task TT_h (sec)	Total assembly time of robot task TT_r (sec)	Total assembly time *TT* (sec)	Total numbers of necessary human stations K_{0h}	Total numbers of necessary robot stations K_{0r}	Sum of necessary stations K_{0L}	Assignment						Total numbers of human stations K_h	Total numbers of robot stations K_r	Total numbers of stations *K*		
									ST1	ST2	ST3	ST4	ST5	ST6					
Robots priority lowest; $\varepsilon_{TD} = 0$	81.0%	0	82	149	231	2	3	5	R	H	H	R	R		2	3	5	0.23	37.54
$\varepsilon_{TD} = 1$	83.3%	1	74	157	231	2	3	5	R	H	H	R	R		2	3	5	0.23	39.31
$\varepsilon_{TD} = 2$	85.7%	2	73	158	231	2	3	5	R	H	R	H	R		2	3	5	0.23	31.70
$\varepsilon_{TD} = 3$	85.7%	3	71	163	234	2	3	5	R	H	R	H	R		2	3	5	0.22	34.34
$\varepsilon_{TD} = 4$	88.1%	4	70	164	234	2	3	5	R	H	R	H	R		2	3	5	0.22	37.15
$\varepsilon_{TD} = 5$	88.1%	5	61	175	236	2	3	5	R	H	R	H	R		2	3	5	0.21	47.31
$\varepsilon_{TD} = 6$	90.5%	6	60	176	236	1	3	4	R	R	H	R			1	3	4	0.02	2.45
$\varepsilon_{TD} = 7$	90.5%	7	51	190	241	1	4	5	R	R	H	R	R		1	4	5	0.20	46.08
$\varepsilon_{TD} = 8$	92.9%	8	50	191	241	1	4	5	R	R	H	R	R		1	4	5	0.20	46.21
$\varepsilon_{TD} = 9$	92.9%	9	46	200	246	1	4	5	R	R	H	R	R		1	4	5	0.18	27.33
$\varepsilon_{TD} = 10$	95.2%	10	45	201	246	1	4	5	R	R	H	R	R		1	4	5	0.18	29.65
$\varepsilon_{TD} = 11$	95.2%	11	36	208	244	1	4	5	R	R	R	H	R		1	4	5	0.19	30.76
$\varepsilon_{TD} = 12$	97.6%	12	35	209	244	1	4	5	R	R	H	R	R		1	4	5	0.19	38.34
$\varepsilon_{TD} = 13$	97.6%	12	3	253	256	1	5	6	R	R	R	R	H	R	1	5	6	0.29	62.24
Robots priority highest; $\varepsilon_{TD} = 14$	100.0%	14	0	259	259	0	5	5	R	R	R	R	R		0	5	5	0.14	27.11

Note: "R" means robot station, while "H" means human staion.

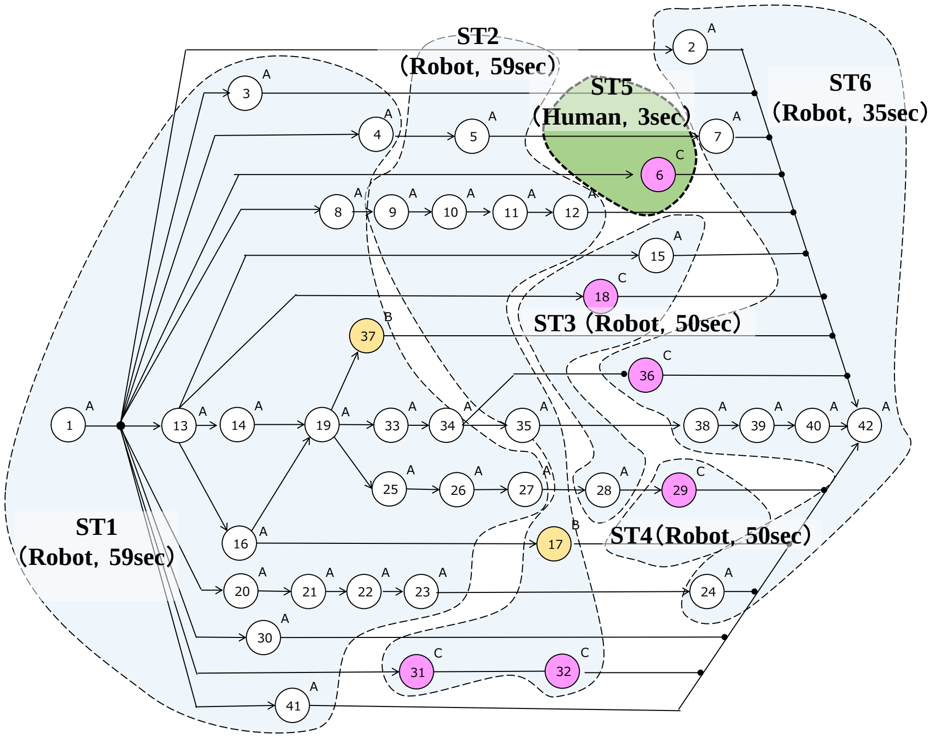


(a) Scenario $\varepsilon_{TD} = 6$ (b) Scenario $\varepsilon_{TD} = 13$

Figure 4: Pitch diagrams ($\varepsilon_{TD} = 6$ and $\varepsilon_{TD} = 13$)



(a) Scenario ε_{TD} = 6



(b) Scenario ε_{TD} = 13

Figure 5: Results of station assignment on assembly precedence relationships (ε_{TD} = 6 and ε_{TD} = 13)

5.3 Effort of objective functions; automation rate for the line vs. total assembly time

In Section 5.1, TA and TD are used as bi-objective functions in Stage 1. Alternatively, another bi-objective functions in the previous study [10] were to minimize the total assembly time TT and the total automation difficulty level TD. The reason for minimizing TT is that reducing the total assembly time brings multiple alternatives for assigning tasks for CT . In this section, the results with the bi-objectives TT and TD in Stage 1 are compared to the results with the bi-objectives TA and TD.

Table 4 shows the results of the station assignments with the bi-objectives TT and TD, when $\varepsilon_{\mathrm{TD}}$ is changed to 0, 1, 2, …, 14, respectively. In this example, TT becomes 220 sec, when $\varepsilon_{\mathrm{TD}}$ = 0 and 1 while when $\varepsilon_{\mathrm{TD}}$ is from 2 to 14, TT is 218 sec. These results show that TT is decreased if the constraint on the total automation difficulty level is relaxed, that is, as $\varepsilon_{\mathrm{TD}}$ is increased. Meanwhile, since TT is used as the objective function instead of TA, TA ranges become from 54.8 % to 57.1 %, which is lower than the results obtained with the bi-objectives TA and TD. Furthermore, the result with the bi-objectives TT and TD is that K is seven, BL is 0.48, and SI is from 87.01 to 90.76. Otherwise, the result with the bi-objectives TA and TD is that K is from 4 to 5, BL is from 0.18 to 0.29, and SI is from 2.45 to 62.24 (Table 3). Therefore, each value of K, BL and SI with the bi-objectives TT and TD is larger than each one with the bi-objectives TA and TD. Hence, it is considered that K becomes larger than the results with the bi-objectives TA and TD, because the idle time and the assembly time fluctuation among stations are larger.

Figure 6 shows the pitch diagram in scenario $\varepsilon_{\mathrm{TD}}$ is from 2 to 14 with the bi-objectives TT and TD in Stage 1. In Figure 6, different types of stations, human and robot stations are assigned next to each other. For this reason, there is a higher idle time at stations 1 and 5 relative to a given cycle time.

Figure 7 shows the assembly precedence relationships with the results of the station with the bi-objectives TT and TD. Then, on the task path for #1→#13→#14→#19→#25→・・・→ #29→#42, the task type—human or robot—are switched six times. In Figure 7, task #1 is assigned to the robot station while task #13 is assigned to the human station. This is because task #1 is selected as a robot task and task #13 is selected as a human task. Thus, when the task type is switched from robot to human or from human to robot in the path, it is necessary to use different types of stations by humans or robots before and after the related tasks. Therefore, the total numbers of stations K require at least one more than the number of task switches. In Figure 7, K becomes seven because on the path of task #1→#13→#14→#19→ #25→・・・→#29→#42, the numbers of task switch are six.

In this section, the results with the bi-objectives TT and TD in the previous study [10] were compared with those with the bi-objectives TA and TD in this study. In the results with the bi-objectives TT and TD, K becomes seven in all scenarios, which is larger than K is 4 or 5 with the bi-objectives TA and TD. Minimizing TT was aimed at bringing multiple alternatives for assigning tasks. However the experiment showed that K was larger than the results with the bi-objectives TA and TD. The reason for this is that the task type was switched from human to robot and from robot to human frequently in some task paths in the results with the bi-objectives TT and TD. Thus, the frequent switch of task type in some task paths seems to be the reason for the larger K.

Moreover, the task type switched was more frequent in the results with the bi-objectives TT and TD than one in the results with the bi-objectives TA and TD. When ε_{TD} is from 2 to 14 with the bi-objectives TT and TD, TA becomes 57.1%, which is close to 50%. It seems that both type tasks may be assigned next to each other in the assembly precedence relationships in Stage 2, if the numbers of human and robot tasks are almost same. Reducing the numbers of task type changes in any task path is a subject for future study.

Table 4: Results of station assignments with the bi-objectives TT and TD

Senario	Results of Stage 1								Results of Stage 2												
	Automation rate for the line TA	Total automation difficulty level of assembly TD	Total assembly time			Necessary numbers of stations			Station											Balance loss BL	Smooth-ness index SI
			Total assembly time of human task TT_h (sec)	Total assembly time of robot task TT_r (sec)	Total assembly time TT (sec)	Total numbers of necessary human stations K_{0h}	Total numbers of necessary robot stations K_{0r}	Sum of necessary stations K_{0L}	Assignment							Total numbers of human stations K_h	Total numbers of robot stations K_r	Total numbers of stations K		
									ST1	ST2	ST3	ST4	ST5	ST6	ST7					
Robots priority lowest; $\varepsilon_{TD} = 0$	54.8%	0	97	123	220	2	3	5	R	H	R	H	R	H	R	3	4	7	0.48	87.01
$\varepsilon_{TD} = 1$	54.8%	0	97	123	220	2	3	5	R	H	R	H	R	H	R	3	4	7	0.48	87.01
$\varepsilon_{TD} = 2$	57.1%	2	105	113	218	2	2	4	R	H	R	H	R	H	R	3	4	7	0.48	90.76
$\varepsilon_{TD} = 3$	57.1%	2	105	113	218	2	2	4	R	H	R	H	R	H	R	3	4	7	0.48	90.76
$\varepsilon_{TD} = 4$	57.1%	2	105	113	218	2	2	4	R	H	R	H	R	H	R	3	4	7	0.48	90.76
$\varepsilon_{TD} = 5$	57.1%	2	105	113	218	2	2	4	R	H	R	H	R	H	R	3	4	7	0.48	90.76
$\varepsilon_{TD} = 6$	57.1%	2	105	113	218	2	2	4	R	H	R	H	R	H	R	3	4	7	0.48	90.76
$\varepsilon_{TD} = 7$	57.1%	2	105	113	218	2	2	4	R	H	R	H	R	H	R	3	4	7	0.48	90.76
$\varepsilon_{TD} = 8$	57.1%	2	105	113	218	2	2	4	R	H	R	H	R	H	R	3	4	7	0.48	90.76
$\varepsilon_{TD} = 9$	57.1%	2	105	113	218	2	2	4	R	H	R	H	R	H	R	3	4	7	0.48	90.76
$\varepsilon_{TD} = 10$	57.1%	2	105	113	218	2	2	4	R	H	R	H	R	H	R	3	4	7	0.48	90.76
$\varepsilon_{TD} = 11$	57.1%	2	105	113	218	2	2	4	R	H	R	H	R	H	R	3	4	7	0.48	90.76
$\varepsilon_{TD} = 12$	57.1%	2	105	113	218	2	2	4	R	H	R	H	R	H	R	3	4	7	0.48	90.76
$\varepsilon_{TD} = 13$	57.1%	2	105	113	218	2	2	4	R	H	R	H	R	H	R	3	4	7	0.48	90.76
Robots priority highest; $\varepsilon_{TD} = 14$	57.1%	2	105	113	218	2	2	4	R	H	R	H	R	H	R	3	4	7	0.48	90.76

Note: "R" means robot station, while "H" means human staion.

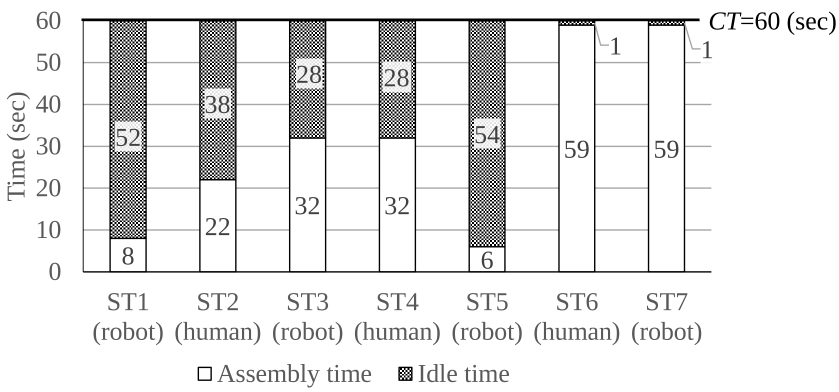


Figure 6: Pitch diagram with the bi-objectives TT and TD (ε_{TD} = 2-14)

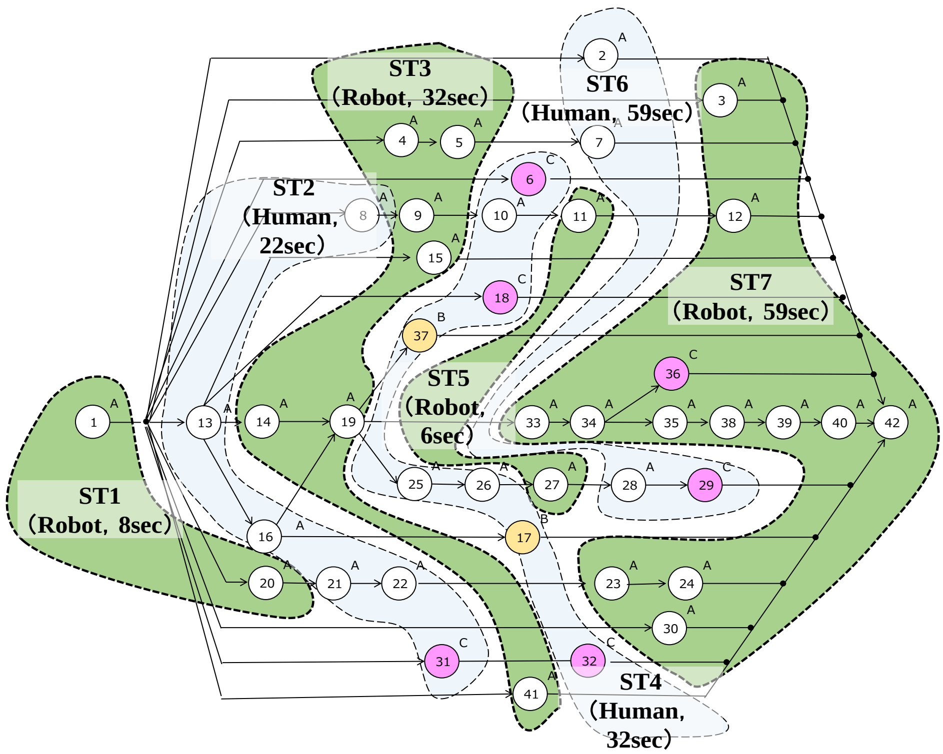


Figure 7: Assembly precedence relationships with the results of station assignment in scenario $\varepsilon_{\mathrm{TD}}$ = 2-14 using TT and TD as objective functions

5.4 Example of line design review using the result of the numerical experiment

Among the results of the numerical experiments, the scenario with $\varepsilon_{\mathrm{TD}}$ = 6 in Section 5.2 obtained the smallest numbers of stations, K = 4 as shown in Figure 4 (a) and Figure 5 (a). Based on this result, a skilled engineer with actual experience for line design reviews items that should be considered in line design. The main review items are listed below.

1) There are some tasks that are assigned to robot stations with high automation difficulty, such as task #6, #17, #18, and #37 in Figure 5 (a). The feasibility automating these tasks with robots and the estimation of investment and running costs should be determined at first.

2) As the idle time at each station was small in Figure 4 (a), improving the assembly time at each task and setting the buffer stock area among stations should be considered to deal with fluctuations in assembly time.

3) The order of stations 1 to 4 is robot, robot, human, and robot as shown Figure 5 (a). However, it is effective to group the robot stations together to reduce the cost installing safety fences and to integrate and manage the robot systems. Specifically, by re-selecting the task # 42 as a human, the order of station 3 (human) and station 4 (robot) can be replaced to station 3 (robot) and station 4 (human). In this way, the order of stations 1 to 4 can become robot, robot, robot, and human.

4) When automating with robots, there are cases where the type of hands or end-effectors applied must be chosen depending on the task. In order to reduce the investment, it is effective to assign tasks that use the same type of hands or end-effectors to the same station. It is

necessary to consider the replacement of tasks among robot stations while satisfying the precedence constraint.

The above review items show the potential for experienced engineers to improve line design using the results of numerical experiments. In the future, it is also expected that the content of these reviews will be added to the formulation in this study.

6 Conclusion

This study proposed and analyzed a hybrid assembly line design with humans and robots using 0-1IP. As the numbers of tasks increased and the precedence relationships became more complex, using traditional empirical line design methods became more difficult; therefore, in this study, the formulated 2-stage design method was adopted for an actual electrical product manufacturing line with 42 tasks.

In Stage 1, all tasks were selected as either human or robot tasks based on the automation difficulty level and the automation rate for the line using 0-1IP. In Stage 2, a line balancing problem was solved by 0-1IP to minimize the numbers of stations.

Next, numerical experiments were solved with a commercial solver on the actual electrical product manufacturing line. In Stage 1, it was confirmed that the numbers of selected robot tasks increased if the constraint of the automation difficulty level was relaxed. In Stage 2, a short idle time and small fluctuation of the assembly time was analyzed. Additionally, it was shown that the task selection results of Stage 1 affected the priority relationship of Stage 2, which could cause inefficient line design results with long idle time. Furthermore, the potential for engineers to improve the line design using the results of numerical experiments was demonstrated.

In future studies, it will be necessary to develop a selection method for either the human or robot task in Stage 1, so that the idle time in Stage 2 would be decreased. In addition, from a managerial point of view, it will be necessary to consider the methods that include equipment costs as well as operation and maintenance ones.

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