In recent years, manufacturing companies have faced difficulties in securing sufficient production capabilities at factories because of many regional risks, such as natural calamities and epidemics. A production line should be designed to be reconfigured to adapt to various risks for satisfying its demands. This paper proposes a flexible and reconfigurable production line composed of a combination of line workers and multipurpose equipment called robotic cells. A robotic cell performs work (similar to a worker) using a programmable arm robot. The required tasks are allocated to workers or robots. However, it is difficult to design the line configuration and task allocation, because the number of combinations is large. Additionally, the production efficiency fluctuates depending on the correlations between the worker’s attitude, skill level, and allocated tasks. This paper describes a production-line design method using a genetic algorithm. The proposed method maximizes the availability ratio and minimizes the cost of the production line by considering the worker’s attitude toward the work.

**Keywords**: reconfigurable production line, robotic cell, task allocation, worker’s attitude, genetic algorithm

### 1. Introduction

Manufacturing companies face difficulties in securing sufficient production resources under many regional risks, such as natural calamities and epidemics. In 2019, the COVID-19 epidemic forced industrial manufacturers to restrict line workers from working. Additionally, owing to the acceleration of e-commerce under outings restrictions, it is becoming increasingly important for manufacturers to respond quickly to consumer needs. Therefore, manufacturers must appropriately allocate production resources according to certain production situations for maximizing production efficiency and minimizing production costs.

The flexible manufacturing system (FMS), which was proposed in the early 1950s, is a method for properly allocating production resources [1]. It can flexibly reconfigure a layout and numerous standardized production facilities. A method of reconfiguring a production line by combining dedicated equipment, including a CNC machine, was also examined [2]. In recent years, “cobots,” which are robots working with human workers in the same working space, have been commercialized, and work has been appropriately shared between human workers and cobots to improve efficiency [3–5].

However, when human workers and robots work in the same space, the driving torque and motion speed of the robot should be limited to ensure the safety of the human workers. As a result, the total working time increases, and the production efficiency may not be improved. Therefore, to improve the production efficiency, it is preferable that human workers and robots are assigned tasks that they can perform effectively and that they perform each task individually. The assignment of tasks to production resources must consider the type of products to be produced and production volume. For human workers, it is necessary to consider their skill levels and preferences. Additionally, robots must be able to change their location and task as human workers for flexibility.

Considering the above, we propose the concept of a flexible production line that maximizes the production efficiency by arranging the human workers and standardized equipment with industrial robots called “robotic cells” and separating the workspaces of the human workers and robotic cells so that they can work in turns. This is called a divisional and highly efficient line (DHEL). The outline of the DHEL is presented with reference to Fig. 1.

---

**Fig. 1.** Outline of proposed production line (DHEL).
A DHEL should have the following features.

- The line configuration can be changed flexibly by increasing or decreasing the number of human workers and robotic cells according to the condition of the production region.
- The line configuration can be changed depending on the type and amount of product, to minimize production costs.
- Robotic cells can be shared among multiple factories and regions, reducing the capital investment.
- Human workers and robotic cells are assigned work that suits them appropriately, to maximize the production efficiency.
- Workers handle multiple tasks while moving to multiple positions.

**Figure 2** shows details of the robotic cell.

- One industrial robot is placed in each cell.
- The task contents can be changed by revising the robot program.
- The robot performs multiple types of work while exchanging tools such as a grasp hand or a welding gun.
- The cell contains multiple tool storage areas and multiple parts supply areas.
- There are carry-in ports where the product is delivered between a worker and the robot.
- There is a conveyor for transporting products between robotic cells.

In Fig. 1, if Factory A suffers a disaster, Factory A may reduce the production of Product A, and Factory B will begin partial production of Product A. In such a case, the manufacturer can continue production by transferring the excess robotic cells of Factory A to Factory B. At this time, the tasks of the production line of Factory B are re-assigned, and the robot programs and tools will be revised so that the line can perform mixed production of Products A and B to maximize the production efficiency.

**Table 1.** Comparison of different types of production lines.

<table>
<thead>
<tr>
<th></th>
<th>FMS</th>
<th>Worker &amp; “cobots”</th>
<th>DHEL (in this study)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image</td>
<td>Machine</td>
<td>Conveyor</td>
<td>Worker</td>
</tr>
<tr>
<td>Productivity</td>
<td>Good (high)</td>
<td>Not good (low)</td>
<td>Good (high)</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Not good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Setup</td>
<td>Quick</td>
<td>Takes time</td>
<td>Takes time</td>
</tr>
</tbody>
</table>

**Figure 3.** Setup steps for the production line.

Additionally, restrictions on the robotic cell should be considered. First, a task that is beyond the capabilities of the robot is not feasible. For example, because there is only one robot in the cell, it is impossible to assemble a part with one hand into a part held by the other hand. Additionally, parts that exceed the payload of the robot cannot be handled. Second, the number of tools and supply parts is limited by the size of the robotic cell. Finally, because the robot cells are connected in a straight line, it is necessary to connect them with a conveyor or an automatic guided vehicle when bending the lines or moving them apart.

**Table 1** presents a comparison between the DHEL and conventional production lines. The DHEL is more flexible than the FMS when workers and robots perform appropriate tasks. When the workspaces of the worker and the robot are separated, the robot can operate at a high speed; thus, the productivity is improved compared with the case where cobots are used. However, because the line configuration becomes complex, the setup for production takes time, e.g., designing the line configuration and programming each robot.

2. Definition

2.1. Setup Steps for Production Line

**Figure 3** shows the three setup steps for the production line.
Step 1: Line design / Task allocation
The designers of the production line set the target value of the task time according to the type and production volume of the product. Then, considering the production efficiency, they determine which resources to allocate to which task and determine the line configuration.

Step 2: Instruction / Programming
For workers in the production line, production engineers create instruction sheets or animations to clearly explain how to complete each task. For robots in the production line, they teach the robots to perform assigned tasks.

Step 3: Production
Production managers plan parts procurement and production schedules and then start production with instructed workers and programmed robots.

Various previous studies aimed at reducing the number of preparatory man-hours in Step 2. There are methods for reducing the number of man-hours for creating instruction sheets and animations, e.g., planning the task sequence in assembly work from product data [6] and generating work instruction sheets and animations based on the planned task sequences [7, 8]. By utilizing these methods, it is possible to quickly change the production-line configuration. To reduce the number of man-hours needed for teaching robots, we developed a robot program-generation technology for assembly using three-dimensional computer-aided design (3D-CAD) data of products in our previous study [9]. In another study, a computerized numerical control (CNC) program-generation technology was developed for machining [10]. These technologies are also effective for immediately changing the configuration of the line.

2.2. Problems and Solutions
This report concentrates on the Step 1, i.e., line design and task allocation. As shown in Fig. 4, the number of tasks, processes, and resource combinations becomes large even when considering the constraints. Skilled line designers may find an appropriate configuration that achieves high productivity and low costs based on their knowledge. However, a systematic or automatic approach is required.

To solve this problem, methods have been developed for modeling production equipment and planning a task-allocation plan [11, 12]. In a previous study, workers in a production line were modeled, and a method was developed for solving complex task-allocation problems [13]. In another study, to maximize the production efficiency, a task-allocation method was developed with consideration of the difficulty of the work and the skill level of the workers [14]. Other researchers performed task allocation considering not only the improvement of the production efficiency but also the improvement of the QCD (quality, cost, and delivery), as an evaluation index [15].

The objective of the present study was to solve the following two problems to maximize the production efficiency and minimize the production cost for realizing a DHEL:

i. Reducing idle time (Fig. 5): In a production line such as a DHEL, which includes human workers performing multiple tasks at different positions, optimizing the task timing of each resource is necessary for maximizing the availability ratio.

ii. Improving worker performance: Workers are not always motivated by being shown an evaluation index (QCD). It is assumed that a production manager needs to know the individual workers’ attitudes toward the work in advance and allocate suitable tasks to each worker based on such knowledge.

We developed a task-timing optimization algorithm to plan a high-efficiency task sequence for reducing the idle time of each resource. Additionally, we developed a method to allocate appropriate tasks with consideration of the worker’s attitude toward the work to improve the workers’ performance.

Previous studies have indicated that the motivation of workers increases with their degree of satisfaction with the work, and as a result, their productivity increases [16, 17]. Workers’ attitudes toward work vary. Some workers find difficult tasks rewarding, while others are more motivated to perform simple tasks. Therefore, we defined “required skill” as an indicator, which is evaluated according to the difficulty of the task for the target product.

In the next section, we explain the “required skill” indicator in detail and categorize workers’ attitudes.

Fig. 4. Example of task allocation.

Fig. 5. Idle time of resources in the DHEL.
3. Required Skill and Worker’s Attitude

3.1. Required Skill

Previous studies have discussed the effect of product design on workability, such as operation time and quality [18]. Parameters used to represent the workability include the size/weight of a product [19], visibility of the workspace and force feedback control [20], position accuracy and speed [21], and time control [22].

In this study, we focused on parameters that depend on workers’ skills and affect the operation time and quality. We extracted three parameters with reference to previous studies [18–22], added a new parameter for task allocation between workers and robots, and evaluated the workability of the target task using these four parameters, which are called “difficulty-level parameters” hereinafter. Fig. 6 shows each parameter.

- Position accuracy of the motion: The press-fitting task requires a higher position accuracy than the insertion task. Local adhesive applications require more accuracy than painting the entire surface.
- Speed and time: If workers must move at a constant speed or complete the task within a time limit, the task may be difficult to complete correctly.
- Necessity of force feedback control: Workers should consider force control to prevent excessive part deformation in an assembly task and to insert a pin into the hole appropriately in a press task.
- Degrees of freedom (DOFs) [new parameter]: The number of DOFs of an assembly task changes depending on the presence or absence of positioning elements. When connecting cables to a socket, 12 DOFs are needed to insert the connector part while maintaining the posture of the entire cable. A robotic cell consisting of a 6 DOF industrial robot cannot be applied to a task requiring ≥ 7 DOFs.

Higher values of the foregoing parameters indicate that a higher worker skill level is needed. In the present study, this corresponds to a higher value of the required skill index.

3.2. Worker’s Attitude

In this study, the worker’s attitude is a value that indicates what type of work style is preferable for the worker. As mentioned in Section 2.2, there is a method of assigning tasks with consideration of the skill level of the worker. However, if the preference of the worker is not taken into consideration, the worker’s motivation will not improve. Thus, productivity will not improve. We classified the workers’ attitudes into four quadrants based on the availability ratio and the required skill of production line, as shown in Fig. 7.

- **Type A: Improve own skill – leave work on time:** Workers in this quadrant have limited skills but wish to improve their skills and to tolerate overtime if they can earn a higher salary.
- **Type B: Improve own skill – allow overtime work:** Workers in this quadrant tend to regard improving their skills as important and to tolerate overtime if they can earn a higher salary.
- **Type C: Prefer light work – leave work on time:** Workers in this quadrant attach little importance to work and are content with the minimum salary.
- **Type D: Prefer light work – allow overtime work:** Workers in this quadrant have limited skills but wish to earn a higher salary by working overtime.

We assumed that the production efficiency is maximized by matching the above four quadrants representing the worker’s attitude toward the work with the workers of a production line. Therefore, we developed a production-line design system for DHELs that can maximize the production efficiency by evaluating performance indices such as the availability ratio, production cost, and required skill of the planned line configuration and allocating tasks accordingly to human workers and robotic cells.

4. Developed System

4.1. System Structure

Figure 8 shows a schematic of the developed production-line design system for DHELs. The system re-
receives information, such as products and production conditions and information about process operation times and costs, from a database. It automatically generates line configuration plans with task allocation based on the input information and calculates the performance indices for each plan. Table 2 presents the variables used in the system.

A product undergoes numerous processes. In the case of the same product ID x and the same lot ID z, the production volume v is the same even for different process IDs y1 and y2, as indicated by Eq. (1).

\[ v(x, y_1, z) = v(x, y_2, z). \]  

(1)

In the case of the same product ID x and the same process ID y, the operation times of tasks \( t_w \) and \( t_r \) are the same even for different lot IDs \( z_1 \) and \( z_2 \) as indicated by Eqs. (2) and (3).

\[ t_w(x, y, z_1) = t_w(x, y, z_2). \]  

(2)

\[ t_r(x, y, z_1) = t_r(x, y, z_2). \]  

(3)

For any product x, process y, and lot z, a task is never assigned to the worker and the robot cell simultaneously. Therefore, either \( s_w \) or \( s_r \) is zero, as indicated by Eq. (4).

\[ \min(s_w(x, y, z), s_r(x, y, z)) = 0. \]  

(4)

The maximum operation time of all resources \( MOT \) is calculated using Eq. (4) with the number of workers \( n(EN_w) \) and the number of robotic cells \( n(EN_r) \).

\[ MOT = \max \left[ \max_{N_w} \left( OT_w \right), \max_{N_r} \left( OT_r \right) \right]. \]  

(5)

The availability ratio and production cost of the planned line configuration – two of the three performance indices – are expressed by Eqs. (5) and (6), respectively.

\[ Ar = \frac{MOT}{FOT}, \]  

(6)

\[ C = \frac{n(EN_w) \cdot C_w}{\sum_v} + \frac{n(EN_r) \cdot C_r \cdot FOT}{DP}. \]  

(7)

Table 2. List of variables.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>Product ID</td>
<td>( m \in N )</td>
</tr>
<tr>
<td>( N_w )</td>
<td>Set of products</td>
<td>( N_w = { x \in N</td>
</tr>
<tr>
<td>p</td>
<td>Process ID</td>
<td>( p \in N )</td>
</tr>
<tr>
<td>( N_p )</td>
<td>Set of processes</td>
<td>( N_p = { y \in N</td>
</tr>
<tr>
<td>q</td>
<td>Lot ID of product</td>
<td>( q \in N )</td>
</tr>
<tr>
<td>( N_q )</td>
<td>Set of lots</td>
<td>( N_q = { z \in N</td>
</tr>
<tr>
<td>G</td>
<td>Multi-set of tasks</td>
<td>( G = { x, y, z</td>
</tr>
<tr>
<td>V</td>
<td>Multi-set of volumes</td>
<td>( f : G \rightarrow V = { x, y, z</td>
</tr>
<tr>
<td>FOT</td>
<td>Operating time of factory</td>
<td></td>
</tr>
<tr>
<td>DP</td>
<td>Depreciation period</td>
<td></td>
</tr>
<tr>
<td>wr</td>
<td>Resource ID</td>
<td>Worker: ( w \in N ), Robotic cell: ( r \in N )</td>
</tr>
<tr>
<td>Cw, Cr</td>
<td>Unit cost</td>
<td>Worker: ( C_w ), Robotic cell: ( C_r )</td>
</tr>
<tr>
<td>( T_wT_r )</td>
<td>Multi-set of operation times of tasks</td>
<td>Worker: ( f : G \rightarrow T_w = { x, y, z</td>
</tr>
<tr>
<td>( S_wS_r )</td>
<td>Multi-set of task-allocation plans</td>
<td>Worker: ( f : G \rightarrow S_w = { x, y, z</td>
</tr>
<tr>
<td>( N_wN_r )</td>
<td>Multi-set of task allocations for each resource</td>
<td>Worker: ( N_w \subseteq S_w ), ( N_r \subseteq S_r )</td>
</tr>
<tr>
<td>( EN_wEN_r )</td>
<td>Set of task allocations for each resource</td>
<td>Worker: ( EN_w \subseteq N_w ), ( EN_r \subseteq N_r )</td>
</tr>
<tr>
<td>( TOT )</td>
<td>Multi-set of total operation times for each resource</td>
<td>Worker: ( OT_w = { x, y, z</td>
</tr>
<tr>
<td>FIT</td>
<td>Forced idle time of task</td>
<td></td>
</tr>
<tr>
<td>( OT_w )</td>
<td>Multi-set of operation times for each resource</td>
<td>Worker: ( OT_w = { x, y, z</td>
</tr>
<tr>
<td>MOT</td>
<td>Maximum operation time</td>
<td></td>
</tr>
<tr>
<td>( Ar )</td>
<td>Availability ratio</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Production cost</td>
<td>Total cost of labor cost and equipment cost calculated from the number of each resource</td>
</tr>
<tr>
<td>Rs</td>
<td>Multi-set of Required skill for each task</td>
<td>( f : G \rightarrow Rs \subseteq N ), ( Rs = { x, y, z</td>
</tr>
<tr>
<td>RSV</td>
<td>Required skill value</td>
<td>Total value of a planned line configuration</td>
</tr>
</tbody>
</table>
Reconfigurable Production Line Design Method for Human Workers – Robotic Cell Collaborated Line Considering Worker’s Attitude Toward Work

4.2. Flowchart of System

In the developed system, a production-line configuration is planned according to the following prerequisites.

- All tasks are assigned to either the workers or robotic cells. However, the operation time changes depending on which task is assigned.
- In the process, a task is conducted continuously for one lot and one product without interruption. For example, in any product m and any lot q, all processes are continuously done.
- The operation time of one lot of one product does not exceed the operating time of the factory FOT. With the following algorithm, we cannot arrive at a task allocation to divide one lot into multiple resources.

It is a time-consuming problem to allocate suitable tasks to workers or robotic cells, because of the large number of combinations. We used a genetic algorithm (GA) to plan a production-line configuration for a quasi-optimal solution while reducing the calculation time. In this study, the number of genes on a chromosome in the GA represents the total number of tasks \( n(G) \), and each gene represents an assigned resource ID \( w \) or \( r \). Here, the operation time of each task \( (t_w \text{ and } t_r) \) is predefined. Therefore, the availability ratio \( Ar \) can be calculated as an evaluation function by calculating the total operation time of each resource using the chromosome generated by the GA. Fig. 9 shows a flowchart of the developed system.

**Fig. 9.** Flowchart of the developed line design system.

First, as an initial plan for task allocation, all tasks are assigned to robotic cells based on product and process information.

Second, to calculate the maximum number of robotic cells needed, task-allocation plans are generated using the GA. For a generated plan, the total operation time of the task assigned to each robotic cell \( OT_r \) is calculated, and then the maximum operation time \( MOT \) and availability ratio \( Ar \) are calculated. These calculations are repeated a predetermined number of times to search for a solution with a small \( Ar \). After searching via the GA, it is determined whether the \( Ar \) is the same as that for the previous plan with different numbers of robotic cells. If so, the number of robotic cells is reduced by 1, and the process is repeated. Otherwise, the production cost \( C \) is calculated by setting the number of robotic cells in the previous plan as the maximum number of robotic cells. This is the production cost when a fully automatic production line is configured.

Third, to allocate appropriate tasks to workers and robotic cells, task-allocation plans were generated using the GA. Each generated plan is revised by a task-timing optimization algorithm, which is described in Section 4.3. For a revised plan, the total operation time of the task assigned to each worker \( OT_w \) and each robotic cell \( OT_r \) is calculated, and then the maximum operation time \( MOT \) and availability ratio \( Ar \) are calculated. These calculations are repeated, and the production cost \( C \) and required skill value \( RSV \) are calculated. The calculation method for the \( RSV \) is described in Section 4.4. It is determined whether the \( Ar \) is the same as that for the previous plan with a different number of robotic cells. If not, the number of workers is increased by 1, and the process is repeated.

Otherwise, it is determined whether the number of robotic cells is \( \geq 1 \). If so, the number of robot cells is reduced by 1, and the process is repeated. If not, three performance indices \( (Ar, C, \text{ and } RSV) \) of the current planned line configuration are determined.

4.3. Task-Timing Optimization Algorithm

The algorithm is described in reference to Fig. 10. In this study, six tasks were allocated to two robotic cells or a worker.

**Fig. 10.** Images of the task-timing optimization algorithm.
First, all tasks of the worker were extracted from the task-allocation plan. Next, two tasks with overlapping task timings were found. Here, it is assumed that tasks II and V are searched to satisfy Eq. (8),
\[ t_E + t_{II} - t_L = \begin{cases} \leq t_L, & \text{if } 0 \leq t_E \leq t_L \end{cases}, \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (8) \]
where \( t_E \) and \( t_L \) represent the start times of the tasks, \( t_{II} \) represents the operation time, and \( v_{II} \) represents the production volume of earlier task II. Then, the start time of the later task \( t_L \) is postponed as given by Eq. (9):
\[ t_L' = t_E + t_{II}, \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (9) \]
where \( t_L' \) represents the revised start time of task V. Here, the total operation time of robotic cell #2 \( OT_{r2} \) is added to the forced idle time \( FIT \), as given by Eq. (10),
\[ OT_{r2} = t_{r2}^T \omega + FIT, \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (10) \]
where \( t_{r2} \) is the vector obtained from the multi-set operation time of robotic cell #2 \( T_{r2} \), and \( \omega \) is the vector obtained from the multi-set of volume \( V \). The foregoing calculation process is repeated until there is no overlapping task. By combining this process with the task-allocation plan generation by the GA, it is possible to set the task timing appropriately and plan a high-efficiency task sequence.

### 4.4. Required Skill Value Calculation

The following four types of difficulty-level parameters defined in Section 3.1 take a value of 0 or 1 with respect to the threshold value.

- Position accuracy: \( PA(m, p, q) \)
- Speed and time: \( SP(m, p, q) \)
- Necessity of feedback control: \( FB(m, p, q) \)
- Degrees of freedom (DOFs): \( AN(m, p, q) \)

Here, \( m \) represents the product ID, \( p \) represents the process ID, and \( q \) represents the lot ID of the product. None of the parameters change from lot to lot. The thresholds of \( PA \) and \( SP \) are adjusted appropriately depending on the product and factory. \( FB \) is set as 1 for tasks that require feedback control based on the experience of the worker. Because a task involving \( \geq 7 \) DOFs requires two-handed work, we set \( AN \) as 1.

Using the difficulty-level parameters, the required skill of each task \( r_s \) can be expressed by Eq. (14).
\[ r_s = 1 + PA + SP + FB + AN, \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (14) \]
The required skill value \( RSV \), which is the sum of the required skill for the whole production line, is calculated using Eq. (15),
\[ RSV = \rho^T \omega, \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (15) \]
where \( \rho \) is the vector obtained from the multiple sets of required skill for each task \( R_s \). As indicated by Eq. (15), higher values of the difficulty-level parameters and production volume correspond to a higher \( RSV \). For a higher \( RSV \), workers with a higher skill level are needed.

### 5. Experimental

#### 5.1. Experimental Conditions

To verify the developed line configuration design system, numerical experiments were performed under the conditions listed in Table 3.

Each of the 12 types of products was completed by two processes and produced in four lots. The production volume was the same regardless of the lot. The operation time and required skill were defined for each process of each product. For the GA parameter, the number of generations was fixed, and the convergence of the solution was evaluated by adjusting other parameters such as the number of chromosomes.

#### Table 3. Experimental conditions.

<table>
<thead>
<tr>
<th>(a) Product, process, production data, and unit cost</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Num. of products</td>
<td>( n(Nm) )</td>
</tr>
<tr>
<td>Num. of processes</td>
<td>( n(Np) )</td>
</tr>
<tr>
<td>Num. of lots</td>
<td>( n(Nq) )</td>
</tr>
<tr>
<td>Operating time of factory</td>
<td>( OT )</td>
</tr>
<tr>
<td>Unit cost of worker</td>
<td>( C_w )</td>
</tr>
<tr>
<td>Unit cost of robotic cell</td>
<td>( C_r )</td>
</tr>
<tr>
<td>Depreciation period</td>
<td>( DP )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(b) Volume, operation time, and required skill</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( Nm )</td>
<td>A</td>
</tr>
<tr>
<td>Process #1</td>
<td></td>
</tr>
<tr>
<td>( Tw )</td>
<td>30</td>
</tr>
<tr>
<td>( Tr )</td>
<td>20</td>
</tr>
<tr>
<td>( Rs )</td>
<td>4</td>
</tr>
</tbody>
</table>

| Process #2 |  |
| \( Tw \) | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 3 | 3 |
| \( Tr \) | 5 | 5 | 5 | 5 | 3 | 3 | 3 | 5 | 3 | 5 | 5 |
| \( Rs \) | 2 | 2 | 1 | 1 | 3 | 2 | 3 | 1 | 2 | 3 | 2 | 1 |

\( Nm \): product ID, \( V \): volume for each lot, \( Tw \): operation time by worker (min), \( Tr \): operation time by robotic cell (min), \( Rs \): required skill (1–5)
5.2. GA Parameter Adjustment

Two typical examples of the results of evaluating the effect of changing the GA parameter on the convergence of the solution are presented below. In this trial, we used an Intel® Xeon® E5-5687W v3, 3.10-GHz CPU.

The effects of the number of chromosomes are shown in Fig. 11. The horizontal axis indicates the number of generations, and the vertical axis indicates the availability ratio in the generated line configuration. The convergence status was almost the same for 250 to 500 chromosomes, and the best solution was obtained at 500.

The effects of the number of elite selections are shown in Fig. 12. The horizontal and vertical axes are the same as those in Fig. 11. The convergence status was good for 40–70 elite selections, and the best solution was obtained at 70.

The GA parameters were set as shown in Table 4, and stable results were obtained (in each experiment, one parameter was fixed and the rest were changed).

Table 4. Determined GA parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Num. of generations</td>
<td>NoG</td>
</tr>
<tr>
<td>Num. of chromosomes</td>
<td>NoC</td>
</tr>
<tr>
<td>Num. of elite selections</td>
<td>NoE</td>
</tr>
<tr>
<td>Crossover</td>
<td>Cro</td>
</tr>
<tr>
<td>Mutation</td>
<td>Mut</td>
</tr>
</tbody>
</table>

5.3. Result of Line Configuration Design

Figures 13 and 14 show the relationships between the availability ratio $Ar$ and the production cost $C$ and the required skill value $RSV$. The production cost $C$ is the total value of labor and equipment costs, which is calculated by the number of workers and robotic cells.

The line configuration with the highest availability ratio $Ar$ and the lowest production cost $C$ under the condition that the availability ratio is $\leq 1.0$ was composed of two cells and two workers, as shown in Fig. 13. When it is difficult to secure workers, a factory can achieve a similar availability ratio $Ar$ and cost $C$ to change the line composed of four robotic cells and zero workers. This line configuration is effective for factories with a frequent flow of workers. If managers of the same factory wish to reduce the capital investment, they can also choose to hire new workers.

In a factory where a worker wishes to earn a higher salary by working overtime, a line composed of two cells and one worker will be available and reduce the production cost $C$ by 25% if the operating time of the factory $FOT$ can be extended by a factor of $\geq 1.2$. If three robotic cells are prepared and the operating time of the factory is extended, it will be possible to realize the same cost without a worker.

The line composed of three cells and one worker and the line composed of one cell and three workers had al-
most the same production cost $C$, as shown in Fig. 13. However, these line configurations differed regarding the availability ratio $A_r$ and required skill value $RSV$, as shown in Fig. 14. Considering the worker’s attitude toward the work, a factory where skilled workers are rewarded for difficult tasks (“type B” as shown in Fig. 7) should adopt the line composed of one cell and three workers. Another factory where a worker prefers to continue a simple task (“type C”) should adopt a line composed of three cells and one worker. If this worker works overtime (“type D”), the number of cells can be reduced by 1 to reduce the production cost $C$.

In the case of a factory where there are enough workers who are not skilled worker but they wish to improve own skill, another method is to train the workers to perform difficult tasks; the line configuration is shifted from three cells and one worker (“type C”) to two cells and two workers (“type A”).

From the above results, it is possible to derive a line configuration plan that maximizes the production efficiency by considering workers’ attitudes.

5.4. Time Required for Line Reconfiguration

Figure 15 shows the calculation results for the time required to configure or reconfigure the production line using the developed system for the DHEL, i.e., the flexible and reconfigurable production line proposed in this paper.

In the conventional system which uses standardized production equipment such as FMS, there is almost no need for equipment design or equipment construction, except for jigs that are product-dependent and require customization. The proposed DHEL is similar in this regard. Additionally, by using the developed production-line configuration design technology, it is possible to plan a production-line configuration with the maximum production efficiency and minimum production cost in a short time, considering the worker’s attitude toward the work.

The line design can be completed in 12 h by using the proposed system under the production conditions shown in Table 3, whereas the manual line design with the FMS takes 24 h. Moreover, the time required for the programming and the instruction can be shortened by introducing a previously developed technology for preparing work instructions [7] and programming robot motion [9]. Both technologies are based on the analysis of the 3D-CAD data of the product. These technologies calculate the assembly sequence, direction, space, and position of the product and then automatically generate the instruction sheets/animations and the robot motion program. Thus, we calculated that the time required to reconfigure the production line can be reduced by 59%.

6. Conclusion

We propose the concept of a flexible and reconfigurable production line (DHEL), which is composed of a combination of line workers and multipurpose equipment called robotic cells. We proposed and verified a production-line design method using a GA, which identifies the line configuration of workers and robotic cells with the maximum production efficiency by considering the worker’s attitude toward the work.

In the future, it is necessary to evaluate whether the production efficiency of the production line improves to consider the required skill value and the worker’s attitude toward the work. Because the man-hours required for preparatory work, such as changes in part supply and equipment layout when reconfiguring the production line, were not considered in this study, development of a line configuration plan technology that minimizes the time required for reconfiguration— including preparation time—is also needed.

References:


Reconfigurable Production Line Design Method for Human Workers – Robotic Cell Collaborated Line Considering Worker’s Attitude Toward Work

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