Assembly Automation

Balancing a mixed-model assembly line with unskilled temporary workers: algorithm and case study

Dongwook Kim, Dug Hee Moon, Ilkyeong Moon,

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Dongwook Kim
Department of Industrial Engineering and Institute for Industrial Systems Innovation, Seoul National University, Seoul, Korea
Dug Hee Moon
Department of Industrial and Systems Engineering, Changwon National University, Changwon, Gyeongnam, Korea, and
Ilkyeong Moon
Department of Industrial Engineering and Institute for Industrial Systems Innovation, Seoul National University, Seoul, Korea

Abstract

Purpose – The purpose of this paper is to present the process of balancing a mixed-model assembly line by incorporating unskilled temporary workers who enhance productivity. The authors develop three models to minimize the sum of the workstation costs and the labor costs of skilled and unskilled temporary workers, cycle time and potential work overloads.

Design/methodology/approach – This paper deals with the problem of designing an integrated mixed-model assembly line with the assignment of skilled and unskilled temporary workers. Three mathematical models are developed using integer linear programming and mixed integer linear programming. In addition, a hybrid genetic algorithm that minimizes total operation costs is developed.

Findings – Computational experiments demonstrate the superiority of the hybrid genetic algorithm over the mathematical model and reveal managerial insights. The experiments show the trade-off between the labor costs of unskilled temporary workers and the operation costs of workstations.

Originality/value – The developed models are based on practical features of a real-world problem, including simultaneous assignments of workers and precedence restrictions for tasks. Special genetic operators and heuristic algorithms are used to ensure the feasibility of solutions and make the hybrid genetic algorithm efficient. Through a case study, the authors demonstrated the validity of employing unskilled temporary workers in an assembly line.

Keywords Assembly line design, Genetic algorithms, Flexible manufacturing

Paper type Research paper

1. Introduction

Among the decisions that arise in managing modern industrial systems, those involving balancing an assembly line are key for implementing a cost-efficient production system because the installation of assembly line systems, which are highly automated, requires considerable investment. The assembly line balancing problem (ALBP) is used to identify the optimal assignment of assembly tasks to workstations under precedence constraints. ALBPs are typically used to minimize the number of workstations for a determined cycle time and the length of the operation time for a specific number of workstations.

Over time, the needs of customers have grown increasingly diverse, and competition among manufacturers has become fierce. For example, German car manufacturer BMW offers a catalogue of optional features that results in 10^{32} different models to satisfy their customer base (Meyr, 2004). Clearly, an efficient methodology for manufacturing multiple products is essential to survive in these days of limitless competitions. A mixed-model assembly line is one of the best responses to this challenging situation. Mixed-model production systems produce several types of standardized commodities in an inter-mixed sequence. The products may differ from each other with respect to size, color, materials used or equipment needed to create them. As a consequence, perfect line balancing is almost impossible, and the line must be flexible to accommodate cycle time violations.

The mixed-model assembly line balancing problem (MMALBP) has received significant attention in recent years and a number of related studies are currently underway. Thomopoulos (1967) was the first to demonstrate the MMALBP by assuming that the variants of each task among all models are restricted to a single station. Under the application

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Assembly Automation
38/4 (2018) 511–523
© Emerald Publishing Limited [ISSN 0144-5154]
[DOI 10.1108/AA-06-2017-070]

The authors are grateful to three anonymous reviewers and the associate editor for their valuable and constructive comments to improve earlier versions of the manuscript. This research was supported by the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning [Grant No.2017R1A2B2007812].

Received 7 March 2017
Revised 7 March 2018
Accepted 8 April 2018

of this restriction, the balancing procedure is similar to that used for solving a single-model ALBP. Specifically, to avoid excessive capacity, the average cycle time of all models is used. As a result, the processing time of some models is longer than the cycle time; that is, work overload occurs. Despite the difficulties with overload, Thomopoulos's paper triggered further study of an MMALBP. Merengo *et al.* (1999) analyzed some typical problems of manual mixed-model assembly lines and introduced a simple assembly line balancing model for minimizing the rate of incomplete jobs with a secondary objective of smoothing workstation loads. Corominas *et al.* (2008) provided important research that informs this paper. They examined the process of rebalancing the line at a Spanish motorcycle assembly plant. They suggested a binary linear programming to minimize the number of unskilled temporary workers required under a specified cycle time and different task groups. Moon *et al.* (2009) designed the integrated ALBP with resource restrictions. They considered multi-skilled workers as resources and formulated the problem using integer linear programming. A genetic algorithm (GA) for addressing the problem of integrated assembly line balancing related to resource restrictions was also developed. Rabbani *et al.* (2012) developed a mixed integer programming method in which two conflicting objectives, including minimizing the cycle time and number of workstations, were considered simultaneously. They also proposed a heuristic algorithm based on GAs. Kalayci *et al.* (2016) proposed a hybrid algorithm that combines a GA with a variable neighborhood search method to minimize the number of disassembly workstations. They also aimed to achieve different objectives corresponding to minimizing total idle time of all workstations and maximizing the removal of high demand components. Roshani and Nezami (2017) proposed a mathematical formulation and a simulated annealing algorithm to solve a mixed-model multi-manned ALBP where multiple workers simultaneously perform different tasks on the same product. Nourmohammadi and Eskandari (2017) formulated a bi-level mathematical model to deal with an ALBP and supermarket location problem. The proposed model optimizes the two long-term decision problems within the line balancing and part feeding contexts.

Because most corporations with assembly operations have hired contract workers, we believed this issue should be studied thoroughly in assembly line balancing. A thorough literature review did not indicate that a mathematical model has been used to solve an MMALBP that accounts for the employment of unskilled temporary workers. In this paper, we present mathematical formulations and a hybrid genetic algorithm (HGA) for an MMALBP to improve efficiency in an assembly line considering the simultaneous assignment of skilled and unskilled temporary workers. Corominas *et al.* (2008) considered the use of temporary workers for the first time. However, they focused solely on minimizing the number of unskilled temporary workers. Although Moon *et al.* (2009) studied an integrated ALBP, they did not take into account the incorporation of unskilled temporary workers. Moon *et al.* (2014) is a key reference of this paper, but limitation of their work is that the model can be adopted only for a single model assembly line. Kim *et al.* (2015) extended a single model ALBP to an integrated MMALBP. In this follow-up paper, two more mathematical models with different objectives are added and an HGA is developed to solve the original problem. In addition, numerical experiments are enhanced. Specifically, the contributions of this paper are as follows:

- This study is the first attempt to present the process of balancing a mixed-model assembly line by incorporating unskilled temporary workers. As far as we know, there has been no research proposing mathematical models and an efficient solution algorithm for the line balancing problem considering both mixed-model assembly lines and the employment of unskilled temporary workers who enhance productivity.
- We develop three mathematical models that can be applied to various scenarios. Each model has a different objective function: total relevant cost, cycle time and work overload. The developed models can provide deeper insight into the way temporary workers affect assembly line balancing.
- An HGA is developed to solve the large size MMALBP. The solution algorithm is efficient enough to apply in real cases. The developed algorithm can bridge the gap between theory and practice.
- A case study is conducted with real data from an automobile company in Korea. Through our case study, we have demonstrated why the employment of unskilled temporary workers should be considered and how our model can efficiently balance an assembly line.

In Section 2, three mathematical models for the integrated mixed-model assembly line balancing situation with unskilled temporary workers are introduced. In Section 3, an HGA is proposed to solve the realistic large problems. In Section 4, computational experiments and a case study are conducted for the developed mathematical model and the proposed algorithm models. Section 5 provides conclusions of this research.

2. Mathematical models

This paper aims to balance a mixed-model assembly line incorporating unskilled temporary workers. In the assembly line, products are manufactured by performing the set of tasks and each product has its own precedence sequence. Variations between products in terms of an operation time can exist because an operation time for the same task can differ based on product type. In fact, total operation time for tasks related to certain product types may exceed the cycle time in a workstation. Baton touch zones provide a buffer for further processing. However, the baton touch zone cannot control all variations. Hence, this model considers an upper limit in the total operation time of each workstation.

Available skill sets for each skilled worker differ. Unskilled temporary workers can perform only part of a task because they lack the necessary experience. So, unskilled temporary workers should be assigned to a task with a skilled worker and can reduce the operation time required to complete tasks by cooperating with skilled workers. Under these assumptions, this paper presents three mathematical models for an integrated MMALBP reflecting operations considering unskilled temporary workers.

2.1 Model I minimization of total cost

Model I minimizes the total costs, including those of operating workstations and the labor costs of skilled and unskilled temporary workers, for a specified cycle time, and this model was introduced in Kim *et al.* (2015). The notations, decision variables, an objective function and constraints used for Model I are presented as follows:

Indices:
i, j = tasks (i, j = 1, 2, . . ., I);
k = product types (k = 1, 2, . . ., K);
s = workstations (s = 1, 2, . . ., S); and
w = skilled workers (w = 1,2, . . ., W).

Parameters:
C = cycle time;
C_u = upper limit of total operation time of each workstation;
K_i = number of different products that requires task i;
D_k = demand of product k;
o_{ik} = operation time for task i for product k when performed by a skilled worker;
r_{ik} = reducible time for task i for product k when performed by a skilled worker and an unskilled temporary worker together;
$P_{(i,j,k)}$ = set of task pairs (i, j) for product k such that there is an immediate precedence relationship between them;
T_w = set of available tasks that can be assigned to skilled worker w;
OC = operation costs of a workstation;
SS_w = salary for skilled worker w;
SU = salary for an unskilled temporary worker;
n = upper bound of the number of workers who can be assigned to a workstation; and
M = a sufficiently large number.

The following two additional parameters are calculated with the above parameters, and Equations (1) and (2) are used for calculation of these added parameters.

$$o_i = \frac{\sum_{k=1}^{K} D_k \cdot o_{ik}}{\sum_{k=1}^{K} D_k} \tag{1}$$

$$r_i = \frac{\sum_{k=1}^{K} D_k \cdot r_{ik}}{\sum_{k=1}^{K} D_k} \tag{2}$$

Decision variables:
F = number of workstations to be used in the assembly line;

$$X_{iksw} = \begin{cases} 1, & \text{if task } i \text{ for product } k \text{ is performed by skilled permanent worker } w \text{ at workstation } s \\ 0, & \text{otherwise} \end{cases}$$

$$Y_{sw} = \begin{cases} 1, & \text{if skilled permanent worker } w \text{ is assigned to workstation } s \\ 0, & \text{otherwise} \end{cases}$$

$$Z_{is} = \begin{cases} 1, & \text{if an unskilled temporary worker is assigned to task } i \text{ at workstation } s \\ 0, & \text{otherwise} \end{cases}$$

$$A_{is} = \begin{cases} 1, & \text{if task } i \text{ is assigned to workstation } s \\ 0, & \text{otherwise} \end{cases}$$

Objective function and constraints:

$$Min \;\; OC \cdot F + \sum_{w=1}^{W} SS_w \left(\sum_{s=1}^{S} Y_{sw} \right) + \; SU \cdot \sum_{i=1}^{I} \sum_{s=1}^{S} Z_{is} \tag{3}$$

Subject to:

$$\sum_{k=1}^{K} \sum_{s=1}^{S} \sum_{w=1}^{W} X_{iksw} = K_i \quad \forall i \tag{4}$$

$$\sum_{k=1}^{K} \sum_{w=1}^{W} X_{iksw} = K_i \cdot A_{is} \quad \forall i, s \tag{5}$$

$$\sum_{s=1}^{S} \sum_{w=1}^{W} X_{iksw} \le M \cdot o_{ik} \quad \forall i, k \tag{6}$$

$$\sum_{i=1, i \ne T_w}^{I} \sum_{k=1}^{K} \sum_{s=1}^{S} X_{iksw} = 0 \qquad \forall w \tag{7}$$

$$\sum_{s=1}^{S} \sum_{w=1}^{W} (s \cdot X_{iksw} - s \cdot X_{jksw}) \le 0 \qquad \forall (i,j,k) \in P_{(i,j,k)} \tag{8}$$

$$Z_{is} \le \sum_{k=1}^{K} \sum_{w=1}^{W} X_{iksw} \qquad \forall i, s \tag{9}$$

$$\sum_{i=1}^{I} \left(\sum_{k=1}^{K} \sum_{w=1}^{W} o_i \cdot X_{iksw} - r_i \cdot Z_{is} \right) \le K \cdot C \quad \forall s \tag{10}$$

$$\sum_{i=1}^{I} \left(\sum_{w=1}^{W} o_{ik} \cdot X_{iksw} - r_{ik} \cdot Z_{is} \right) \le C_u \quad \forall k, s \tag{11}$$

$$\sum_{s=1}^{S} Y_{sw} \le 1 \qquad \forall w \tag{12}$$

$$\sum_{i=1}^{I} \sum_{k=1}^{K} X_{iksw} \le M \cdot Y_{sw} \quad \forall s, w \tag{13}$$

$$\sum_{w=1}^{W} Y_{sw} + \sum_{i=1}^{I} Z_{is} \le n \qquad \forall s \tag{14}$$

$$\sum_{w=1}^{W} X_{iksw} \le 1 \qquad \forall i, k, s \tag{15}$$

$$\sum_{s=1}^{S} s \cdot X_{iksw} \leq F \qquad \forall i, k, w \tag{16}$$

$$X_{iksw}, \quad Y_{sw}, \quad Z_{is}, \quad A_{is} \in \{0, 1\} \tag{17}$$

The Objective Function (3) minimizes the sum of the total workstation costs and the labor costs of skilled and unskilled temporary workers. Constraint (4) ensures that every task should be performed by one skilled worker at one workstation. Constraint (5) indicates that the same task for different products should be assigned to the same workstation. Constraint (6) prevents inconsistency of X_{iksw} which can be greater than zero when o_{ik} is not zero. Zero operation time means that the task is not required for the product. Therefore, X_{iksw} can be 1 if task i is necessary to manufacture product k. Constraint (7) prevents skilled worker w from being assigned to a workstation with a task that the worker cannot complete according to the skilled worker's available task set T_w. Constraint (8) ensures that the precedence relationships between tasks are considered for product k. Constraint (9) imposes that an unskilled temporary worker can be assigned to task i only when a skilled worker is also assigned to task i. Constraint (10) represents the total operation time under conditions of a demand rate of each workstation that is smaller than a specific time. Constraint (11) represents the total maximum operation time to manufacture product k at each workstation; it is smaller than the specified upper limit. Constraint (12) guarantees that a skilled worker is assigned to exactly one workstation. Constraint (13) demands that a task is assigned to a skilled worker at the workstation; X_{iksw} can be 1 when a skilled worker is assigned to a workstation. Constraint (14) restricts the number of total workers to one workstation to prevent overcrowding. Constraint (15) ensures that the same task for different product types is assigned to the same worker. Constraint (16) is used to decide the total number of workstations needed. Constraint (17) demonstrates the binary nature of the decision variables.

2.2 Model II minimization of cycle time

ALBPs are typically used to minimize the number of workstations for a given cycle time or the length of the operation time for a specific number of workstations. So, it is also meaningful for developing the model to reduce cycle time, the length of period required to complete one cycle of an operation for a workstation. The cycle time can be minimized with Model II. Model II is similar to Model I. It is used to minimize cycle time for a specific number of workstations. In this model, F is not a decision variable. Instead, the cycle time of workstation s is a decision variable. The ratio of total operation time to workstation cycle time is considered in this model. Some constraints are also changed in Model II. Specifically, Constraint (10) in Model I is replaced by Constraint (10-2) in Model II. Likewise, Constraint (11) is replaced with Constraint (11-2). Additional notation used, modified objective function and constraints are presented as follows:

Parameters:

- F = number of workstations used in the assembly line;
- T_w = set of available tasks that can be assigned to skilled worker w; and
- U = ratio of total operation time to cycle time of each workstation.

Additional decision variable:

C_s = Cycle time of workstation s.

Objective function:

$$\text{Min} \ \max_{s} \ C_s \tag{3-2}$$

Modified constraints from Model I:

$$\sum_{i=1}^{I}\left(\sum_{k=1}^{K}\sum_{w=1}^{W} o_i \cdot X_{iksw} - r_i \cdot Z_{is}\right) \leq K \cdot C_s \quad \forall s \tag{10-2}$$

$$\sum_{i=1}^{I}\left(\sum_{w=1}^{W} o_{ik} \cdot X_{iksw} - r_{ik} \cdot Z_{is}\right) \leq U \cdot C_s \quad \forall k, s \tag{11-2}$$

2.3 Model III minimization of work overload

If workers of a station do not complete the assigned tasks before the work pieces leave the station, work overload occurs, causing inefficiency that should be eliminated. If work overload occurs, then assembly line should be stopped and generate opportunity costs. Work overload can be ameliorated by the employment of unskilled temporary workers. Model III is developed to minimize work overload of each workstation. Model III is similar to Model II. It is used to minimize the work overload at a predetermined number of workstations. The cycle time of a workstation for each product is defined as a decision variable. The ratio of total operation time to workstation cycle time U is not used in Model III. Furthermore, Constraint (11-2) is replaced by Constraint (11-3). Additional notation, modified objective function and constraints used to explain Model III are presented as follows:

Additional decision variable:

C_{ks} = Cycle time of workstation s for product k.

Objective function:

$$Min \sum_{k=1}^{K}\sum_{s=1}^{S}(C_{ks} - C_s)^{+} \tag{3-3}$$

Modified constraints from Model II:

$$\sum_{i=1}^{I}\left(\sum_{w=1}^{W} o_{ik} \cdot X_{iksw} - r_{ik} \cdot Z_{is}\right) \leq C_{ks} \quad \forall k, s \tag{11-3}$$

3. Hybrid genetic algorithm

A GA is a population-based search and optimization method inspired by Darwin's theory of evolution. The two main concepts of evolution, natural selection and genetic dynamics, play a key role in this method. A GA and the basic principles behind it were first introduced by Holland (1975) and have been widely used in various research efforts over the past four decades. One of the advantages of the GA is its usability with other techniques to improve search performance. In this paper, an HGA is proposed to solve large and real-world problems. Although we developed three mathematical models, the main objective was minimization of total costs, including those associated with the operation of workstations and the labor costs of skilled and unskilled temporary workers. Therefore, our HGA presents a cost-oriented objective function, and the heuristic algorithms included in the HGA were built using the cost-minimization approach. The suggested HGA structure is shown in Figure 1.

3.1 Chromosome representation

The proper representation of a solution is critical in the development of an HGA. Traditionally, chromosomes are represented as simple binary strings; however, this representation is not well suited for solving complex problems such as those associated with mixed-model assembly line balancing. Therefore, this paper features a chromosome that consists of two genes: one that represent tasks in order of precedence and another that stands for unskilled temporary worker assignments. Figure 2 shows the chromosome structure of genes used in this algorithm.

In this paper, one part of the chromosome offers solutions for assigning tasks to workstations, while the other part, shown as a binary string, offers solutions for unskilled temporary worker assignments as generated through a heuristic procedure. The efficiency of the algorithm greatly depends on the initial solution. Therefore, a simple heuristic is proposed to create a feasible initial solution. This heuristic consists of a sorting procedure based on task precedence restrictions. An example of initialization through use of a heuristic algorithm is shown in Figure 3.

Figure 1 Flowchart of the proposed hybrid genetic algorithm

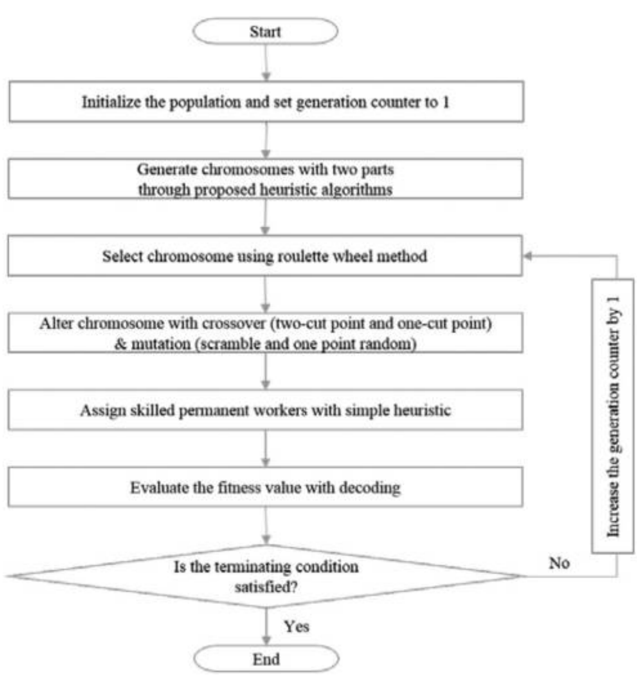


Figure 2 Chromosome structure

Task	2	1	4	3	5	7	6	8	9
Unskilled temporary worker	0	1	1	0	1	0	1	1	0

The steps for the heuristic are as follows:

- Step 1. Find all tasks with predecessor Φ and assign one of them that is used the most in the first gene, which has no value assigned to it yet.
- Step 2. Update the table by deleting the selected task from the predecessor table.
- Step 3. Go back to Step 1 until all tasks have been assigned.

Ties are broken arbitrarily. After the task assignment is complete, unskilled temporary workers are assigned in another gene of the chromosome. For the unskilled temporary worker assignment, another simple heuristic is proposed; it is based on trade-offs between the operation cost of a workstation and the salary of an unskilled temporary worker. The steps for the heuristic are as follows:

- Step 1. Calculate a critical value $cv = \frac{SU}{OC} \cdot C$.
- Step 2. Assign unskilled temporary workers to all tasks with reducible time r_i larger than cv.

3.2 Fitness function

The fitness function plays a role similar to that of the environment in evolution. Each individual in the population represents a potential solution to the problem. A fitness function is computed for each chromosome in the population and the string with the minimum fitness function value is selected. Equation (3) is used as a fitness function in the proposed HGA. To calculate fitness value, information about the assignment of skilled workers is needed. Hence, a simple heuristic that sorts on the basis of skilled workers' available task sets is proposed to assign skilled workers to each workstation. The steps for the heuristic are as follows:

- Step 1. Calculate the cumulative operation time of assigned tasks in the chromosome and divide workstations using the predetermined cycle time and its upper limit.
- Step 2. Arrange skilled worker candidates for each workstation.
- Step 3. Select the workstation with the fewest candidates. If a tie occurs, then select a workstation arbitrarily.
- Step 4. Select the worker with the lowest salary.
- Step 5. If the index of skilled worker candidates is empty for any workstation, then go back to Step 4 and select the worker with the next lowest salary.
- Step 6. Repeat the algorithm until skilled workers have been assigned to all workstations.

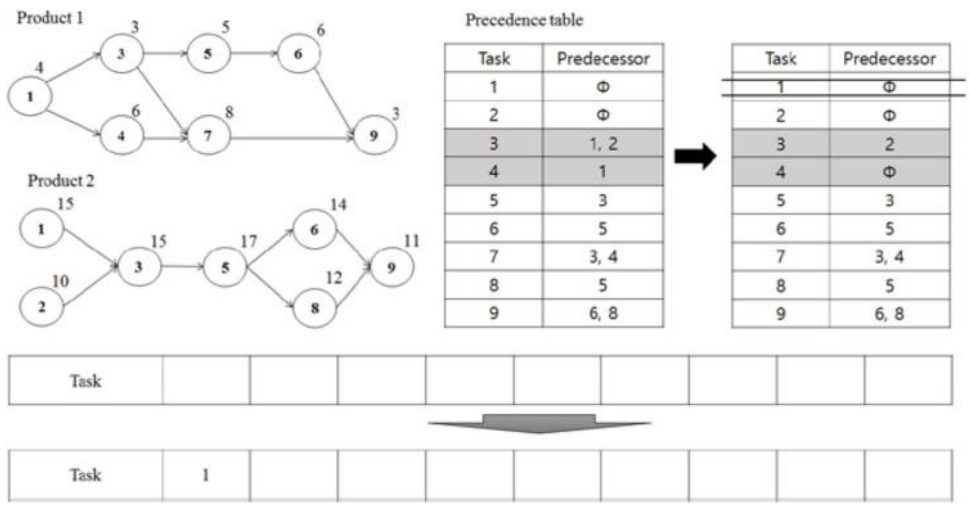
3.3 Genetic operator

Genetic operators are used to produce the next generation of chromosomes. The use of genetic operators – selection, crossover and mutation – can change the next population in a way that encourages genetic diversity.

3.3.1 Selection

Selection is the stage in which individual chromosomes are chosen from a population. In this algorithm, the parent chromosomes are chosen by a roulette wheel method. In this approach, one calculates the fitness of a chromosome as a solution and determines the probability that it will be selected as a solution. This method derives a solution from a range of possibilities that include some weaker solutions. These weak solutions have survived the spin of the wheel; that is, they

Figure 3 Example of initial solution creation



remain in the selection process through several iterations. The inclusion of the weaker solutions (chromosomes) proves advantageous because they may include some qualities (genes) useful in the recombination process.

3.3.2 Crossover

The crossover operation is a diversification mechanism that enables the HGA to generate a solution in previously unvisited areas of the gene pool. In this algorithm, a two-cut crossover operator is used for the task assignment and a one-cut point crossover operator is used for the unskilled temporary worker assignment. A direct swap method is impossible for part of the task assignment because of precedence constraints between tasks. Hence, a special two-cut crossover method is applied as shown in Figure 4. This crossover method was proposed by Leu *et al.* (1994) to guarantee that the resulting offspring is always feasible.

For the unskilled temporary worker assignment, the position of the cut point is randomly generated from the range [1, (length of the chromosome – 1)].

3.3.3 Mutation

In an HGA, mutation produces a random change in a chromosome. The main difference between mutation and crossover is that the mutation operators affect one chromosome. Mutation plays the crucial role of replacing genes in chromosomes during evolution so that they can maintain diversity in the population. In the algorithm used in this paper, a scramble mutation operator is used for the task assignment and a random point mutation operator is used for the unskilled temporary worker assignment. Leu *et al.* (1994) proposed the scramble mutation to move the search out of a local neighborhood and avoid the possibility of finding a local optimum; this mutation ensures the feasibility of the offspring. The random point mutation involves changing the value on a randomly selected gene to another value from the range [0, length of the chromosome].

3.4 Terminating conditions and parameters

The terminating condition was determined when 100,000 generations were produced or when the fitness value of the best chromosome was not improved over 3,000 generations. For the proposed HGA, the crossover and mutation operators were used with the parameters listed in Table I. A pilot test was conducted to find appropriate parameter values.

4. Computational experiments

As aforementioned, the MMALBP in which temporary workers were taken into account has rarely been researched. Hence, benchmark examples for comparison were difficult to find. Therefore, to conduct numerical experiments, we must

Figure 4 Two-cut point crossover of a chromosome for the task assignment

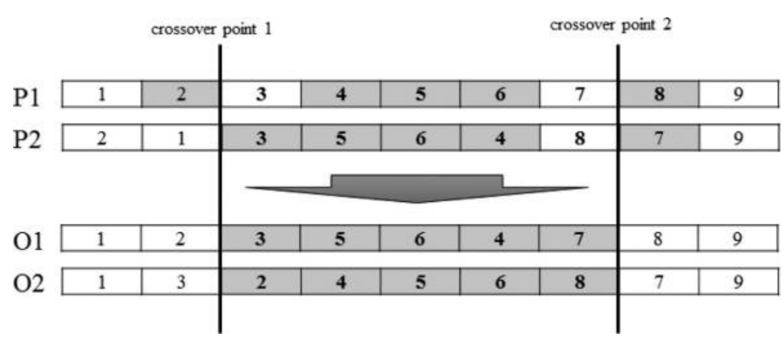


Table I Parameters used in the hybrid genetic algorithm

Parameters	Value
Population size	150
Two-cut crossover probability	0.6
One-cut point crossover probability	0.6
Scramble mutation probability	0.7
One point mutation probability	0.7

generate the instances by modifying real data published in other papers. The information about the precedent sequence of tasks came from Kim *et al.* (1991) who presented real-world data on truck production in a motor manufacturing facility in Korea. The data on available operating task sets of multifunctional workers and their salaries were taken from Moon *et al.* (2009). Employment of temporary workers was addressed by Corominas *et al.* (2008) who referenced a rebalanced line at a Spanish assembly plant for small-engine motorcycles; results from Corominas *et al.* (2008) were applied in practice.

The mathematical models were solved with FICO Xpress-IVE version 7.3 with the time limited to 259,200 seconds. HGAs were run in C++ language. Numerical experiments were conducted with an Intel(R) Xeon(R) 3.5GHz processor with 16GB RAM on the Microsoft Windows Server 2008 *R2* operating system. Although the specifications of the computer used in the experiments were good, these models were not able to solve problems as large as those with 26 tasks, 3 product types and 14 workers within the time limit. However, HGAs can find solutions in a reasonable computation time even for large problems.

Table II Cycle time and operation cost of a workstation

Example no.	No. of tasks	Cycle time	Upper limit of operation time	Operation cost of a workstation
1	9	30 min	45 min	$30,000
2		30 min	36 min	
3		25 min	37.5 min	
4		25 min	30 min	
5		20 min	30 0min	
6		20 min	24 min	
7		30 min	45 min	$3,000
8		30 min	36 min	
9		25 min	37.5 min	
10		25 min	30 min	
11		20 min	30 min	
12		20 min	24 min	
13	14	20 min	30 min	$30,000
14		20 min	24 min	
15		15 min	22.5 min	
16		15 min	18 min	
17		12 min	18 min	
18		12 min	14.4 min	
19		20 min	30 min	$3,000
20		20 min	24 min	
21		15 min	22.5 min	
22		15 min	18 min	
23		12 min	18 min	
24		12 min	14.4 min	
25	26	30 min	36 min	$30,000
26	46	25 min	30 min	$30,000

4.1 Experiments for Model I

We conducted experiments for 26 examples with Model I, which is used to minimize the total cost for a specific cycle time. The operation costs of a workstation and cycle time are necessary to implement the model. They are given in Table II. The upper limit of the operation time is also shown in Table II. In this model, the maximum number of workers allowed at one workstation is fixed at 5 for all examples. Other cost coefficients and necessary parameters are described in Section 2.1. The results of the examples are summarized in Table III.

Some obvious managerial insights can be confirmed through the results of these experiments. The shorter the cycle time, the more costs are incurred. If a baton touch zone is large, then the assembly line can be balanced in a more flexible manner and cost savings are delivered. In one of the most interesting findings, few unskilled temporary workers are assigned when the operation costs of workstations are low. Managers need not reduce the operation time of tasks at a workstation to meet a specific cycle time. Instead, they just need to install more workstations and assign fewer tasks to a workstation. Therefore, installation of additional workstations is a better choice than employing unskilled temporary workers. Evidence of the success of this cost-reduction strategy is illustrated in Tables IV and V which show the different versions of solutions for Example 1. The total relevant cost of assembly line balancing without unskilled temporary workers is $107,500. The number of necessary workplaces is reduced by hiring unskilled temporary workers. As a result, costs could be reduced by 23.5 per cent.

4.2 Experiments for Model II

In this section, experiments for 26 examples were undertaken with Model II, which minimizes the cycle time for a specified number of workstations. Table VI shows the necessary parameters: the number of workstations that can be installed, the number of workers allowed at a workstation and the ratio of total operation time to the cycle time of each workstation. The results are summarized in Table VII. Table VIII shows the solution for Example 10.

Some managerial insights can be confirmed through the results of these experiments. If a baton touch zone is large, then the assembly line can be balanced in a more flexible manner and the cycle time can be reduced. In one of the most interesting findings, the length of the cycle time is not directly related to the number of tasks that should be assigned. The number of temporary workers can be employed and the number of tasks that can be performed by one worker are more critical issues in minimizing the cycle time. Therefore, employing many temporary workers and multifunctional workers is a key element in the flexible mixed-model assembly line and the improvement of productivity.

As shown in Table VIII, the longest cumulative aggregated operation time of workstations is 16.5 minutes. However, if Product 2 is being manufactured, then the operation time required for Workstation 3 is at least 27 minutes. The upper limit of the operation time should be less than 1.5 times that of the cycle time. Hence, the optimal cycle time in this example is 18 minutes.

Table III Results of each example solved through Model I

Example no.	No. of assigned skilled workers	No. of assigned unskilled temporary workers	No. of assigned workstations	Objective value
1	5	3	2	$82,200
2	5	1	3	$109,000
3	5	0	3	$107,800
4	5	3	3	$112,000
5	5	3	3	$113,000
6	5	3	4	$142,000
7	5	0	3	$26,500
8	5	1	3	$28,000
9	5	0	3	$26,800
10	5	0	4	$29,500
11	5	1	4	$31,000
12	5	3	4	$34,000
13	3	1	2	$74,900
14	3	3	2	$77,900
15	3	3	3	$109,700
16	4	4	3	$113,800
17	5	4	3	$118,100
18	4	5	4	$146,000
19	3	1	2	$20,900
20	3	3	2	$23,900
21	3	3	3	$28,700
22	4	0	4	$30,900
23	4	2	4	$33,500
24	4	5	4	$38,000
25		Not found		
26		Not found		

4.3 Experiments for Model III

In this section, experiments for 26 examples were undertaken using Model III, which minimizes the total work overload for a specified maximum number of workstations. Table IX shows the necessary parameters: the number of workstations that can be installed and the number of workers allowed in each workstation. The results for the examples solved with this model are summarized in Table X. Table XI shows the solution for Example 11.

The managerial insights that can be gleaned from these experiments are similar to the findings from the experiments for Model II. The number of temporary workers can be employed and the number of tasks can be performed by one worker are more critical issues in minimizing the work overload. Therefore, temporary workers and multifunctional workers are key elements for smoothing the assembly line.

4.4 Validation of a hybrid genetic algorithm

To validate the proposed algorithms, mathematical Model I was compared with the proposed HGA. The results are presented in Table XII. An HGA can overcome the computational burden of the mathematical models. Skilled workers are assigned by heuristics in the final step of the HGA. So, the gap between the result of an HGA and the optimal value is a bit large for some examples. However, given the complexity of the problem, this degree of optimality gap is well tolerated. Therefore, the developed algorithm can be applied well to an actual industrial field.

4.5 Case study demonstrating the applicability of unskilled temporary workers

We demonstrated the value of our research by performing a case study. We used real data from an automobile company in Korea. Because the entire assembly line is extremely complex, we limited our scope to one part of the process. Figure 5 shows the tasks and their precedence sequences operated on the right-hand side of the subassembly line. The operation time for the tasks in the figure are summarized in Table XIII. The company needs to produce 30 automobiles per hour. Therefore, assuming 95 per cent efficiency, the target cycle time is 114 seconds.

In our case study, one of company's leading automobile models is analyzed. Four types of options can be added, resulting in $24(2 \times 2 \times 3 \times 2)$ types of automobiles that can be produced. However, only 13 types of cars are actually

Table IV Solution of Example 1 solved through Model I

Task sequence	i	k	s	o_{ik}	r_{ik}	o_i	r_i	Cumulative workstation time	w	Temporary worker
1	1	1	1	4	1	9.5	2	7.5	3	0
2		2		15	3					
3	2	2		10	3	5	3	12.5	4	
4	3	1		3	1	9	3	18.5	4	0
5		2		15	5					
6	5	1		5	3	11	3.5	26	3	0
7		2		17	4					
8	4	1	2	6	2	3	2	3	2	
9	6	1		6	2	8	3	11	2	
10		2		10	4					
11	7	1		8	4	4	4	15	6	
12	8	2		12	3	6	3	21	5	
13	9	1		3	1	7	2	28	2	
14		2		11	3					

Source: Adapted from Kim *et al.* (2015)

Table V Solution of Example 1 without assignment of unskilled temporary workers

Task sequence	i	k	S	o_{ik}	r_{ik}	o_i	r_i	Cumulative workstation time	w	Temporary worker
1	1	1	1	4	1	9.5	2	9.5	6	
2		2		15	3					
3	2	2		10	3	5	3	14.5	6	
4	3	1		3	1	9	3	23.5	1	
5		2		15	5					
6	4	1	2	6	2	3	2	26.5	2	
7	5	1		5	3	11	3.5	11		
8		2		17	4					
9	6	1		6	2	8	3	19		
10		2		14	4					
11	8	2		12	4	6	3	25		
12	7	1	3	8	3	4	4	4	3	
13	9	1		3	1	7	2	11		
14		2		11	3					

Table VI Upper limit ratio of cycle time and number of workstations

Example no.	No. of tasks	Upper limit of number of workers allowed	Ratio of total operation time to cycle time	No. of workstations can be installed
1	9	3	1.5	2
2				3
3			1.2	2
4				3
5		4	1.5	2
6				3
7			1.2	2
8				3
9		5	1.5	2
10				3
11			1.2	2
12				3
13	14	3	1.5	2
14				3
15			1.2	2
16				3
17		4	1.5	2
18				3
19			1.2	2
20				3
21		5	1.5	2
22				3
23			1.2	2
24				3
25	26	5	1.2	8
26	46	5	1.2	8

Table VII Results of each example solved through Model II

Example no.	No. of assigned skilled workers	Number of assigned unskilled temporary workers	Cycle time
1	4	1	33.33 min
2	5	4	22.00 min
3	5	1	41.67 min
4	6	3	27.50 min
5	5	2	30.67 min
6	6	4	20.00 min
7	5	3	38.33 min
8	5	6	25.00 min
9	5	3	28.67 min
10	6	8	18.00 min
11	6	4	35.83 min
12	5	6	22.50 min
13	4	2	18.74 min
14	5	4	12.00 min
15	3	2	20.83 min
16	4	5	14.17 min
17	4	4	18.38 min
18	6	6	11.48 min
19	4	4	19.25 min
20	4	8	13.10 min
21	5	5	18.05 min
22	7	8	11.30 min
23	5	5	18.93 min
24	5	10	13.05 min
25	Not found		
26	Not found		

produced. In the scope of this case study, three types of options can be added in the subassembly line, and five types of automobiles are available. Table XIV lists the production ratios reflecting these research backgrounds.

Limitation to the task assignment for skilled workers at this automobile plant does not exist. Hence, only one skilled worker was assigned to each workstation. The installation and operation costs of a workstation are about \$30,000, and the annual salary of a skilled worker is about \$80,000. In the present state, there was a workstation at which the target cycle time could not be met, and the work overload became severe. Therefore, the assembly line needed to be stopped intermittently. The performance indicators for the current assembly line are summarized in Table XV.

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Table VIII Solution of Example 10 solved through Model II

Task sequence	i	k	S	o_{ik}	r_{ik}	o_i	r_i	Cumulative workstation time	w	Temporary worker
1	1	1	1	4	1	9.5	2	7.5	6	0
2		2		15	3					
3	2	2		10	3	5	1.5	11	6	0
4	4	1		6	2	3	1	14	2	
5	3	1	2	3	1	9	3	6	4	0
6		2		15	5					
7	5	1		5	3	11	3.5	13.5	5	0
8		2		17	4					
9	7	1		8	4	4	2	15.5	4	0
10	6	1	3	6	2	10	3	7	1	0
11		2		14	4					
12	8	2		12	3	6	1.5	11.5	1	0
13	9	1		3	1	7	2	16.5	3	0
14		2		11	3					

Table IX Upper limit of numbers of workers and workstations

Example no.	No. of tasks	Upper limit of number of workers allowed	Maximum number of workstations can be installed
1	9	2	2
2			3
3			4
4		3	2
5			3
6			4
7		4	2
8			3
9			4
10		5	2
11			3
12			4
13	14	2	2
14			3
15			4
16		3	2
17			3
18			4
19		4	2
20			3
21			4
22		5	2
23			3
24			4
25	26	5	8
26	46	5	8

Table X Results of each example solved through model III

Example no.	No. of assigned skilled workers	No. of assigned unskilled temporary workers	Total work overload
1	3	1	36.25 min
2	4	2	32.75 min
3	5	3	30.25 min
4	3	3	30.75 min
5	5	4	28.00 min
6	6	6	23.75 min
7	4	4	28.00 min
8	5	6	23.75 min
9	6	9	21.75 min
10	4	6	23.75 min
11	6	7	21.75 min
12	6	7	21.75 min
13	3	1	36.10 min
14	3	3	32.75 min
15	4	4	29.68 min
16	3	3	21.34 min
17	4	5	18.53 min
18	6	6	18.31 min
19	3	5	14.95 min
20	4	7	13.11 min
21	6	8	12.90 min
22	3	7	11.40 min
23	4	9	10.16 min
24	6	9	10.16 min
25	Not found		
26	Not found		

We assumed that cooperation between skilled and unskilled temporary workers could reduce the operation time of a task by 40 per cent. The performance indicators of the assembly line after line balancing are summarized in Table XVI. All workstations exceeding the target cycle time are eliminated. Work overload can also be ameliorated. Through our research, we can solve the problems arose in this plant, and it is possible to pursue cost efficiency and workload smoothing.

5. Conclusions

This paper extends the idea of the integrated ALBP introduced by Moon *et al.* (2009) to the mixed-model

Table XI Solution of Example 11 solved through Model III

Task sequence	i	k	S	o_{ik}	r_{ik}	o_i	r_i	Cumulative workstation time	w	Temporary worker
1	1	1	1	4	1	9.5	2	7.5	6	0
2		2		15	3					
3	2	2		10	3	5	1.5	11	6	0
4	3	1	2	3	1	9	3	6	4	0
5		2		15	5					
6	4	1		6	2	3	1	9	2	
7	5	1		5	3	11	3.5	16.5	5	0
8		2		17	4					
9	6	1	3	6	2	10	3	7	1	0
10		2		14	4				1	
11	8	2		12	3	6	1.5	15.5	1	0
12	7	1		8	4	4	2	11	3	
13	9	1		3	1	7	2	20.5	3	0
14		2		11	3				3	

Table XII Comparison of Model I and the proposed hybrid genetic algorithm

	Mathematical model I		Hybrid Genetic Algorithm		
Example no.	**Objective value**	**Remark**	**Objective value**	**Remark**	**Gap (%)**
1	\$82,200	Optimal	\$82,300		0.12
2	\$109,000	Optimal	\$112,000		2.75
3	\$107,800	Optimal	\$109,000		1.11
4	\$112,000	Optimal	\$112,000		0.44
5	\$113,000	Optimal	\$113,500		0.44
6	\$142,000	Optimal	\$142,200		0.14
7	\$26,500	Optimal	\$26,500	Optimal	0
8	\$28,000	Optimal	\$31,000		10.71
9	\$26,800	Optimal	\$28,000		4.48
10	\$29,500	Optimal	\$29,500	Optimal	0
11	\$31,000	Optimal	\$32,000		3.22
12	\$34,000	Optimal	\$34,200		0.59
13	\$74,900	Optimal	\$75,000		0.13
14	\$77,900	Optimal	\$78,000		0.13
15	\$109,700	Optimal	\$112,600		2.64
16	\$113,800	Optimal	\$116,000		1.93
17	\$118,100	Optimal	\$118,500		0.34
18	\$146,000	Optimal	\$146,400		0.27
19	\$20,900	Optimal	\$21,000		0.48
20	\$23,900	Optimal	\$24,000		0.34
21	\$28,700	Optimal	\$31,100		8.36
22	\$30,900	Optimal	\$35,600		15.21
23	\$33,500	Optimal	\$33,600		0.30
24	\$38,000	Optimal	\$38,400		1.05
25	Not found		\$128,200		
26	Not found		\$496,000		

assembly line and considers employment of unskilled temporary workers. In the industrial problem described herein, the available skill sets of each skilled worker can differ, and the operation time for completing tasks can be reduced by assigning unskilled temporary workers to cooperate with skilled workers. Three mathematical models were developed by integer linear program and mixed integer linear program for the integrated MMALBP featuring unskilled temporary workers. The models were designed to minimize total costs, including those associated with operation cost of workstations and the labor costs of skilled and unskilled temporary workers for a specified cycle time, to minimize the maximum cycle time for a specified number of workstations and to minimize the

Figure 5 Precedence diagram for the right-hand side of the subassembly line

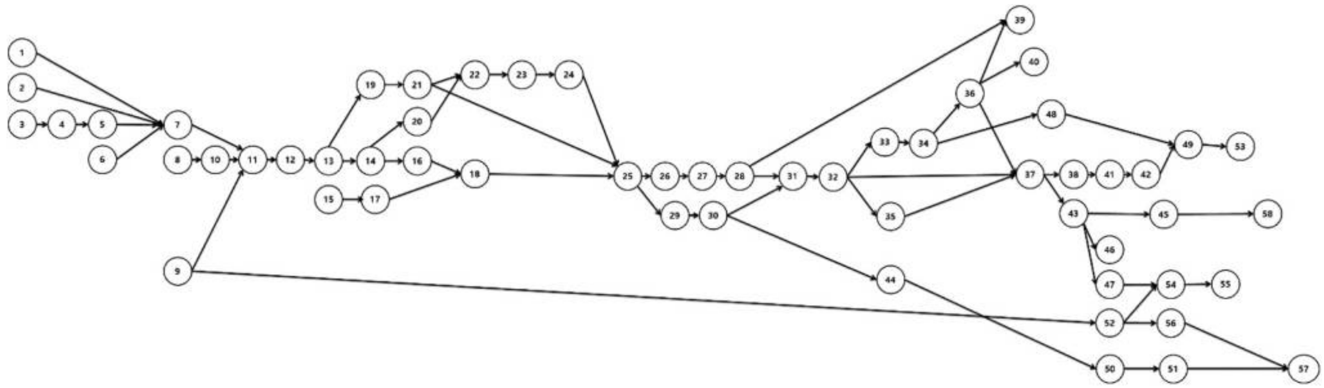

Table XIII Operation times of tasks

Task	Operation time	Task	Operation time	Task	Operation time
1	3	21	13	41	25
2	20	22	17	42	18
3	60	23	8	43	28
4	8	24	9	44	31
5	9	25	20	45	38
6	20	26	67	46	13
7	23	27	8	47	22
8	50	28	20	48	18
9	4	29	73	49	72
10	20	30	3	50	50
11	11	31	13	51	20
12	5	32	15	52	12
13	16	33	54	53	45
14	5	34	36	54	15
15	6	35	21	55	22
16	28	36	8	56	16
17	24	37	20	57	17
18	18	38	14	58	6
19	18	39	90		
20	17	40	20		

Table XIV Production ratios of an automobile

No option	BEST	ABS	RHS	RHD + ABS
68%	16%	6%	9%	1%

total work overload for a specific number of workstations. Computational experiments were conducted for each model to reveal managerial insights. Assembly line data from an automobile company in Korea were used to see how our research results could be applied to make the assembly line more efficient.

Furthermore, an efficient HGA was created to solve the problems. Effective heuristic algorithms were combined with the GA, and the efficiency of solution processes and the quality of solutions were taken into account. The proposed algorithm overcame the computational burden of the mathematical models. Therefore, the HGA was shown to be a more helpful means than the mathematical models for designing a cost-effective assembly line with worker assignments for large problems in the real world.

Table XV Performance indicators of current assembly line

No. of workstations & skilled workers	No. of workstations exceeding the target cycle time	Maximum total operation times for a specific model in a workstation	Total relevant costs
11	2	195	$ 1,210,000

Table XVI Performance indicators of the assembly line after line balancing

No. of workstations & skilled workers	No. of temporary workers	Salary of temporary workers	Maximum total operation times for a specific model in a workstation	Total relevant costs	Cost savings (%)
10	1	$35,000	150	$ 1,135,000	6.2
9	4	$25,000	165	$1,090,000	9.9
8	10	$15,000	178	$1,030,000	14.9

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Corresponding author

Ilkyeong Moon can be contacted at: ikmoon@snu.ac.kr