Design method of material handling systems for lean automation—Integrating equipment for reducing wasted waiting time

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A B S T R A C T

The production systems of today are required to meet changing market conditions. To date, most conventional flexible systems depend on human flexibility. However, the demand for flexible automation systems is increasing owing to rising labor costs and quality requirements, even in emerging countries. To implement automation systems in the unpredictable market, cost reduction is essential to reduce the investment risk. However, there is no systematic design method for reducing the cost of automation systems. In this study, we propose a new design method wherein the waiting time of material handling equipment is reduced by allocating multiple operations to the equipment.

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1. Introduction

The struggle for survival of manufacturers has become more critical in global competition. Up to now, developed countries have maintained their cost competitiveness by transferring the production site of low value products to low labor cost countries. However, there are many issues in this strategy today, such as continuous increase of labor cost, uneven quality owing to human errors, and difficulty in hiring and training associates. In such circumstances, there is a growing global need for automation systems. On the other hand, automation systems face various challenges such as inflexibility against market fluctuation [1] and the management risk owing to high investment costs [2]. To date, many efforts have been made to reduce cycle time using various methods such as line balancing and enhancement of line speeds, which resulted in the reduction of investment costs [3]. However, few studies have been conducted on the reduction of investment cost from the perspective of optimizing the equipment configuration of automation systems. In our previous study, we proposed a new design method focusing on the waiting loss of material handling equipment. With this method, we can reduce the investment of automation systems and enhance competitiveness [4]. In our previous paper, we presented a concept of lean automation, and proposed a basic design procedure for material handling systems for lean automation systems. We also applied the method to an actual assembly line as a case study. However, design optimization based on quantitative evaluation has remained a challenge. In this study, therefore, we propose a method for optimizing the design of material handling systems of the lean automation lines by means of cluster analysis and genetic algorithm (GA).

The remainder of this paper is organized as follows. Section 2 explains the concept of lean automation. Section 3 describes the design method of material handling systems for lean automation using cluster analysis and GA. In Section 4, the description of the proposed method being applied to an assembly line of an electric engine control unit (ECU) to verify its effectiveness is presented. Section 5 discusses the method and Section 6 concludes the paper.

2. Concept of lean automation

We analyzed the current investment for automation lines. We can broadly divide operations into two categories: value added operations ("main operations", hereafter) and auxiliary operations primarily for material handling, which do not create values. The cost of the equipment for executing the value-added operations, which varies from product to product, accounts for approximately 60% of the total investment in the case of automobile parts manufacture, regardless of the type of operations, such as assembling or machining. Execution of main operations is a core competence of the company and directly relates to product competitiveness; hence, it is difficult to discuss the cost reduction of such operations in a general way. The remaining 40% of the total investment comes from the cost for material handling operations, such as transferring workpieces between machines, or feeding and taking parts to and from the main operations. These operations are basically the same, regardless of the products, and can be executed by general purpose equipment. In this study, therefore, we focus on the method for the cost reduction of this equipment. In the conventional design method of an automation line, the equipment for material handling operations is selected in each station,
which consists of the line and corresponds with the main operation, after their order is determined, as shown in Fig. 1(a). Consequently, the operation ratio of each material handling equipment is quite low, because each equipment is used for material handling operations associated with only one main operation. This is regarded as a huge waste from the perspective of “lean production,” in which waiting loss should be eliminated as much as possible. In this study, we focus on this waste, which has been overlooked up to now. The proposed new design method of material handling equipment aims at maximum utilization of each equipment by allocating it to multiple operations even though it is distributed in different stations, as shown in Fig. 1(b). This enables a decrease in the wasted waiting time of each equipment, and results in a reduction of the number of equipment and the investment cost of automation lines. This result occurs when the reduction of the equipment costs owing to the decreased number of the equipment is larger than the increase of the equipment cost, which, in turn, is induced by the enhanced capability of the equipment, as well as the cost for transferring the equipment to conduct multiple material handling operations across the stations. Traditionally, the concept of elimination of seven losses operations has been developed focusing on waste of human motions and called “lean production.” We apply the concept to automation systems; therefore, we call such systems “lean automation systems.”

3. Design method of material handling systems for lean automation

3.1. Outline of the design method

To realize the concept of lean automation system described in the previous section, we propose the method to minimize the total equipment cost for material handling operations by aggregating the operations and allocating them to the proper equipment, with the following procedure.

1) All material handling operations associated with all main operations are enumerated.
2) Characteristics of each operation are described in terms of the attributes of the object to be handled and the motions necessary to execute the operation.
3) The operations enumerated in step (1) are grouped into a given number of operation groups by means of this clustering analysis.
4) The set of operation groups obtained by cluster analysis is improved considering other factors such as a cycle time constraint, as well as the time and cost for transferring the equipment by means of GA, wherein the total equipment cost is used as the fitness value. In calculating the fitness value, the least expensive equipment among those capable of executing all operations included in one group in terms of the time to travel to the positions and the cost for the transferring equipment. Secondly, we must consider other factors when allocating the equipment to each operation group. First, we should consider the distance among the positions of the operations included in one group in terms of the time to travel to the positions and the cost for the transferring equipment. Secondly, we must consider that the equipment that can execute complicated operations may execute simpler operations as well. For example, 6-axes industrial robots can execute simple pick and place operations, which can be executed by 4-axes SCARA robots. Therefore, the operation groups obtained by the clustering algorithm are not necessarily the optimal ones. We adopt GA for improving the operation groups and selecting the most cost effective configuration of the material handling equipment, taking these factors into account.

3.2. Description method of operations and equipment functions

Similar operations can be executed by the same equipment; therefore, we aggregate the material handling operations based on their similarities in step (3), as described in the previous section. For this purpose, the characteristics of each operation are described in terms of two sets of attributes: those related to the object to be handled, and those related to the motions necessary to execute the operation.

These attributes and their values are indicated in Table 1. The attribute values are quantified within the range from 0 to 1. The similarities between the operations are evaluated in terms of the square Euclidean distances between the attribute vectors.

![Fig. 1. Concept of lean automation system.](image)

<table>
<thead>
<tr>
<th>Main Operation A</th>
<th>Main Operation B</th>
<th>Main Operation C</th>
<th>Main Operation D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3</td>
<td>1 2 3</td>
<td>1 2 3</td>
<td>1 2 3</td>
</tr>
</tbody>
</table>

Table 1 Attributes and their values for representing operation characteristics.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Workspace characteristics</th>
<th>Transfer characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>Mass</td>
<td>Shape</td>
</tr>
<tr>
<td>10kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
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<tr>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The set of attributes defined in Table 1 is also used for describing the capability of the equipment when selecting the equipment which can execute the operations involved in each operation group.

3.3. Optimization of operation aggregation and equipment selection

3.3.1. Clustering of operations

To categorize the operations into a certain number of groups, we apply the K-means clustering algorithm [5]. We can group the operations into a given number of groups by means of this algorithm. The clustering is executed solely by the similarities among the operations measured by the distances among the attribute vectors. However, we must consider other factors when allocating the equipment to each operation group. First, we should consider the distance among the positions of the operations included in one group in terms of the time to travel to the positions and the cost for the transferring equipment. Secondly, we must consider that the equipment that can execute complicated operations may execute simpler operations as well. For example, 6-axes industrial robots can execute simple pick and place operations, which can be executed by 4-axes SCARA robots. Therefore, the operation groups obtained by the clustering algorithm are not necessarily the optimal ones. We adopt GA for improving the operation groups and selecting the most cost effective configuration of the material handling equipment, taking these factors into account.

3.3.2. Optimizing operation groups and equipment selection

We apply GA to improve the set of operation groups for minimizing total equipment cost, considering the factors mentioned in the previous section. The optimization using GA is repeated by changing the number of the operation groups within the range from 1 to \( n_{op} - 1 \), where \( n_{op} \) denotes the number of all operations included in the production line. The set of operation groups with the minimum equipment cost (among the best solutions for each number of the operation groups) is selected as the optimal solution.

The operation groups are described by the chromosome as presented in Table 2. Each gene locus represents the operation...
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