Development of information system to generate assembly order of parts considering work difficulty

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Abstract. In this study, we develop an information system to generate the assembly order of parts to reduce work difficulty during parts assembly. Several types of tables are proposed to store the relationship of connection and contact between parts and characteristics related to the structure between parts causing work difficulty. In addition, a mathematical model is constructed to generate the assembly order of parts to reduce work difficulty. The effectiveness of the developed system is evaluated based on numerical and assembly experiments using an actual product.

1. Introduction
In many assembly processes of parts, multiprocess holding works are introduced because their flexibility allows complex works to be performed in a short time. Therefore, even in high-mix low-volume productions, production conditions are assessed and works are performed in a short time; therefore, workers must be able to flexibly manipulate a plurality of parts successively. In the mass production or continuous production of the same product, the work is repeated; therefore, learning and jigs can be easily introduced for productivity enhancement. However, when high-mix low-volume production or single-product manufacturing is enhanced, a process line tends to be constructed through the assignment of multiple handling works to single workers [1]. Although different works and parts are allocated to the process line for processing different products, similar products and works are included [2].

However, in the current manufacturing industry, several problems exist, such as difficulty in reducing workers, increasing wages, adjustment of number of workers owing to fluctuations in demand, and management of worker skills. Hence, to measure the productivity enhancement of parts assembly, we developed a method to determine the order of parts assembly that facilitates a reduction in work operation time. If we can seamlessly determine the assembly order of parts using information of Computer Aided Design (CAD) software for product design, then both product and work designs can be performed simultaneously, and the period of work design can be reduced. In addition, if an information system to estimate the operation time of a work process is developed, then works can be managed easily. To realize this mechanism, the following processes must be combined: a process for generating information to determine the assembly sequence from CAD; a process for calculating the sequence to assemble the parts; and a process for estimating the operation time.

In this study, an information system including the mechanism combining the processes above was developed, and the effectiveness of the system is demonstrated through a case study.
2. Evaluation method of work difficulty by product structure

The purpose of this study is to construct an information system combining product design and work design. We assumed that work difficulty is evaluated from the structure of parts that constitute a product. We focus on multiple factors that cause work difficulty to generate from the part structure and evaluate the difficulty by combining the evaluation values of factors. Parts assembly can be expressed as repeating the work of “assembling one part into a semi-finished product” and the assembly of a single part is regarded as one work unit. Subsequently, factors of work difficulty that affect the structure of parts appearing in one work unit are evaluated. We assume that this one work unit is composed of the following tasks:

(w1) picking and moving a single part,
(w2) assembling a single part into a semi-finished product.

Tasks (w1) and (w2), are used to calculate the operation time considering the difficulty using the method time measurement (MTM) method.

We categorize the factors causing the work difficulty into parts to assemble, semi-finished products, and support parts, such as bolts and nuts. Table 1 shows a list of the factors, which are used to evaluate the difficulty from the parts structure [3].

| Objects                | Categories | Factors                                      |
|------------------------|------------|----------------------------------------------|
| Parts                  | Positioning| (1) Direction or side to assemble a single part |
|                        |            | (2) Size and weight                          |
|                        | Method to assemble a part | (3) Clearance |
|                        |            | (4) Usage of tool to assemble a single part   |
| Semi-finished product  | Supporting | (5) Obstacles generated when a part is assembled |
|                        |            | (6) Unsteadiness generated when a part is assembled |
|                        |            | (7) Obstacles generated when a support part is used |
|                        |            | (8) Unsteadiness generated when a support part is used |
| Support parts          | Positioning| (10) Direction or side to use a support part |
|                        |            | (11) Size and weight                         |
|                        | Method to use a support part | (12) Clearance |
|                        |            | (13) Usage of tool to use support parts       |

3. Construction of data matrix based on parts structure using design information by CAD

3.1. Matrices to express the characteristic relationship between parts

From the design information in CAD, matrices that express the connection between parts and the evaluation values of the factors of work difficulty related to the structure of the parts were constructed. Several types of matrices were created to store the structure of the parts from CAD. Subsequently, these matrices were used to determine the assembly order of the parts.

The following matrices were created to represent the characteristic relationship between parts:

(m1) A matrix to present the connection between parts with the direction to assemble the part,
(m2) A matrix to present the characteristics of obstacles that appear when a single part is assembled,
(m3) A matrix to present the relationship between parts causing an unstable state of the semi-finished product when a single part is assembled.
In matrix (m1), part numbers are assigned to both rows and columns, whereas ±x, ±y, and ±z are allocated in the elements of row i and column j to present the direction in which part pi at row i connects to part pj at column j. The directions of ±x, ±y, and ±z are denoted in Figure 1.

In matrix (m2), part numbers are assigned to both rows and columns, and the evaluation value of the connection between parts pi and pj is described in the element of row i and column j. When no contact exists between these parts, 0 is allocated to the element.

In matrix (m3), part numbers are assigned to both rows and columns. If part pi of column j is not included in the semi-finished product and the semi-finished product is determined as an unstable state when part pj is about to be assembled, then the evaluation values are assigned to the element of row i and column j. Otherwise, 0 is assigned to the element.

3.2. Construction of characteristic relationships between parts using CAD

3.2.1 Structure including no inclusive relationship between parts

We developed a process to create the matrices from the relationship between parts in three-dimensional (3D) CAD. The 3D-CAD software used was Rhinoceros6, and the software to create the matrices was generated using Python. In this CAD, the position of a shape’s vertex for each part and the vertex positions of a cube created from the outermost circumference of the part can be obtained. Figure 1 shows the schematic diagram of the structure of parts including no inclusive relationship between parts. In a cube created from the outlines of the parts, vertices having minimum values in the x, y, and z-coordinates are regarded as the origin, and the vertices are denoted as Point10 (x10, y10, z10) in Figure 1. The direction vectors dx1, dy1, and dz1 in the x, y, and z-coordinates were investigated by comparing the origin with the vertices in the x, y, and z-directions.

The x vertices and the direction vector in the x-coordinates were compared to evaluate the connection. Under the condition that $x_{10} \geq x_{20}$, the connection between different parts in the x-direction vector was assessed based on the following conditions:

1. $x_{10} - x_{20} < dx_2 - \delta$,
2. $dx_2 - \delta \leq x_{10} - x_{20} \leq dx_2 + \delta$,
3. $x_{10} - x_{20} > dx_2 + \delta$.

Here, $\delta$ denotes a small number. Because the overlapping area of two different parts is determined from these conditions, either the connection, contact, or noncontact of these parts is evaluated in the x-direction. In addition, similar comparisons are made in the y and z-directions to determine the relationship between the parts. Finally, the connection, contact, or noncontact relationship between the two parts is determined by evaluating the relationships between the parts in the x, y, and z-coordinates simultaneously.

Furthermore, product structures that have internal relationships between parts exist. However, if the overlapping area of two parts is evaluated in the product with the internal relationship, the internal relationship in the parts cannot be identified, and the relationship is regarded as the connection relationship between parts. Hence, engineers are required to modify the relationship between the parts with the internal relationship from connection to noncontact, as shown in Figure 2.

![Figure 1](image1.jpg)  
**Figure 1.** Schematic diagram of parts structure including no inclusive relationship of parts.

![Figure 2](image2.jpg)  
**Figure 2.** Schematic diagram of parts structure including inclusive relationship of parts.
3.3. Evaluation of factors of work difficulty in assembly process

3.3.1 Evaluation of obstacles in assembling a single part

We address the presence of obstacles, which is a factor causing work difficulty, when a single part is assembled. The difficulty caused by the contact relationship between the part that becomes an obstacle at the time of assembling a single part to the semi-finished product and the single part is classified into the following four levels:

L1: When no connection and no contact exist between the parts, the evaluation value is 0.
L2: When the parts are contacted at points or edges, the evaluation value is 10.
L3: When the parts are contacted at the surface of each of the other parts, the evaluation value is 50.
L4: When the parts are connected, the evaluation value is 0.

3.3.2 Evaluation of unstable state of semi-finished products at the time of assembling a single part

The unstable state of a semi-finished product at the time of assembling a single part is regarded as a factor of work difficulty. The unstable state is typically caused when the parts required to yield a stable state are not assembled to the semi-finished product. For example, an unstable state of a semi-finished product is generated by the presence of unconnected parts at a lower position than the assembling position of a part. The following evaluation values are used to evaluate the unstable state:

L1: When the semi-finished product does not include more than one part required to yield a stable state, the condition is judged as an unstable state and the evaluation value is 100.
L2: When the semi-finished product includes all parts required to yield a stable state, the condition is judged as a stable state and the evaluation value is 0.

3.3.3 Evaluation of assembling direction of parts

The following evaluation is performed from the assembling direction of a single part when the part is assembled to a semi-finished product. Here, the right hand is assumed as the dominant arm.

L1: When the single part is assembled in the +x-direction, the evaluation value is 100.
L2: When the single part is assembled in the -y-direction, the evaluation value takes 50.
L3: When the single part is assembled in the +z-direction, the evaluation value takes 10.
L4: When the single part is assembled in the -x, +y, and -z-directions, the evaluation value is 1.

All of the x, y, and z-directions were determined according to the coordinate system shown in Figure 1.

3.3.4 Evaluation of weight of parts to be assembled

At the time of assembling a single part to a semi-finished product, the weight of the part to be assembled is evaluated according to the following conditions:

L1: For 5.6 kg or more, the evaluation value is 1.5.
L2: For 3.4–5.6 kg, the evaluation value is 1.2.
L3: For 1.1–3.4 kg, the evaluation value is 1.1.
L4: For 1.1 kg or less, the evaluation value is 1.0.

4. Method for determining parts assembly order considering work difficulty

4.1. Construction of mathematical model

We developed a method to determine the assembly order of parts to facilitate the work. The work difficulty is evaluated from the factors when a single part is assembled to a semi-finished product in Table 1. The order of parts to assemble the product is generated by minimizing the sum of the values of the difficulty when all parts are assembled. Equation (1) shows the objective function in the mathematical model.

\[
\min z = \sum_{j=1}^{J} \sum_{i=1}^{I} s_{ij} D_{ij} \alpha_{ij} n_{ij} + \sum_{j=1}^{J} \sum_{i=1}^{I} s_{ij} D_{ij} F_{ij} b_{ij} \tag{1}
\]

In Equation (1), \(i\) denotes the part number to determine the order of parts to assemble the product. \(n_{ij}\) is the number of obstacles when part \(j\) is assembled under the condition that part \(i\) is assembled prior to
part \( j \). \( \alpha_{ij} \) is the evaluation value of part \( i \) as an obstacle from the point of view of part \( j \). From these symbols, the first term of Equation (1) denotes the sum of evaluation values related to obstacles in the assembly order of parts generated. \( F_{ij} \) denotes the evaluation value related to the unstable state of the semi-finished product, in which part \( i \) is NOT assembled when part \( j \) is about to be assembled. \( b_{ij} \) is variable, which is 1 when part \( i \) is assembled prior to part \( j \), and 0 otherwise. From these symbols, the second term of Equation (1) denotes the sum of evaluation values related to the unstable state of the semi-finished product. \( s_j \) denotes the evaluation values of the weight of part \( j \). \( D_{ij} \) denotes the evaluation values of the direction of part \( j \) to assemble when part \( j \) is assembled to part \( i \).

To generate the assembly order of parts, the evaluation values of obstacles in the assembly order of parts and the unstable state of the semi-finished product are simultaneously reduced by minimizing Equation (1). By minimizing the objective function, we assume that the assembly order of parts that removes the difficult state to work to the maximum is obtained. The evaluation values of \( \alpha_{ij} \), \( F_{ij} \), \( D_{ij} \), and \( s_j \) are as shown in Sections 3.3.1, 3.3.2, 3.3.3, and 3.3.4, respectively. These variables are treated as the factors of difficulty.

4.2. Numerical experiment

A mathematical model was used to calculate the assembly order of parts. A product composed of LEGO blocks was used as the final product. Figure 3 shows a photograph of the product, and the number of parts of the product was 42.

Numerical experiments were performed for each of the semi-finished products A, B, C, and D shown in Figure 3. The weight and direction of the parts to be assembled were assumed to be the same for all parts because of the small weight of all blocks and the downward direction, and both evaluation values were set to 1. Table 2 shows the objective function values obtained from the numerical experiments.

![Figure 3. External form of the product used for assembly experiment.](image)

| Semi-finished product | Value of terms of objective function | Objective function |
|-----------------------|--------------------------------------|--------------------|
|                       | Obstacles | Unstable state of the semi- |                  |
|                       | Min       | finished product           |                  |
| A                     | Min       | 9050                      | 2500              | 11550              |
|                       | Max       | 14650                     | 3650              | 18300              |
| B                     | Min       | 15750                     | 5150              | 20900              |
|                       | Max       | 36250                     | 6800              | 43050              |
| C                     | Min       | 12550                     | 2700              | 15250              |
|                       | Max       | 23850                     | 4150              | 28000              |
| D                     | Min       | 400                       | 200               | 600                |
|                       | Max       | 600                       | 300               | 900                |
| Assembly process of the final product | Min | 1000                      | 500               | 1500               |
|                       | Max       | 1550                      | 700               | 2250               |
5. Estimation of work time using MTM and evaluation of proposed system

The work time was estimated using the MTM method [4] from the assembly order of parts obtained in the numerical experiment. Because the parts assembly process is described as “repeating a single part assembled to a semi-finished product,” the process for assembling a single part is regarded as the unit work process, and the operation time is calculated from motions included in the unit work process using MTM. The operation time is estimated according to the following procedure:

1. The basic motion in the unit work process is composed of M (MOVE), G (GRASP), M, P (POSITION), P, and M.
2. The MTM representation related to the distance from the work area to the parts storage space is generated as the same data in all unit works.
3. The differences in work motion modified by the assembly order of parts from the basic work motion presented in (1) are evaluated, and MTM representation is modified.
4. The operation times of all work units are calculated using the MTM representation modified in (2). Subsequently, the total operation time is estimated from all work units.

Table 3 shows the operation time calculated by MTM for the assembly processes of different semi-finished products. In this table, “max: and “min” denote the operation times of the parts assembly process obtained at the maximum and minimum of the objective function, respectively.

From the results of products A, B, and C, it was shown that the operation time calculated from MTM was not necessarily short even in the case of the work sequence at the minimum objective function. We speculate that this result was caused by the following characteristics in the calculation of MTM: the unstable state of the semi-finished product was not considered, and the effects of obstacles were evaluated to be small owing to the simple structure of the product, as the evaluation of the unstable state of the semi-finished product was not included in MTM method originally.

Table 3 shows the results of the experiment using the actual product based on the assembly order of the parts obtained from the numerical experiment. Six participants were recruited for the experiment. Three participants performed the assembly work thrice using the order of the parts obtained from the minimization of the objective function, followed by the assembly work thrice using the order obtained from the maximization of the objective function three times. These participants were named the A-Group. The remaining three participants performed the work with the opposite order related to the objective function and were named the B-Group.

Figure 4 shows that the operation time of the work obtained from the minimization of the objective function was shorter than that obtained from the maximization of the objective function, and that the learning effect of the work obtained from the minimization of the objective function was higher than those of other works. The results demonstrate the effectiveness of the proposed mathematical model for calculating the assembly order of parts.

The total operation time estimated by MTM differed by approximately 25 s from that of the assembly experiment. This difference was assumed to be due to the non-consideration of the unstable state in the calculation using MTM. However, the difference in the time required (less than 20% in 170 s in the experiment) was considered to be effective for practical use.

| Semi-finished product | Estimated time (s) | Assembly process of the final product | Total |
|-----------------------|-------------------|--------------------------------------|-------|
| Min                   |                   |                                      |       |
| A                     | 32.414            | 48.919                               | 9.344 | 136.053 |
| B                     | 36.865            | 35.253                               | 8.511 |       |
| C                     | 8.511             |                                      | 9.344 |       |
| D                     | 9.344             |                                      | 9.344 |       |
| Max                   |                   |                                      |       |
| A                     | 32.011            | 47.307                               | 8.511 |       |
| B                     | 35.253            |                                      | 9.344 |       |
| C                     | 8.511             |                                      | 9.344 |       |
| D                     | 9.344             |                                      | 9.344 |       |
6. Summary
In this study, we developed a data structure to relate the characteristics of parts using CAD information and a method to generate the assembly order of parts considering work difficulty in the parts assembly process. In addition, we developed a system to estimate the operation time of the generated assembly order of the parts using MTM. These procedures were combined to form a total information system. The effectiveness of the total information system was demonstrated through numerical and assembly experiments.

In future work, we will investigate the effectiveness of the system for products with more complex component structures.

7. References
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