Standardizing Components and Rotating Workers Using GT-Based Algorithm—A Case Study

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Abstract: In both manufacturing and remanufacturing systems, exploiting bulk buying and avoiding delivery delays due to material shortages are crucial. One method that aids in these processes is component standardization. Additionally, company managers seek to reduce labor costs and mitigate the risk of sudden worker resignation or absence due to, for example, reasons associated with the COVID-19 pandemic. The aforementioned problems could be solved using the sorting algorithm proposed in this study. The concept of the proposed algorithm is based on group technology. One numerical example and two case studies are presented to demonstrate the utility of the proposed algorithm. The first example suggested that the performance of the algorithm proposed in this study is superior to another one in the literature. The second one demonstrated that the algorithm in this work achieves component standardization by reducing an initial number of 12 components down to 6. The final case study provides an effective means of grouping workers with similar operational abilities and suggests how to assign new tasks to other skilled workers if a worker resigns suddenly or cannot attend work due to pandemic prevention measures.

Keywords: remanufacturing system; component standardization; group technology; sorting algorithm; similarity coefficient

1. Introduction

Industry 4.0 has profoundly changed manufacturing and remanufacturing. While the two systems differ, they both require finished goods to be delivered on time. Company leaders place tremendous importance on timely deliveries, but delays can be difficult to avoid. Two factors contribute to delays: a lack of materials and the low performance of manufacturing and remanufacturing systems. A shortage of materials can result when a company has too many types of components and not enough of each in stock. In other words, the more parts there are, the higher the risk of a shortage. Manufacturing and remanufacturing systems can perform poorly when workers are suddenly absent.

The two cases in this study consider a manufacturer whose major products are DC sources, AC sources, and power supplies. The R&D staff are divided into teams, with each responsible for different projects. This results in team A not knowing which components are used by team B, making component standardization more difficult. The vice president of manufacturing found that the products were not being delivered on time. One of the reasons was a lack of materials. More than 15,000 components were on the bill of materials, and not enough of each part was kept in stock. The vice president wanted to exchange one part for another, but if part $i$ has not been approved by the R&D engineers, then it cannot be used to replace part $j$, even if the two are similar. The vice president wanted to reduce the number of components and increase the safety stock levels. In addition, the vice president wanted to rotate the workers so that the finished goods could be delivered on time, but the substituted workers were initially inefficient because some of them had never performed the tasks.
Component standardization could solve the problem of the lack of materials, and the rotation of workers with similar skills could keep performance high even though workers were absent.

2. Component Standardization in Manufacturing and Remanufacturing Systems

2.1. Manufacturing

Traditionally, manufacturing is a process that transforms raw material into finished products to be sold to customers. The changing environment, especially an uncertain market, places company management under pressure to reduce costs and deliver products on time. The company that uses the manufacturing system best suited to its environment can increase its production efficiency. There are many types of manufacturing systems. Dorf and Kusiak [1] give four manufacturing systems: custom, intermittent, continuous, and flexible. Classifying manufacturing systems based on machining type gives dedicated machining systems, flexible machining systems, and reconfigurable machining systems [2]. The introduction of Industry 4.0 has brought new trends to the design of manufacturing systems. Three concepts—focused-flexibility manufacturing systems (FFMSs), reconfigurable manufacturing systems (RMSs), and smart manufacturing systems (SMSs)—have met the challenges of the Industry 4.0 philosophy [3].

The characteristics of manufacturing systems are uncertain due to the uncertainty inherent in customer demand, the supply chain, and the manufacturing process. There are at least two factors that increase the complexity of a manufacturing system: labor and the number of parts [4]. For example, a worker might be absent due to circumstances related to the COVID-19 pandemic, and the greater the number of parts, the greater the risk that some materials are lacking. One Industry 4.0 trend is advanced manufacturing systems [5]. Advanced manufacturing technology (AMT) has in part become critical due to the need for high-value, low-volume products [2]. As AMT requires workers with advanced skills, the effectiveness and efficiency of the manufacturing process and the quality of the goods produced depend on the skills of the workforce [6]. The training of workers has taken on new significance, with managers showing proficiency at sending select workers to attend essential classes on a limited budget.

2.2. Remanufacturing

In addition to waste disposal, three end-of-life strategies are available for industrial companies: reuse, remanufacturing, and recycling [7]. Supporting a sustainable environment on Earth is essential. Several product recovery options promote a sustainable environment. Recycling and remanufacturing are the two most advanced product recovery options [8]. Remanufacturing has become a prominent topic, especially in the last 20 years. Because the concepts of product multilife cycle and extended producer responsibility have been popularized [9,10], remanufacturing has become an integral part of many supply chain operations [11].

Rather than being disposed of, numerous used products and their components can be reused. Reusing older product components or semiproductions and reinstating them back into the manufacturing process for new product production may be efficient policies for manufacturing enterprises. Remanufacturing is defined as “recycling by manufacturing ‘good as new’ products from used products” [7].

The key difference between manufacturing and remanufacturing is that manufacturing involves the use of new components, whereas remanufacturing involves the use of used components. In addition, the basic life cycle stages of the manufacturing system include design, sourcing materials, production, assembly, and quality control; the remanufacturing system stages include disassembly, sorting, inspection, cleaning, refurbishment, reassembly, and quality control [2].

Because the life cycle stages of the remanufacturing system include cleaning and refurbishment, parts that are renewable are used in the remanufacturing process. Hence, producing components from raw materials at the outset is not required, and, therefore, the
remanufacturing process reduces the energy consumed in the process of production and thus limits environmental damage [12]; it also prolongs the lifetime of products [13].

Apart from reduced energy consumption, the benefits of remanufacturing compared with traditional manufacturing are as follows: less consumption of raw materials [7,14,15], less pollution, and less required investment [2]. In addition, Das and Dutta’s [16] research indicated that product and component remanufacturing can reduce order variations and the bullwhip effect at both the retailer and distributor levels. In the life cycle of reusable products, especially in reverse logistics management or in a closed-loop supply chain, remanufacturing continues to play a critical role. Thus, the remanufacturing model is not only circular in nature but also economical [17].

Although remanufacturing can, compared with traditional manufacturing, reduce pollution, investment, and energy consumption, some risks arise. The major risk is uncertainty [2,18,19]. The uncertain quality and quantity associated with remanufacturing affect the confidence in and support for remanufacturing businesses. Industry 4.0 focuses on the integration of the Internet of Things (IoT). In the IoT, modern smart technology is used that offers solutions for remanufacturing. Fatimah et al. [20] used Industry 4.0 technologies to develop a sustainable waste management system that includes mixed collecting, sorting, transportation, varied treatment, and chained disposal functions. However, the problem of uncertain quality persists.

Sorting and inspection are vital processes of the remanufacturing system. Before the dispatch of reusable items to the remanufacturing chain, all waste items must be sorted and classified to determine which items can be recycled. Whether a component is to be reused or becomes waste depends on its quality. Yan et al. [21] demonstrated that a recycled product can be used as a second-hand product, repaired, or disassembled into materials according to its quality. Generally, for companies, the higher the ratio of reusable to disposable components, the greater is the economic profit.

2.3. Component Standardization

The cost of inventory in a remanufacturing system is higher than in a manufacturing system [2]. One resolution to this issue is component standardization. The term component standardization implies that several components can be replaced by a single component that has the specific functions of all the aforementioned components [22]. The traditional manufacturing system has less need for a costly inventory, and profits are obtained through bulk buying to achieve component standardization. In addition, component standardization can reduce labor costs and the requirement for multiskilled operators [22]. Achieving component standardization in the remanufacturing system can also reduce the number of material types, maximize homogeneous material recovery, and facilitate the disassembly and remanufacture of components [15]. Even the waste sorting step in the remanufacturing system can eventually become unnecessary [23].

However, component standardization has some disadvantages in the manufacturing and the remanufacturing system, such as resisting change, blocking progress, and favoring only large companies [24]. The standardized components might also have excess functionality [22] because the components must meet all of the requirements of the semiproduct or finished product that uses them.

The COVID-19 pandemic affected the global economy and supply chain considerably in 2020. However, retaliatory consumption triggered substantial growth in production demand when vaccines began to be deployed, and a resultant material and component shortage ensued. By implementing component standardization and stockpiling components earlier in preparation, such suboptimal situations could have been avoided. The benefits of component standardization are being leveraged in manufacturing systems based in one factory, but these benefits are being ignored in remanufacturing systems. Thus, component standardization can reduce costs as well as the dependence on the parts provision in the reverse logistics process. In addition, component standardization can be
applied across different factories, enabling the recycling of parts at different locations if such parts have the same specification.

2.4. Aim

Companies need to handle the absence of workers and achieve component standardization. In the literature, the declarative model and constraint programming (CP) technology are used to resolve the problem of absent workers [25,26]. Szwarc et al. [27] even used this method to solve the teacher allocation problem. Several methods have been proposed to achieve component standardization, such as neural networks [28], the shape similarity algorithm [29], and the zero-based approach [30].

The aim of this study is to solve these two problems by using the concept of group technology (GT), both for manufacturing systems and remanufacturing systems.

3. Methodology

The algorithm discussed in this article is based on the concept of GT, especially in terms of the algorithm’s definition of the similarity coefficient.

3.1. GT

In a manufacturing or remanufacturing system, a manager must reduce relative costs and material handling. The cost of material handling constitutes 15% to 70% of the total manufacturing cost of a product [2]. The principal benefits associated with cellular manufacturing (CM) are reductions in throughput time, setup time, and inventory [31,32]. Hence, reductions in the overall processing time and material handling costs can be achieved through the optimum machine cell and part family formation [33,34]. The concept of GT has been implemented in CM [35–40].

GT algorithms can be used to group similar parts or machines [41,42], meaning that GT provides a method of sorting machines into machine cells and parts into part families [43–49]. Several algorithms have been developed to solve the component standardization problem, such as heuristics [50–55], genetic algorithms [56–60], and closed neighbor algorithms [43,44,61]. In addition, conventional GT was limited to two dimensions, but Parkin and Li expanded it to multidimensional GT in 1997 [44].

Conventional GT has the benefits of reducing material handling and part movement times. Consider the following incidence matrix $A$, where $a_{11} = 1$ implies that $p_1$ must be operated on by $m_1$, and $a_{21} = 0$ implies that $p_1$ should not be operated on by $m_2$.

$$
A = \begin{bmatrix}
m_1 & p_1 & p_2 & p_3 & p_4 \\
m_2 & 1 & 1 & & \\
m_3 & 1 & 1 & & \\
m_4 & 1 & 1 & & \\
m_5 & 1 & 1 & & 
\end{bmatrix}
$$

If the plan of the incidence matrix is to let $\{m_1,m_2,m_3,p_1, p_2\}$ be a group and $\{m_4,m_5,p_3, p_4\}$ be another group, then, for instance, part $p_1$ must be moved between two groups. However, when the GT algorithm is used in this example, two groups can be formed, and then all parts can be operated on in only one group without the requirement to move to another group.

$$
A^{sort} = \begin{bmatrix}
m_1 & 1 & 1 & & \\
m_2 & 1 & 1 & & \\
m_3 & 1 & 1 & & \\
m_4 & 1 & 1 & & \\
m_5 & & & & 
\end{bmatrix}
$$
Some authors have noted that the method of sorting different parts into a part family is based on the relationships between a part’s figure, operating process, and characteristics [62]. Won and Logendran [48] as well as Huang and Yan [63] have used a new similarity coefficient method to solve cell formation problems, and a typical similarity coefficient algorithm used for GT was proposed by McAuley [50].

\[ sc_{ij} = \frac{\epsilon_{ij}}{\epsilon_i + \epsilon_j - \epsilon_{ij}} \]

where \( \epsilon_i \) and \( \epsilon_j \) represent the number of parts processed by machines \( i \) and \( j \), respectively, and \( \epsilon_{ij} \) represents the number of parts processed by both machines \( i \) and \( j \).

The major obstacle in component standardization is the difficulty in ascertaining which parts can be standardized in large inventory data sets (bills of materials). Thus, initially, the groups include parts, and the products for which these parts are used must be identified. The aim of component standardization can be identified through discussion with R&D engineers. A further problem in both manufacturing systems and remanufacturing systems is high labor costs [64]. This study can also solve this problem as explained in example 3.

Conventional GT has two dimensions: machines and parts. However, the part figures, operating processes, and characteristics are the focus of this article, not machines.

To achieve component standardization, the following assumptions have been made:

1. The sequences of operations among parts are not considered.
2. The volumes of parts are not considered.

Suppose an incidence matrix \( A \) exists with order \( m \times n \), which means it includes \( m \) machines and \( n \) parts. The incidence matrix is defined as follows: \( A = \{a_{ij}\} \), where

\[ a_{ij} = \begin{cases} 1 & \text{if part } j \text{ interacts with machine } i, \text{ then } a_{ij} = 1; \text{ otherwise, } a_{ij} = 0. \end{cases} \]

The parts used in a manufacturing process generally follow this sequence. Thus, the operational sequence of the incidence matrix is defined as follows:

\( OS = \{os_{ij}\}_{m \times n} \) where \( os_{ij} \) is the \( os_{ij} \)th operating process of part \( j \).

The algorithm proposed in this study must transfer matrix \( OS \) to matrix \( A \) first. Thus,

\[ a_{ij} = \begin{cases} 1, & \text{if } os_{ij} \neq 0 \\ 0, & \text{otherwise} \end{cases} \tag{1} \]

3.2. Machines Sorting

The relationship between two machines in incidence matrix \( A \) is called the similarity coefficient and is defined as follows:

\[ SC_m = \{sc_{ij}\}_{m \times m} \tag{2} \]

where

\[ sc_{ij} = \frac{\epsilon_{ij}}{\epsilon_i + \epsilon_j - \epsilon_{ij}} \tag{3} \]

and

\[ \epsilon_{ij} = \sum_{k=1}^{n} a_{ik}a_{jk}, \ i \neq j; \ \epsilon_{kk} = 0 \]

\[ \epsilon_i = \sum_{k=1}^{n} a_{ik} \]

\[ \epsilon_j = \sum_{k=1}^{n} a_{jk} \]

Forming a machine cell involves six steps as follows:

Step 1: Let the maximum similarity coefficient of each machine form the maximum similarity coefficient matrix, \( W = \{w_i\}_{m \times 1} \), where \( w_i = \max \{x | x = sc_{ik}, \ 1 \leq k \leq m \} \).
Step 2: Form the ordering matrix \( O = \{o_{ij}\}_{m \times 1} \), where \( o_i = m_k \) and \( w_k \) is the \( k \)th high value in matrix \( W \). Ties are broken by choosing the larger number of \( w_k \) values in row \( k \) of matrix \( SC_m \). If a tie occurs again, then the smaller \( k \)-value is chosen.

Step 3: Let the association set matrix, \( A = \{\lambda_i\}_{m \times 1}, \lambda_i = \{m_x | sc_{m_x} = w_i, 1 \leq x \leq m\} \).

Step 4: Let \( o_1 \in MC_1 \)

Step 5: Let

\[
\begin{align*}
\{o_i \in MC_j \} & \text{ if } (o_k \in \lambda_o) \land (\exists o_k \in MC_j) \\
\text{A tie is broken by choosing the smallest } n(MC_x) & \text{ (4)}
\end{align*}
\]

Step 6: Repeat step 5 until all machines are sorted.

3.3. Parts Sorting

Let \( SC_u = \{sc_{ij}\}_{n \times n} \) be the similarity coefficient between two parts in incidence matrix \( A \). The parts sorting algorithm is similar to that for machines. The difference is that in this case, \( A^T \) (transpose of incidence matrix \( A \)) is used instead of \( A \).

Now, \( MC_m \) machine cells and \( PF_n \) part families are present; thus, the final number of groups is as follows (although the value of \( MC_m \) is generally equal to that of \( PF_n \)):

\[
q(G_i) = \min(\{n(MC_m)\}, n(PF_n))
\]

If \( MC_m < PF_n \), \( PF_x \subset MC_y \) where \( \sum a_{ij} = \max. (\sum a_{xb} | x \in MC_x, y \in PF_x) \), \( i \in MC_y, j \in PF_x, 1 \leq MC_y \leq MC_m \)

A tie is broken by choosing the smallest group size

otherwise, \( MC_x \subset PF_y \) where \( \sum a_{ij} = \max. (\sum a_{xb} | x \in MC_x, y \in PF_y) \), \( i \in MC_x, j \in PF_y, 1 \leq PF_y \leq PF_n \)

A tie is broken by choosing the smallest group size

3.4. GT Efficiency

One GT efficiency measurement equation was defined by Chandrasekharan and Rajagopalan [65] as follows. In this work, let \( q \) be equal to 0.5.

\[
\eta = q\eta_1 + (1 - q)\eta_2 = q\frac{c_0}{\sum Q_i P_i} + (1 - q)\left(1 - \frac{c_0}{mn - \sum Q_i P_i}\right)
\]

4. Numerical Example and Case Studies

Three examples were examined in this study: one traditional GT problem and two case studies. All three demonstrate how the algorithm proposed in this article can operate.

4.1. A Comparison with Ahi’s Algorithm

This example is taken from Ahi et al. [66], who referred to Boulif and Atif [67]. The original part–machine incidence matrix with consideration for the operational sequences of machines for producing parts is as follows:

|   | \( p_1 \) | \( p_2 \) | \( p_3 \) | \( p_4 \) | \( p_5 \) | \( p_6 \) | \( p_7 \) | \( p_8 \) | \( p_9 \) | \( p_{10} \) | \( p_{11} \) | \( p_{12} \) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| \( m_1 \) | 1 | 2 | 1 | 1 | 3 | 1 | 1 | 3 | 1 | 1 |
| \( m_2 \) | 1 | 1 | 1 | 4 | 2 | 2 |
| \( m_3 \) | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 1 | 2 |
| \( m_4 \) | 5 | 2 | 2 | 2 | 2 | 1 | 1 |
| \( m_5 \) | 2 | 2 | 5 | 3 | 1 | 2 | 2 |
| \( m_6 \) | 2 | 1 | 3 | 3 | 1 | 2 | |
| \( m_7 \) | 3 | 3 | 3 | 3 | 1 | 2 | 4 | 4 |
| \( m_8 \) | 4 | 4 | 4 | 1 | 3 | 5 |
After Equation (1) is applied, the incidence matrix is obtained as follows:

\[
A = \begin{bmatrix}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\end{bmatrix}
\]

4.1.1. Machine Sorting

The relationship between the two machines must be obtained first. For instance, by using Equation (3), the relationship between machines \( m_2 \) and \( m_4 \) can be obtained as follows:

\[
s_{c_{24}} = \frac{\varepsilon_{24}}{\varepsilon_2 + \varepsilon_4 - \varepsilon_{24}} = \frac{6}{7 + 8 - 6} = 0.667
\]

Thus, the similarity coefficient matrix \( S_{C_m} \) is obtained as follows by using Equation (2).

\[
S_{C_m} = \begin{bmatrix}
0.133 & 0.059 & 0.063 & 0.067 & 0.125 & 0.067 \\
0.067 & 0.667 & 0.077 & 0.083 & 0.667 & 0.857 \\
0.9 & 0.067 & 0 & 0 & 0.067 & 0.071 & 0.063 & 0 \\
0.067 & 0.667 & 0 & 0 & 0.25 & 0.167 & 0.6 & 0.75 \\
0.063 & 0.077 & 0.067 & 0.25 & 0 & 0.444 & 0.154 & 0.083 \\
0.067 & 0.083 & 0.071 & 0.167 & 0.444 & 0 & 0.167 & 0.091 \\
0.125 & 0.667 & 0.063 & 0.6 & 0.154 & 0.167 & 0 & 0.75 \\
0.067 & 0.857 & 0.75 & 0.083 & 0.091 & 0.75 & 0 & 0 \\
\end{bmatrix}
\]

Through step 1 to step 3 in Section 2.1, the maximum similarity coefficient matrix \( W \), ordering matrix \( O \), and association set matrix \( \Lambda \) are obtained as follows:

\[
W = \begin{bmatrix}
0.9 \\
0.857 \\
0.9 \\
0.75 \\
0.444 \\
0.444 \\
0.75 \\
0.857 \\
\end{bmatrix},
O = \begin{bmatrix}
m_1 \\
m_3 \\
m_4 \\
m_5 \\
m_6 \\
m_7 \\
m_8 \\
\end{bmatrix}, \quad \Lambda = \begin{bmatrix}
\{m_3\} \\
\{m_8\} \\
\{m_1\} \\
\{m_8\} \\
\{m_2\} \\
\{m_5\} \\
\{m_7\} \\
\{m_2\} \\
\end{bmatrix}
\]

The first machine, belonging to the first machine cell (MC₁), is \( m_1 \) in step 4. The next machine to be chosen is machine \( m_3 \), and it belongs to MC₁ because \( o_2 = m_3 \), and \( (m_1 \in \lambda_3 \land m_1 \in MC_1) \) in step 5 of using Equation (4). The third machine, belonging to the second machine cell (MC₂), is \( m_2 \). This is because \( o_3 = m_2 \), and \( (m_8 \in \lambda_2 \land m_8 \notin MC_1) \); thus, \( m_2 \) must belong to a new machine cell called MC₂ in step 5 of Equation (4).

Finally, three machine cells are present: \( MC_1 = \{m_1, m_3\} \), \( MC_2 = \{m_2, m_8, m_4, m_7\} \), and \( MC_3 = \{m_5, m_6\} \).
4.1.2. Part Sorting

First, the transpose of matrix $A$ ($A^T$) instead of $A$ is ascertained as follows:

$$A^T = \begin{bmatrix}
p_1 & m_1 & m_2 & m_3 & m_4 & m_5 & m_6 & m_7 & m_8 \\
p_2 & 1 & 1 & & & & & & \\
p_3 & 1 & 1 & 1 & 1 & 1 & & & \\
p_4 & 1 & 1 & 1 & 1 & 1 & & & \\
p_5 & & 1 & 1 & 1 & & & & \\
p_6 & 1 & 1 & 1 & 1 & 1 & & & \\
p_7 & 1 & 1 & 1 & 1 & & & & \\
p_8 & 1 & 1 & & & & & & \\
p_9 & 1 & 1 & 1 & & & & & \\
p_{10} & 1 & 1 & 1 & 1 & 1 & & & \\
p_{11} & 1 & 1 & 1 & 1 & & & & \\
p_{12} & 1 & 1 & 1 & & & & & \\
p_{13} & 1 & 1 & & & & & & \\
p_{14} & 1 & 1 & & & & & & \\
p_{15} & 1 & 1 & & & & & & \\
p_{16} & 1 & 1 & & & & & & \\
p_{17} & 1 & 1 & 1 & & & & & \\
p_{18} & 1 & 1 & 1 & 1 & & & & \\
p_{19} & 1 & 1 & & & & & & \\
p_{20} & 1 & 1 & 1 & 1 & 1 & & & \\
\end{bmatrix}$$

Through step 1 to step 3 in Section 2.1, the maximum similarity coefficient matrix $W$, ordering matrix $O$, and association set matrix $\Lambda$ are obtained as follows:

$$W = \begin{bmatrix}
1 & \{p_2\} \\
1 & \{p_8\} \\
0.8 & \{p_{13}\} \\
1 & \{p_{16}\} \\
1 & \{p_{19}\} \\
0.8 & \{p_4\} \\
1 & \{p_7\} \\
1 & \{p_{18}\} \\
0.667 & \{p_1\} \\
0.667 & \{p_5\} \\
0.667 & \{p_3\} \\
0.667 & \{p_6\} \\
1 & \{p_{20}\} \\
0.667 & \{p_9\} \\
0.667 & \{p_{11}\} \\
1 & \{p_{14}\} \\
1 & \{p_{17}\} \\
1 & \{p_{10}\} \\
0.8 & \{p_{12}\} \\
0.8 & \{p_{15}\} \\
\end{bmatrix}, \quad O = \begin{bmatrix}
p_2 \\
p_8 \\
p_{13} \\
p_{16} \\
p_{19} \\
p_4 \\
p_7 \\
p_{18} \\
p_1 \\
p_5 \\
p_3 \\
p_6 \\
p_{20} \\
p_9 \\
p_{11} \\
p_{14} \\
p_{17} \\
p_{10} \\
p_{12} \\
p_{15} \\
\end{bmatrix}, \quad \Lambda = \begin{bmatrix}
\{p_5\} \\
\{p_8, p_{13}, p_{16}, p_{19}\} \\
\{p_4, p_7, p_{18}\} \\
\{p_{10}, p_{12}\} \\
\{p_{13}, p_{16}, p_{19}\} \\
\{p_7, p_{18}\} \\
\{p_{18}\} \\
\{p_{13}, p_{16}, p_{19}\} \\
\{p_2, p_{13}, p_{16}, p_{19}\} \\
\{p_{13}, p_{16}, p_{19}\} \\
\{p_{15}\} \\
\{p_{13}, p_{16}, p_{19}\} \\
\{p_4, p_7\} \\
\{p_{13}, p_{16}, p_{19}\} \\
\{p_{13}, p_{16}, p_{19}\} \\
\{p_4, p_{17}\} \\
\{p_{17}\} \\
\{p_4, p_{17}\} \\
\{p_{17}\} \\
\end{bmatrix}$$

Thus, by using the same method, three part families are identified: $PF_1 = \{p_2, p_8, p_{13}, p_{16}, p_{19}, p_9, p_{11}, p_{14}, p_{17}\}$, $PF_2 = \{p_4, p_7, p_{18}, p_3, p_6, p_{20}\}$, and $PF_3 = \{p_1, p_5, p_{10}, p_{12}, p_{15}\}$. Finally, the three groups are ordered as detailed in Table 1.
The sorted incidence matrix and sorted operational sequences of the incidence matrix are as follows:

Table 1. Three groups in example 1.

| Group | Member in the Group |
|-------|---------------------|
| $G_1$ | $m_1, m_3, p_2, p_8, p_{13}, p_{16}, p_{19}, p_9, p_{11}, p_{14}, p_{17}$ |
| $G_2$ | $m_2, m_6, m_4, m_7, p_4, p_7, p_{18}, p_3, p_6, p_{20}$ |
| $G_3$ | $m_5, m_6, p_1, p_5, p_{10}, p_{12}, p_{15}$ |

The final result obtained using the algorithm introduced by Ahi et al. [66] is as follows:
However, two parts—\( p_{11} \) and \( p_{14} \)—belong to \( G_2 \); \( m_5 \) and \( m_6 \) do not operate on these two parts.

The GT efficiency of the algorithm proposed in this study is obtained using Equation (6), as follows:

In the sorted incidence matrix \( A_{\text{sort}} \) with order \( 8 \times 20 \), \( e_6 = 18 + 24 + 9 \) because there are eighteen 1s in group 1, twenty-four 1s in group 2, and nine 1s in group 3.

\[
\sum Q_i P_j = 2 \cdot 9 + 4 \cdot 6 + 2 \cdot 5 \text{ because the order of these three groups are } 9 \times 2, 4 \times 6, \text{ and } 2 \times 5, \text{ respectively.}
\]

\( e_0 = 10 \) because there are ten 1s not in these three groups.

Thus,

\[
\eta = 0.5 \cdot \frac{18 + 24 + 9}{29 + 4 \cdot 6 + 2 \cdot 5} + 0.5 \cdot \left(1 - \frac{10}{8 \cdot 20 - 2 \cdot 9 + 4 \cdot 6 + 2 \cdot 5}\right) = 0.944.
\]

In the same way, GT efficiency is calculated using Ahir’s algorithm, as follows:

\[
\eta = 0.5 \cdot \frac{14 + 9 + 24}{2 \cdot 7 + 2 \cdot 7 + 4 \cdot 6} + 0.5 \cdot \left(1 - \frac{14}{8 \cdot 20 - 2 \cdot 7 + 2 \cdot 7 + 4 \cdot 6}\right) = 0.887.
\]

4.2. Case Study of Component Standardization

To solve the component standardization problem in a manufacturing or remanufacturing system by using the GT algorithm, the first step is to identify the product, the figure of parts, operating process of parts, or characteristics of parts (in substitute for machines) in a part–machine incidence matrix. This example illustrates how to locate the relevant components and then achieve component standardization. Eleven products or semiproducts and 12 parts are chosen. The parts are wires, and the specification is American wire gauge, as indicated in Table 2.

Table 2. Specification of parts.

| Part | Spec. | Length (mm) |
|------|-------|-------------|
| \( p_1 \) | AWG16 | 7.5 |
| \( p_2 \) | AWG21 | 10.0 |
| \( p_3 \) | AWG13 | 12.0 |
| \( p_4 \) | AWG13 | 5.5 |
| \( p_5 \) | AWG20 | 13.5 |
| \( p_6 \) | AWG17 | 8.0 |
| \( p_7 \) | AWG19 | 10.5 |
| \( p_8 \) | AWG14 | 12.0 |
| \( p_9 \) | AWG16 | 10.0 |
| \( p_{10} \) | AWG18 | 8.0 |
| \( p_{11} \) | AWG15 | 13.0 |
| \( p_{12} \) | AWG17 | 9.5 |
The incidence matrix is as follows:

\[
\begin{bmatrix}
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 \\
\end{bmatrix}
\]

The groups are sorted by using the algorithm proposed in this article, as indicated in Table 3, and four groups were categorized in the sorted incidence matrix as follows:

\[
A^{sort} = \begin{bmatrix}
p_2 & p_7 & p_1 & p_1 & p_1 & p_1 & p_1 & p_1 & p_1 & p_1 \\
p_1 & p_5 & p_6 & p_9 & p_9 & p_8 & p_8 & p_8 & p_8 & p_8 \\
p_1 & p_5 & p_6 & p_9 & p_9 & p_8 & p_8 & p_8 & p_8 & p_8 \\
p_1 & p_5 & p_6 & p_9 & p_9 & p_8 & p_8 & p_8 & p_8 & p_8 \\
p_1 & p_5 & p_6 & p_9 & p_9 & p_8 & p_8 & p_8 & p_8 & p_8 \\
p_1 & p_5 & p_6 & p_9 & p_9 & p_8 & p_8 & p_8 & p_8 & p_8 \\
p_1 & p_5 & p_6 & p_9 & p_9 & p_8 & p_8 & p_8 & p_8 & p_8 \\
p_1 & p_5 & p_6 & p_9 & p_9 & p_8 & p_8 & p_8 & p_8 & p_8 \\
p_1 & p_5 & p_6 & p_9 & p_9 & p_8 & p_8 & p_8 & p_8 & p_8 \\
p_1 & p_5 & p_6 & p_9 & p_9 & p_8 & p_8 & p_8 & p_8 & p_8 \\
p_1 & p_5 & p_6 & p_9 & p_9 & p_8 & p_8 & p_8 & p_8 & p_8 \\
p_1 & p_5 & p_6 & p_9 & p_9 & p_8 & p_8 & p_8 & p_8 & p_8 \\
p_1 & p_5 & p_6 & p_9 & p_9 & p_8 & p_8 & p_8 & p_8 & p_8 \\
p_1 & p_5 & p_6 & p_9 & p_9 & p_8 & p_8 & p_8 & p_8 & p_8 \\
\end{bmatrix}
\]

| Group | Member in the Group |
|-------|---------------------|
| \( G_1 \) | \( p_2, p_7, p_1, p_4, p_9, p_10, p_{dt5}, p_{dt2} \) |
| \( G_2 \) | \( p_1, p_5, p_{dt12}, p_{dt8}, p_{dt5}, p_{dt10} \) |
| \( G_3 \) | \( p_9, p_3, p_{dt11}, p_{dt7}, p_{dt11} \) |
| \( G_4 \) | \( p_4, p_8, p_{dt3}, p_{dt9}, p_{dt4} \) |

### 4.3. Case Study of a Printed Circuit Board Assembly Line

As mentioned in Section 3.1, manufacturing and remanufacturing systems are subject to the problem of high labor costs and absent workers. The problem of worker rotation can also be solved using the algorithm proposed in this study.

Consider that the factory outlined in the previous example contains a printed circuit board (PCB) assembly line that includes surface mount technology and insertion processes. Workers were absent due to COVID-19. The major operations of a PCB assembly line are divided among 14 workstations, as described in Table 4.
In addition, 23 operators are working on this assembly line. The incidence matrix is as follows, but the workstations are substituted for machines and operators substituted for parts. In this incidence matrix, entry “1” implies that the worker can operate the process or has previously undertaken the relevant training course involved with the workstation.

The five groups generated using the proposed algorithm are specified in Table 5 as follows:

Table 4. Fourteen workstations.

| wk1 | Solder paste printing |
|-----|-----------------------|
| wk2 | Glue dispensing       |
| wk3 | High-speed placement  |
| wk4 | Multifunctional mounter |
| wk5 | Manual insertion for surface mount technology |
| wk6 | Reflow                |
| wk7 | Visual inspection     |
| wk8 | Auto-optical inspection |
| wk9 | Axial insertion       |
| wk10| Radial insertion      |
| wk11| Dual in-line package insertion |
| wk12| Manual insertion for general insertion |
| wk13| Wave soldering        |
| wk14| In-circuit test       |

$$A = \begin{bmatrix}
0_1 & 0_2 & 0_3 & 0_4 & 0_5 & 0_6 & 0_7 & 0_8 & 0_9 & 0_{10} & 0_{11} & 0_{12} & 0_{13} & 0_{14} & 0_{15} & 0_{16} & 0_{17} & 0_{18} & 0_{19} & 0_{20} & 0_{21} \\
wk_1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
wk_2 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
wk_3 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
wk_4 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
wk_5 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
wk_6 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
wk_7 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
wk_8 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
wk_9 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
wk_{10} & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
wk_{11} & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
wk_{12} & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
wk_{13} & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
wk_{14} & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1
\end{bmatrix}$$

Table 5. Five groups in example 3.

| Group | Member in the Group |
|-------|---------------------|
| $G_1$ | $wk_1, wk_2, wk_6, wk_9, 0_{10}, 0_{17}, 0_{19}, 0_{1}, 0_{3}, 0_{20}, 0_{21}$ |
| $G_2$ | $wk_{12}, wk_{13}, 0_5, 0_{22}, 0_{4}, 0_{9}, 0_{14}, 0_{16}$ |
| $G_3$ | $wk_7, wk_{14}, wk_{11}, 0_8, 0_{11}$ |
| $G_4$ | $wk_9, wk_{10}, 0_{13}, 0_{15}, 0_{2}, 0_{18}$ |
| $G_5$ | $wk_3, wk_4, wk_8, 0_7, 0_{12}, 0_{23}$ |
The sorted incidence matrix is as follows.

\[
A_{\text{sort}} = \begin{bmatrix}
\begin{array}{cccccccccccc}
0_1 & 0_1 & 0_6 & 0_1 & 0_3 & 0_2 & 0_1 & 0_6 & 0_1 & 0_1 & 0_1 & 0_1 \\
wk_9 & wk_{10} & wk_{12} & wk_{13} & wk_4 & wk_5 & wk_6 & wk_7 & wk_{14} & wk_{11} & wk_3 & wk_8
\end{array}
\end{bmatrix}
\begin{bmatrix}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\end{bmatrix}
\]

5. Results and Discussion

In the numerical example, the algorithm proposed in this study is used to categorize three groups, as detailed in Section 4.1. Ahi’s algorithm was compared to the GT efficiency measure proposed by Chandrasekharan and Rajagopalan. The GT efficiency of the algorithm proposed in this study is 0.944, higher than the 0.887 shown in the literature for Ahi’s algorithm. Thus, the GT algorithm proposed in this study works and can perform better than some algorithms in the literature.

All parts in each group are to be operated on by at least one machine that is in the same group; this specification is applied using the proposed algorithm in this study. In Ahi’s algorithm, however, the two parts \( p_{11} \) and \( p_{14} \) belong to group \( G_2 \), but all machines \( (m_5 \) and \( m_6) \) that are in the same group do not operate on these two parts.

Example 2 contains four groups, as indicated in Section 4.2. After discussions with the R&D engineers, however, it became clear that some parts, such as components \( p_5 \) and \( p_6 \), could not be standardized due to their electrical characteristics, but some parts could be standardized. Part \( p_3 \) could be substituted for \( p_9 \) and \( p_{11} \). In addition, two new components were created: \( p_{13} \) and \( p_{14} \), which replaced \{ \( p_2, p_7, p_{10} \) \} and \{ \( p_1, p_{12}, p_6 \) \}, respectively. The specifications of \( p_{13} \) and \( p_{14} \) were 10.5 mm long AWG18 and 9.5 mm long AWG16, respectively.

The new sorting incidence matrix is as follows:

\[
A_{\text{sort}} = \begin{bmatrix}
\begin{array}{cccccccc}
p_{1} & p_5 & p_{1} & p_3 & p_4 & p_8 \\
pdt_6 & pdt_9 & pdt_5 & pdt_{10} & pdt_7 & pdt_{11} & pdt_3 & pdt_4
\end{array}
\end{bmatrix}
\begin{bmatrix}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\end{bmatrix}
\]

Example 3 features five groups. In group \( G_1 \), operators \( o_{10} \) and \( o_{17} \) are both present in the same group, which means they can perform similar tasks \( (wk_6 \) and \( wk_3) \). If operator \( o_{10} \) takes leave, then operator \( o_{17} \) can be substituted for \( o_{10} \) immediately. In addition, if the manager wishes to train the operators on a limited budget, then they can choose certain operators to attend relevant courses (rather than sending all operators indiscriminately).
entry “0” is entered in the groups, as illustrated in the following sorted matrix. For instance, worker \( o_9 \) can be trained to operate \( wk_{13} \). Thus, the adverse effects of worker resignation or a sudden enforced quarantine due to the COVID-19 pandemic can be mitigated.

\[
A_{\text{sort}} = \begin{bmatrix}
\text{wk}_9 & \text{wk}_{10} & \text{wk}_{12} & \text{wk}_{13} & \text{wk}_1 & \text{wk}_2 & \text{wk}_6 & \text{wk}_5 & \text{wk}_7 & \text{wk}_{14} & \text{wk}_3 & \text{wk}_4 & \text{wk}_8 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

6. Conclusions

Rather than being lost to waste disposal, some used products and their components can be recycled. Using as few types of parts as possible in the manufacture of a product is ideal for two reasons: the business reaps the benefit of bulk buying and avoids risks of material shortages. Lacking just one type of material may result in product delivery delays, a suboptimal scenario for businesses. The fewer the types of parts employed, the lower is the business risk. One method of achieving this aim is component standardization, which can be used not only in manufacturing systems but also in remanufacturing systems. In addition, all company managers want to reduce labor expenses and reduce the risk of sudden employee resignation. In this study, a sorting algorithm based on the concept of GT was proposed. There are limitations to the study’s approach: First, it assumes that the substitute worker has the same pay, performance, and workstation efficiency as the original worker; second, it assumes that the substitute component does not affect the product’s performance. This algorithm facilitates component standardization and worker rotation.

One numerical example and two case studies were presented to demonstrate the utility of the proposed algorithm. The first example demonstrated that the performance of the algorithm proposed in this study is superior to that of a previously described algorithm. The second example revealed that an original range of 12 distinct parts can be reduced to 6 by using the algorithm proposed in this work. Making provisions for emergency business scenarios is crucial; thus, the final case study demonstrated how to group workers with similar operational abilities and suggested how to assign tasks to alternate workers if a worker resigns suddenly or is quarantined due to the pandemic alleviation measures.

Traditional GT considers only machines and parts, but this study uses the concept of GT to solve the issues of component standardization and absent workers. The proposed method can reduce the number of parts and mitigate the risk of an unexpected worker absence. As this is the era of AMS, different operation processes, robots, and operators must all be considered. Future studies could examine how companies can use algorithms to manage robots breaking down or requiring maintenance at the same time that workers are absent.

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Nomenclature

\[ m \] Number of machines
\[ n \] Number of parts
\[ A = \{ a_{ij}\}_{m \times n} \] Incidence matrix
\[ m_i \] ith machine
\[ p_i \] ith part
\[ OS = \{ os_{ij}\}_{m \times n} \] Operational sequences of the incidence matrix
\[ os_{ij} \] osijth operating process of part j
\[ SC_m \] Similarity coefficient matrix of machines
\[ sc_{ij} \] Similarity coefficient of \( m_i \) and \( m_j \)
\[ W \] Maximum similarity coefficient matrix
\[ O \] Ordering matrix
\[ \Lambda \] Association set matrix
\[ MC_m \] Number of machine cells
\[ MC_i \] ith machine cell
\[ PF_n \] Number of part families
\[ PF_i \] ith part family
\[ A^T \] Transpose of incidence matrix A
\[ G_i \] ith group
\[ \eta \] Group efficiency
\[ e_b \] Total number of 1s in the major blocks
\[ e_0 \] Total number of 1s in the stray blocks
\[ Q_i \] Number of machines in the ith cell
\[ P_i \] Number of parts in the ith family
\[ q \] Weighting factor
\[ pdt_i \] ith product or semiproduct
\[ wk_i \] ith workstation

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