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An Energy-Saving Optimization Method of Dynamic Scheduling for Disassembly Line

Yicong Gao [1], Qirui Wang [1], Yixiong Feng [1,*], Hao Zheng [1,*], Bing Zheng [2] and Jianrong Tan [1]

[1] State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou 310027, China; gaoyicong@zju.edu.cn (Y.G.); wangqirui89@126.com (Q.W.); egi@zju.edu.cn (J.T.)
[2] School of Business Administration, Zhejiang Gongshang University, Hangzhou 310018, China; scottgao@163.com
* Correspondence: fyxtv@zju.edu.cn (Y.F.); haozheng@zju.edu.cn (H.Z.)

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Abstract: Concerns have been increasing regarding the environmental sustainability of disassembly activities that take place in various recovery operations at end of life stage of products, and subsequently, disassembly activities have been gaining increased exposure. The disassembly line is a good choice for automated disassembly of end-of-life products. Although interest in addressing energy saving in manufacturing is rising, the study of incorporating energy consumption reduction and disassembly efficiency improvement into disassembly line balancing is still limited. The analysis, design, and balanced decision-making for disassembly lines are urgently needed in order to make the disassembly line as energy-saving as possible. In this paper, an energy-saving optimization method, which was used in scheduling workstation selection and the disassembly sequence for the disassembly line, is proposed. Energy consumption of each stage of the disassembling process was analyzed and modeled. Then, a mathematical model of the disassembly line balancing problem with energy saving considerations was formulated and the objective of energy consumption was integrated into the objectives of cost and working load in order to balance a disassembly line. Optimal solutions for the disassembly line balancing problem with an energy saving consideration were obtained by using an artificial bee colony algorithm, which was a feasible way of minimizing workstations, and ensuring similar working load, as well as minimizing energy consumption. Finally, a case study of disassembly line balancing for a typical driving system is presented to illustrate the proposed method.

Keywords: energy consumption; energy-efficient scheduling; disassembly line balancing; multi-robotic system collaborative work

1. Introduction

Nowadays, manufacturing has evolved and become more automated, intelligent, and complex. Due to the high precision and accuracy of manufacturing, robots play an important role in the automation line of manufacturing. However, manufacturing is facing an enormous environmental challenge as well as strong economic pressure because of increasing energy requirements and the associated environmental impacts of robots. Reducing the energy consumption of an automation line has been identified as an important strategy to develop economical and environmentally-friendly modes of intelligent manufacturing. Therefore, the issues of energy consumption in automatic production processes are becoming increasingly important.

Different studies relating to energy consumption modeling [1–3], energy consumption evaluation [4–7], and energy consumption optimization [8–10] can be found in the literature. However, research on energy consumption of a disassembly line is seldom performed. Therefore, it is necessary to collaborate on energy consumption, cost, and working load in order to optimize the trade-off among economic, working load, and energy performance of a disassembly line. The aim of this paper is to find a new way to deal with energy saving in a disassembly line in a quantitative manner that can make disassembly as profitable and energy efficient as possible. In comparison with the existing studies, this paper has three contributions. (1) In order to deal with high energy consumption in a disassembly line, the energy consumption of each stage in the disassembling process was analyzed and modeled. (2) To solve the disassembly line balancing problem with an energy saving consideration, this paper established a mathematical model of workstation selection and disassembly sequence with minimum energy consumption, minimum number of workstations, and maximum similarity degree of working load. (3) By comparing the solutions to the disassembly line balancing problem (DLBP), which does not have an energy saving consideration, this paper shows that, by considering energy consumption, and cutting unnecessary operations of direction and tool change in a disassembly line, a greater amount of energy can be saved.

The rest of this paper is organized as follows. In Section 2, the related literature is provided and the contributions to the study are clearly identified. Section 3 describes the problem of a disassembly line with an energy saving consideration. Section 4 contains analyses and formulates the energy consumption of a disassembly line. Section 5 establishes a mathematical model of the DLBP, incorporating energy consumption reduction and efficiency improvement. Section 6 applies the proposed model to find the best schedule of workstation selection and disassembly sequence which achieves a lower energy consumption and cost with a high level of similarity degree of working load. A discussion of the energy consumption reduction of a disassembly line is given. Section 7 concludes this paper by elaborating about future research issues.

2. Literature Review

2.1. Disassembly Line Evaluation and Optimization

In recent years, there has been growing interest in modeling and optimization of disassembly lines. Gungor and Gupta [11] first introduced specific considerations related to disassembly lines and developed a mathematical model relating to these considerations. Bentaha et al. [12] proposed a model of task times with known probability distributions to deal with the uncertainty of task times of disassembly line balancing. Tang and Zhou [13] presented an extended Petri net model for designing efficient automatic and semiautomatic industrial disassembly systems. Altekin and Akkan [14] proposed a predictive model of task failures for a disassembly line in order to recover the loss of performance when task failures occurred. Aydemir-Karadag and Turkbey [15] established a mathematical model for a parallel disassembly line based on the AND/OR Graph. Kalayci et al. [16] discussed the influence on the removal order of hazardous components and presented a mathematical formula relevant to a sequence-dependent disassembly line. Kalaycilar et al. [17] presented a model of a disassembly line with a fixed number of workstations considering a specified finite supply and specified release quantities. In order to solve the DLBP, Kalayci and Gupta [18] proposed a methodology based on the particle swarm algorithm to solve the DLBP while satisfying the disassembly precedence constraints and optimizing the effectiveness. Later, Kalayci et al. [19] proposed a hybrid algorithm that combined a genetic algorithm with a variable neighborhood search method to solve the sequence-dependent DLBP. Recently, Mete et al. [20] proposed a heuristic approach for the joint design of a parallel assembly/disassembly line with profit maximized based on the ant colony algorithm. Liu and Wang [21] developed a new mathematical model for sequence-dependent disassembly lines and proposed a multi-objective algorithm to solve the sequence-dependent DLBP. Pistolesi et al. [22] presented a hybrid genetic algorithm to solve the DLBP with considerations of the number of workstations, profit, and disassembly depth.

2.2. Energy Consumption Modeling and Evaluation

As a mechanism for energy-saving and reducing environmental negative effects, some methods on designing and scheduling the energy consumption of automation lines have been proposed. Gutowski et al. [23] proposed an energy framework to model the power for different machine tools in industrial systems. Chen et al. [24] developed an analytical tool to evaluate the energy performance of production systems and manage the scheduling of machine startup and shutdown in order to reduce energy consumption. Li et al. [25] presented a Petri net model to predict energy behaviors in flexible machining systems. Mokhtari and Hasani [26] proposed a production scheduling model of production and maintenance operations. To cope with the higher complexity of designing and scheduling for energy consumption of automation lines, some tools involving artificial intelligence have been considered. Yildirim and Mouzon [27] developed a genetic algorithm to solve the single machine scheduling problem under energy consumption constraints. Dai et al. [28] proposed an improved genetic-simulated annealing algorithm for flexible flow shop scheduling in order to trade-off between makespan and energy consumption. Liu et al. [29] established a scheduling method with the objectives of energy consumption and weighted tardiness. Tang et al. [30] proposed an improved particle swarm optimization algorithm for solving the dynamic flexible flow shop scheduling problem.

As mentioned above, the existing studies have mainly focused on modeling and optimization of the automatic line in order to minimize the number of workstations or maximize profit. Studies on the energy consumption of a disassembly line are seldom performed. Although interest in addressing energy saving in manufacturing is rising, disassembly has unique characteristics and cannot be considered a manufacturing operation. Wide distribution and high energy consumption in disassembly means it is crucial to design and balance the disassembly line incorporating an energy consumption reduction. To do so, this paper proposes an energy-saving optimization method that considers workstation selection and the disassembly sequence for disassembly line balancing. The energy consumption of a disassembly line was analyzed and a detailed model for the quantification of energy consumption of a disassembly line was formulated. We aim to find a new way to balance a disassembly line by making determinations about the number of workstations, working load, and energy consumption.

3. Description of the Problem

Disassembly lines automatically remove valuable components and materials from discarded end-of-life (EOL) products through an assignment of disassembly operations with precedence constraints to an ordered sequence of workstations so that precedence constraints are satisfied. Depending on the workstation selection and disassembly operation sequence, the energy efficiency of a disassembly line will be different. For example, a disassembly line with four workstations is given to completely disassemble an EOL product consisting of eight components. It allows the cycle time CT = 45 s for each workstation of the disassembly line to perform its required disassembly operations. Table 1 shows the precedence relationships and details of the disassembly. For component C_6, component C_2 and C_3 are the predecessors. Suppose that the working energy cost and idle energy cost are respectively 2.5 units of energy consumption and 1 units of energy consumption. Two feasible operation schedules and workstation alternatives of this particular disassembly line are shown in Figure 1. The EOL product is processed with 399 units of energy consumption in solution I and 397.5 units of energy consumption in solution II. Although the cycle time of both solutions are equal to 45 s, the energy consumption of solution I is 1.5 units more than solution II. Thus, the energy consumption of disassembly lines may vary at different milestones depending on workstation selection and disassembly sequence. The objective of the optimization for disassembly lines with an energy saving consideration is to determine the best workstation selection and disassembly sequence in order to minimize energy consumption as well as minimize the number of workstations and maximize the similarity degree of working load.

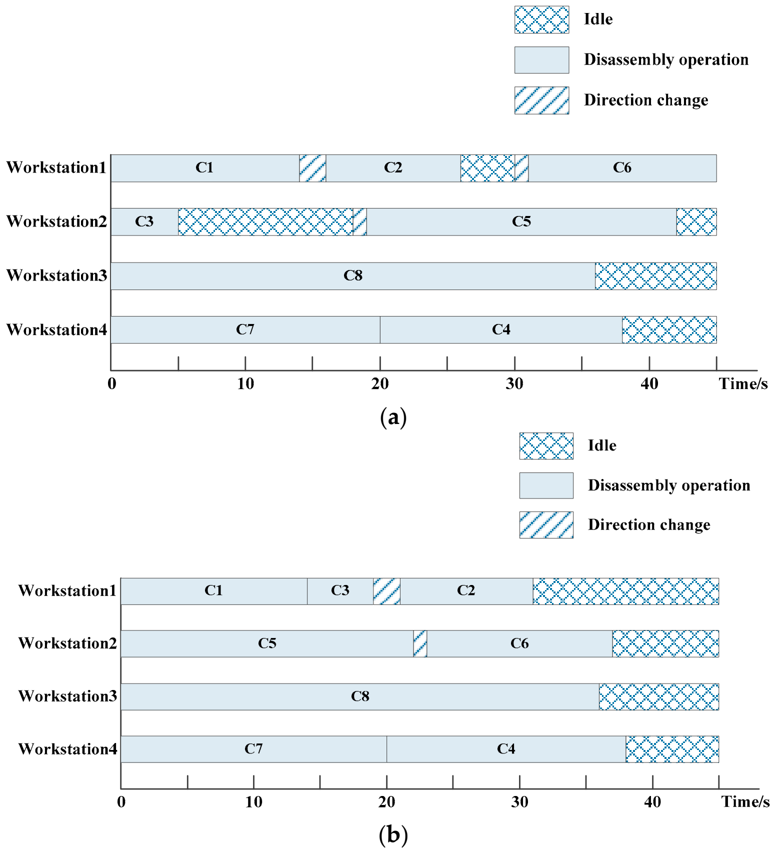


Figure 1. Example of the disassembly line balancing problem (DLBP) with an energy saving consideration. (**a**) Solution I for workstation selection and disassembly sequence; (**b**) Solution II for workstation selection and disassembly sequence.

Table 1. Operation data for the disassembly.

Component	Disassembly Time/s	Direction	Precedence Constraint
C_1	14	$-$X	
C_2	10	+X	$\{C_1\}$
C_3	5	$-$X	$\{C_1\}$
C_4	18	$\pm$X, $\pm$Y	$\{C_7\}$
C_5	22	+Y	$\{C_1\}$
C_6	14	+Z	$\{C_2, C_3\}$
C_7	20	$\pm$X, $\pm$Y	$\{C_8\}$
C_8	36	+Z	$\{C_5, C_6\}$

4. Modeling of Energy Consumption in Disassembly Line

4.1. Analysis of Energy Consumption in Disassembling Process

According to characteristic of disassembly operation, the disassembling process divides into five categories of procedures: standby, disassembling, direction changing, tool changing, and idling [11]. Standby is the operation of loading and clamping the EOL product at the start of disassembly. Disassembling is the operation and removal of a component from the EOL product. Direction changing is the operation of turning the EOL product to the direction that corresponds to the operations necessary for the removal component. Tool changing is the operation of changing the disassembly tool corresponding to the operation necessary for the removal component. Idling is the operation of the running workstation without disassembling.

The energy consumption of an EOL product in the whole disassembling process is shown in Figure 2. Based on the power demand, process parameters, and time, the energy consumption of each disassembly operation in the whole disassembling process can be calculated. Then, the total energy consumption can be established on the foundation of each disassembling operation (standby, disassembling, direction changing, tool changing, and idling).

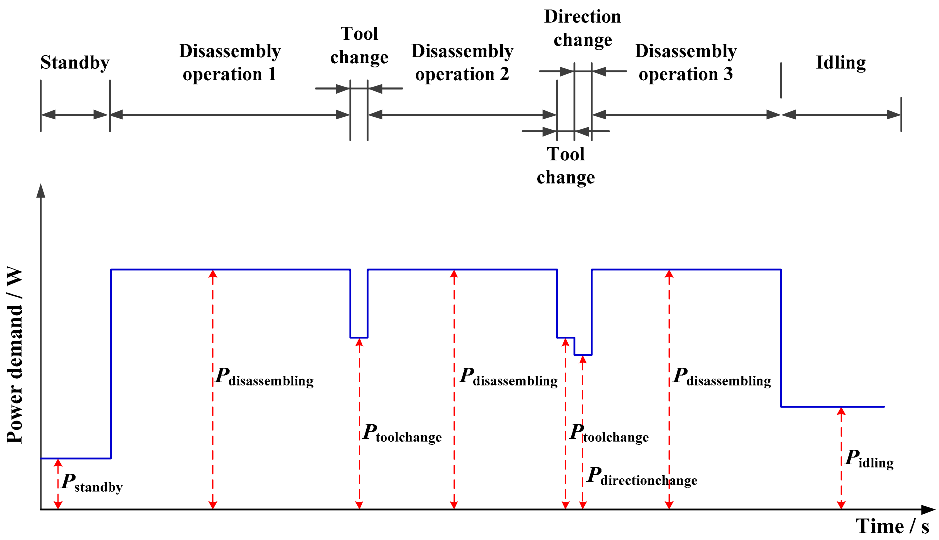


Figure 2. A schematic diagram of the power in the disassembling process.

4.2. Model of Standby Energy Consumption

According to the definition of standby, the power demand of standby refers to the working power of loading and clamping. The power demand of standby can be obtained from the manual or measured directly. Thus, the standby energy consumption can be calculated as follows:

$$E_{sbi} = P_{sbi} \cdot (t_{loading} + t_{claming i}) \tag{1}$$

where P_{sbi} is the standby power of the i-th workstation, $t_{loading}$ is the automatic loading time, and $t_{claming i}$ is the average clamping time of an EOL product of the i-th workstation.

4.3. Model of Idling Energy Consumption

Idling is the phase that the workstation is running when it is not disassembling an EOL product; it is waiting to process next disassembling operation. The energy consumption of the idling depends on the idling time; idling can consume a huge amount of energy. For example, idling consumes nearly 13% of the total consumed energy with an 8 h work shift [31]. The idling energy consumption can be calculated as follows:

$$E_{idle i} = P_{0i} \cdot t_{idle i} \tag{2}$$

where P_{0i} is the idle power of the i-th workstation and $t_{idle i}$ is the idle time for the next operation of the i-th workstation.

4.4. Model of Disassembling Energy Consumption

The disassembling energy consumption is the energy consumption of removing a component from an EOL product using a tool. Considering the j-th component of the EOL product, the disassembling energy consumption is defined by the following expression:

$$E_{dsij} = P_{dsi} \cdot t_{ndj} \cdot n_{ej} \tag{3}$$

where P_{dsi} is the disassembling power of the i-th workstation, t_{ndj} is the normalized disassembly time of the j-th component, and n_{nej} is the normalized execution time for the removal of the j-th component. Table 2 shows the disassembly data for each component typology [32].

Table 2. Index of component typology and their characterization.

Description	Normalized Disassembly Time/s t_{ndj}	Normalized Execution Times n_{nej}
Component, to be removed	1.25	1
Screw, to be removed	0.6	0.48
Snap fit, to be opened	1.5	1.2
Clip, to be removed	1	0.8
Connection, to be broken	2	1.6

4.5. Model of Direction Changing Energy Consumption

Direction changing energy consumption takes into account the possible change in disassembly direction when a change of direction takes place, passing from the removal of the $(j-1)$-th component to the j-th component. The direction changing energy consumption o is formulated as follows:

$$E_{dcij} = P_{dci} \cdot t_{dc0} \cdot n_{dcj} \tag{4}$$

where P_{dci} is the direction changing power of the i-th workstation, t_{dc0} is the average direction changing time, and n_{dcj} is the time of direction changing of the j-th component.

4.6. Model of Tool Changing Energy Consumption

According to the disassembly method of two adjacent disassembly operations in the disassembly sequence, it may be necessary to change a tool. Tool change is categorized into two classes, manual tool change and automatic tool change. For manual tool change, the average tool changing time can be obtained using the statistical method. The energy consumption of the manual tool change can be formulated as follows:

$$E_{MTCi} = P_{0i} \cdot t_{MTC} \tag{5}$$

where t_{MTC} is the average manual tool changing time.

The automatic tool change is divided into the tool pick, tool place, and rotation of the tool magazine [33]. The energy consumption of the automatic tool change can be calculated as follows:

$$E_{ATCij} = P_{tci} \cdot (t_{fix} + \Delta pos_j \cdot t_{tc0}) \tag{6}$$

where P_{tci} is the tool changing power of the i-th workstation, t_{fix} is the fixed time of tool pick and tool place, Δpos_j is the rotated number from the tool of the $(j-1)$-th component to that of the j-th component, and t_{tc0} is the unit time of the rotation of tool magazine.

Thus, the total tool changing energy consumption is defined as:

$$E_{tcij} = E_{MTCi} + E_{ATCij} \tag{7}$$

5. Modeling of the DLBP with Energy Saving Consideration

Based on the concept and assumptions made by Gungor and Gupta about the deterministic version of the DLBP [11], the assumptions of the DLBP with an energy saving consideration are:

1. A disassembly line is used to disassemble a single product type.
2. The supply of the EOL product is infinite.
3. The workstations are capable to process only one disassembly operation at a time.
4. Each component should be assigned to one workstation.
5. The time of all the components assigned to a workstation must not exceed the cycle time CT.
6. The precedence relationships among the components must be satisfied.

Given an EOL product consisting of M components, the set of components in the EOL product is denoted as $\boldsymbol{C}_{\mathbf{set}} = \{C_1, C_2, \ldots, C_j, \ldots, C_M\}$. A matrix defines the precedence removal relationships of components, which determines the feasibility of disassembly sequences. The precedence matrix is defined as a $M \times M$ square matrix:

$$PL = \left[pl_{jl}\right]_{M\times M} \tag{8}$$

where $pl_{jl} = 1$, if disassembly of C_j can precede disassembly of C_l; otherwise $pl_{jl} = 0$.

The disassembly sequence of $\boldsymbol{C_{set}}$ can be characterized by a design vector X and is defined as:

$$X = \left[x_{jk}\right]_{M\times M} \tag{9}$$

where $x_{jk} = 1$, if C_j is removed as the k-th disassembly operation in the disassembly sequence; otherwise $x_{jk} = 0$.

In the disassembly line, there are N workstations $\boldsymbol{W}_{\mathbf{set}} = \{W_1, W_2, \ldots, W_i, \ldots, W_N\}$. Each workstation is assigned a set of disassembly operations, a relation matrix is introduced to describe the relation between the workstation and disassembly operation as follows:

$$Y = [y_{ik}]_{N\times M} \tag{10}$$

where $y_{ik} = 1$, if the k-th disassembly operation is assigned to W_i; otherwise $y_{ik} = 0$.

The relation matrix satisfies such constraints: $\sum_{i=1}^{N}\sum_{k=1}^{M} y_{ik} = N$ and $\sum_{i=1}^{N} y_{ik} = 1$, implying that a component should exclusively belong to one subassembly only. Figure 3 shows an example of a disassembly sequence and an assignment of operations to workstations of solution I in Figure 1. As shown in Figure 3, the disassembly sequence is $C_1 \to C_2 \to C_3 \to C_6 \to C_5 \to C_8 \to C_7 \to C_4$. Thus, $x_{11} = 1$, $x_{22} = 1$, $x_{33} = 1$, $x_{48} = 1$, $x_{55} = 1$, $x_{64} = 1$, $x_{77} = 1$, and $x_{86} = 1$. According to the disassembly operation assignment matrix $\boldsymbol{Y}$, C_1, C_2, and C_6 are assigned to workstation W_1, C_3, and C_5 are assigned to workstation W_2, C_8 is assigned to workstation W_3, and C_4 and C_7 are assigned to workstation W_4. Due to organizational requirements while performing disassembly, disassembly operations cannot be carried out in an arbitrary sequence but are subject to certain precedence relationships. The operation time of the sequence in which precedence independent operations are performed is influenced based on the order in which they are performed. One component may hinder the other component which may require additional movements to overcome the hindrance and/or the other components prevent it from using the most efficient or convenient disassembly process. For example, for the precedence sequence dependent disassembly operations ds_3 (C_3) and ds_4 (C_6), the time of the disassembly operation of ds_4 is affected by the disassembly operation of ds_3 if disassembly operation ds_3 is yet to be performed in the disassembly sequence. Thus, idling units have been added to compute the total processing time of the disassembly operation of ds_4 until the disassembly operation of ds_3 is finished.

According to the analysis and model of energy consumption in the disassembling process, the energy consumed by a workstation can be calculated as follows:

$$\begin{aligned} E_i = & \sum_{j=1}^{M}\sum_{k=1}^{M} E_{\mathrm{sb}i}\cdot x_{jk}\cdot y_{ik} + E_{\mathrm{idle}i} + \sum_{j=1}^{M}\sum_{k=1}^{M} E_{\mathrm{ds}ij}\cdot x_{jk}\cdot y_{ik} + \\ & \sum_{j=1}^{M-1}\sum_{p=1}^{M}\sum_{l=j+1}^{M}\sum_{q=1}^{M} E_{\mathrm{dc}ij}\cdot dc_{jl}\cdot\left(x_{jp}\cdot x_{lq}\right)\cdot\left(\sum_{k=1}^{M} x_{jk}\cdot y_{ik}\right)\cdot\left(\sum_{k=1}^{M} x_{lk}\cdot y_{ik}\right) + \\ & \sum_{j=1}^{M-1}\sum_{p=1}^{M}\sum_{l=j+1}^{M}\sum_{q=1}^{M} E_{\mathrm{tc}ij}\cdot tc_{jl}\cdot\left(x_{jp}\cdot x_{lq}\right)\cdot\left(\sum_{k=1}^{M} x_{jk}\cdot y_{ik}\right)\cdot\left(\sum_{k=1}^{M} x_{lk}\cdot y_{ik}\right) \end{aligned} \tag{11}$$

where dc_{jl} is the direction change coefficient ($dc_{jl} = 1$, if the direction of disassembly operations of C_j and C_l are different; otherwise $dc_{jl} = 0$) and tc_{jl} is the tool change coefficient ($tc_{jl} = 1$, if the disassembly operations of C_j and C_l use different tools; otherwise $tc_{jl} = 0$).

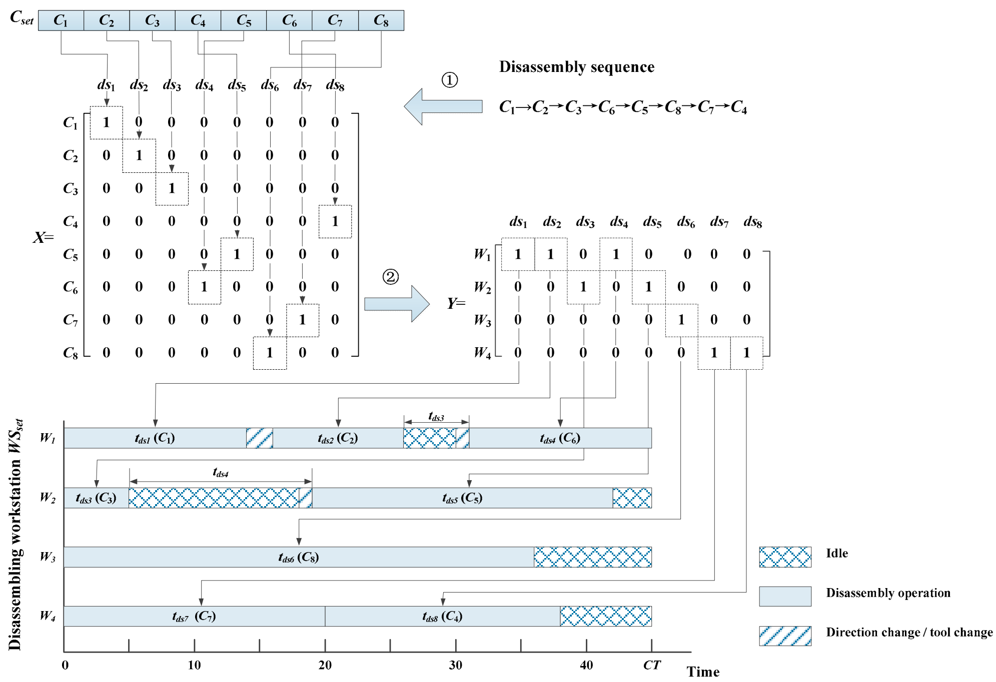


Figure 3. Example of scheduling the DLBP with an energy saving consideration.

Thus, there exist three kinds of decisions in the DLBP with energy saving consideration that should be made:

1. Determining the number of workstations in order to minimize the total cost.
2. Determining the assignment of each disassembly operation and ensuring that the working load of each workstation is similar.
3. Finding the sequence of disassembly operations assigned to each workstation with the minimal total energy consumption.

The mathematical model of the DLBP with energy saving consideration further extends our previous research [34] and is formulated as follows:

$$\min f_1 = N \tag{12}$$

$$\max f_2 = \frac{-1}{\ln N}\sum_{i=1}^{N}\left\{\frac{CT-t_{\mathrm{DS}}}{\sum_{i=1}^{N}[CT-t_{\mathrm{DS}}]}\cdot\ln\frac{CT-t_{\mathrm{DS}}}{\sum_{i=1}^{N}[CT-t_{\mathrm{DS}}]}\right\}$$
$$t_{\mathrm{DS}} = \sum_{j=1}^{M}\left(t_{\mathrm{nd}j}\cdot n_{\mathrm{ne}j}\right)\cdot\sum_{k=1}^{M}\left(x_{jk}\cdot y_{ik}\right) \tag{13}$$

$$\min f_3 = \sum_{i=1}^{N} E_i \tag{14}$$

s.t.

$$\sum_{i=1}^{N}\sum_{k=1}^{M} y_{ik} = N \tag{15}$$

$$\forall k \in M : \sum_{i=1}^{N} y_{ik} = 1 \tag{16}$$

$$\forall k \in M : \sum_{j=1}^{M} x_{jk} = 1 \tag{17}$$

$$\forall j \in M : \sum_{k=1}^{M} x_{jk} = 1 \tag{18}$$

$$\forall j \in M : \sum_{l=1}^{M} pl_{lj} \leq h, \left\{ h \middle| x_{jh} = 1, x_{jh} \in X \right\} \tag{19}$$

$$\left| \frac{\sum_{i=j}^{M} (t_{\mathrm{nd}j} \cdot n_{\mathrm{ne}j})}{CT} \right| \leq N \leq M \tag{20}$$

$$\begin{gathered}
\forall i \in N : \sum_{j=1}^{M} \sum_{k=1}^{M} (t_{\mathrm{nd}j} \cdot n_{\mathrm{ne}j} \cdot x_{jk} \cdot y_{ik}) + t_{\mathrm{da}i} + t_{\mathrm{dc}i} + t_{\mathrm{tc}i} \leq CT \\
t_{\mathrm{da}i} = \sum_{p \neq i}^{N} \sum_{j=1}^{M} \sum_{k=1}^{M} \sum_{l=1}^{M} (t_{\mathrm{nd}j} \cdot n_{\mathrm{ne}j} \cdot pl_{jl}) \cdot (x_{jk} \cdot y_{pk}) \\
t_{\mathrm{dc}i} = \sum_{j=1}^{M-1} \sum_{p=1}^{M} \sum_{l=j+1}^{M} \sum_{q=1}^{M} (t_{\mathrm{dc}0} \cdot n_{\mathrm{dc}j}) \cdot dc_{jl} \cdot \left(x_{jp} \cdot x_{lq} \right) \cdot \left(\sum_{k=1}^{M} x_{jk} \cdot y_{ik} \right) \cdot \left(\sum_{k=1}^{M} x_{lk} \cdot y_{ik} \right) \\
t_{\mathrm{tc}i} = \sum_{j=1}^{M-1} \sum_{p=1}^{M} \sum_{l=j+1}^{M} \sum_{q=1}^{M} (t_{\mathrm{fix}} + \Delta pos_j \cdot t_{\mathrm{tc}0}) \cdot tc_{jl} \cdot \left(x_{jp} \cdot x_{lq} \right) \cdot \left(\sum_{k=1}^{M} x_{jk} \cdot y_{ik} \right) \cdot \left(\sum_{k=1}^{M} x_{lk} \cdot y_{ik} \right)
\end{gathered} \tag{21}$$

where $t_{\mathrm{da}i}$ the additional time of W_i corresponding to precedence constraints, $t_{\mathrm{dc}i}$ is the direction changing time of W_i, and $t_{\mathrm{tc}i}$ is the tool changing time of W_i.

The first objective given in Equation (12) is to minimize cost of the disassembly line, which depends on the number of workstations.

The second objective given in Equation (13) is to ensure that the working load of each workstation is similar. It was computed by the information entropy theory as well as the smaller variation of the idle time at each workstation, the smaller discrete probability distribution of data information, and the greater information entropy. In particular, information entropy should be at a maximum of 1 when the idle time of each workstation is the same. Therefore, a lower resulting value is more desirable as it indicates the maximum similarity of idle time across all workstations of the disassembly line.

As the third objective in Equation (14), the total energy consumption of a disassembly line is quantified by the sum of energy consumption of each workstation.

The constraint given in Equations (15) and (16) ensure that each disassembly operation is assigned to one workstation only.

The constraints given in Equations (17) and (18) address the feasibility of a disassembly sequence.

The constraint given in Equation (19) addresses the precedence feasibility of a disassembly sequence. This constraint ensures that the component is removed only when its precedence components are already removed.

The constraint given in Equation (20) makes sure that the number of workstations does not exceed the number of components and that there are enough workstations to complete all disassembly operations in the cycle time CT.

The constraint given in Equation (21) addresses the availability of work time and disassembly operations assigned to the workstation that must be completed in the cycle time CT. Automatic tool change is selected in this paper.

6. Case Study

To understand the utility of the method proposed above, the optimal set of energy-saving workstation selections and disassembly sequences in the disassembly line balancing problem with an energy saving consideration for a typical driving system was investigated. The trade-off between cost, working load, and energy consumption of the disassembly line was considered. A drawing showing the main components of the driving system is shown in Figure 4, and the disassembly characteristics of the driving system are listed in Table 3. The idle power P_{0i} was set to 0.10 kW·h, the disassembling power $P_{\mathrm{ds}i}$ was set to 0.25 kW·h, the direction changing power $P_{\mathrm{dc}i}$ was set to 0.15 kW·h, the tool changing power P_{tci} was set to 0.15 kW·h, and the cycle time CT was 60 s. In addition, standby time was short compared with the whole disassembling process time; standby is not considered in this paper. Due to the combinatorial nature of the optimization model of the DLBP with an energy saving consideration, it was solved based on the artificial bee colony algorithm [18]. The proposed approach was implemented in MATLAB R2014b and was run on a laptop computer (Intel/Core i5 CPU, 3.10 GHz and 8 GB RAM with a Windows 7 operating system).

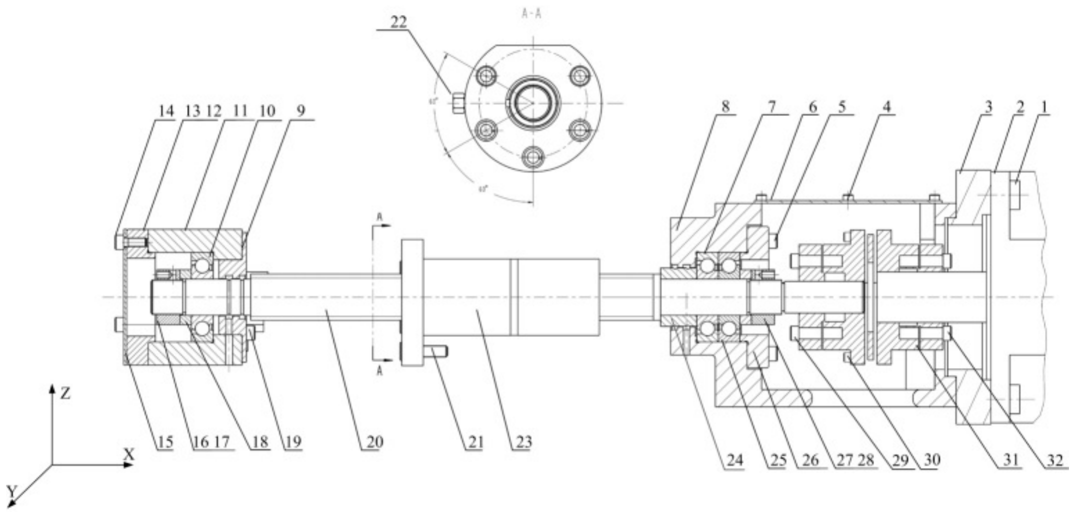


Figure 4. A drawing of the main components of the driving system.

Table 3. Disassembly characteristics of the driving system.

Index	Name	Quality	Specification	Direction	Tool	Predecessor
c_1	screw	4	M12 × 40	+X	Tool-1	
c_2	servo motor	1		+X	Tool-2	1, 4, 6, 32
c_3	seal flange	1		+X	Tool-3	1, 2, 4, 6, 32
c_4	screw	6	M4 × 8	+Z	Tool-4	
c_5	screw	4	M8 × 25	+X	Tool-5	4, 6
c_6	top cover	1		+Z	Tool-6	4
c_7	bearing	1	25 × 62 × 15	+X	Tool-7	4, 5, 6, 25, 26, 27, 28, 29
c_8	motor base	1		+X	Tool-2	1, 2, 3, 4, 5, 6, 7, 24, 25, 26, 27, 28, 29, 30, 31, 32
c_9	seal flange	1		+X	Tool-3	12, 13, 14, 15, 16, 17, 19
c_{10}	bearing	1	25 × 62 × 15	−X	Tool-7	12, 13, 14, 15, 16, 17, 18
c_{11}	bearing block	1		−X	Tool-2	9, 10, 12, 13, 14, 15, 16, 17, 18, 19
c_{12}	screw	5	M8 × 25	−X	Tool-5	14, 15
c_{13}	bearing shield	1		−X	Tool-8	12, 14, 15
c_{14}	screw	3	M6 × 16	−X	Tool-9	
c_{15}	front cover	1		−X	Tool-6	14
c_{16}	adjusting shaft sleeve	1		−X	Tool-8	12, 13, 14, 15, 17
c_{17}	lock screw	4	M6 × 10	−X	Tool-9	14, 15
c_{18}	shaft sleeve	1		−X	Tool-10	12, 13, 14, 15, 16, 17
c_{19}	screw	6	M6 × 20	+X	Tool-9	
c_{20}	lead screw	1		+X/−X	Tool-11	4, 6, 12, 13, 14, 15, 16, 17, 21, 22, 23, 27, 28, 29
c_{21}	screw	5	M8 × 25	−X	Tool-5	
c_{22}	positioning screw	1	M8 × 25	−Y	Tool-5	
c_{23}	sleeve	1		+X/−X	Tool-2	4, 6, 21, 22, 27, 28, 29
c_{24}	shaft sleeve	1		−X	Tool-10	4, 6, 27, 28, 29
c_{25}	bearing	1		+X	Tool-7	4, 5, 6, 26, 27, 28, 29
c_{26}	bearing shield	1		+X	Tool-8	4, 5, 6, 27, 28, 29
c_{27}	adjusting shaft sleeve	1		+X	Tool-8	4, 6, 28, 29
c_{28}	lock screw	4	M6 × 10	+X	Tool-9	4, 6
c_{29}	screw	4	M8 × 15	−X	Tool-5	4, 6
c_{30}	screw	4	M6 × 20	−X	Tool-9	4, 6
c_{31}	coupling	1		+Z	Tool-2	1, 2, 4, 6, 29, 30, 32
c_{32}	screw	4	M8 × 25	+X	Tool-5	4, 6

6.1. Results

Figure 5 provides the Pareto optimal set, and each point on the Pareto curve shown in Figure 6 represents a feasible solution to the DLBP with an energy saving consideration. As shown in Figure 5, the energy consumption was between 92,412.2 J and 93,449.7 J for disassembling the same driving system, and the similarity degree of working load of the disassembly line was between 0.733 and 0.923. This means that 1037.5 J would be saved if the worst working load rate of disassembling was allowed. From the scatter diagrams of objective values of the Pareto optimal solutions in Figure 5, the conflict relationships for the cost of disassembly line, the similarity degree of idle time, and energy consumption can be obtained. It is clear that when an objective value increases, another objective value will decrease. The optimal solution was selected as the trade-off optimal solution of the DLBP with an energy saving consideration by using a method based on the fuzzy set [35].The minimal number of workstations was $f_1 = 7$, the maximal similarity degree of working load was $f_2 = 0.913$, and the minimal total energy consumption was $f_3 = 92{,}899.7$ J.

Figure 6 lists the trade-off optimal disassembly schedule of the optimal solution in the form of a Gant chart. Table 4 shows the energy breakdown of the trade-off optimal disassembly schedule of the optimal solution. For the optimal disassembly schedule, the energy consumption was 81,249.5 J, where approximately 87.46% of the total energy consumption was spent on disassembling, 5.60% was associated with workstation idling. Moreover, W_2 consumed 14,279.5 J for its operations; the largest energy and largest idle energy consumed was by W_6.

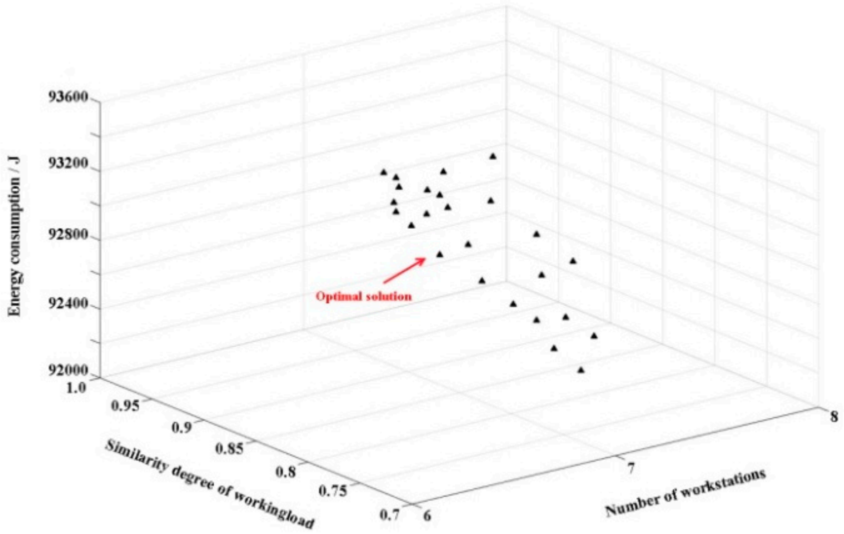


Figure 5. The optimal solutions of the DLBP with an energy saving consideration.

Table 4. Energy breakdown of the optimal solution.

Index	Energy Consumption/J				
	Idle	Disassembly	Direction Change	Tool Change	Total
W_1	306.2	12,984.5	150.0	600.0	14,040.7
W_2	347.0	13,632.5	0.0	300.0	14,279.5
W_3	268.0	11,330.0	300.0	1500.0	13,398.0
W_4	1067.0	11,832.5	0.0	300.0	13,199.5
W_5	642.0	12,145.0	150.0	600.0	13,537.0
W_6	1400.0	10,250.0	150.0	600.0	12,400.0
W_7	1170.0	9075.0	600.0	1200.0	12,045.0
Total	5200.2	81,249.5	1350.0	5100.0	92,899.7

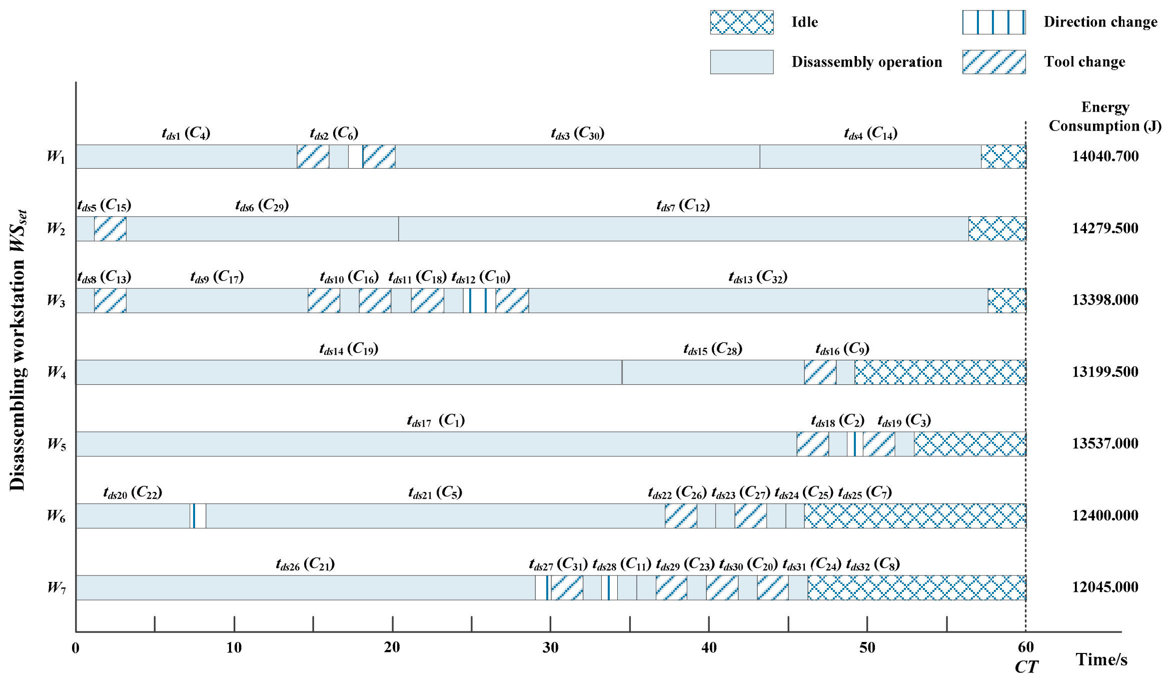


Figure 6. The trade-off optimal solution of the DLBP with an energy saving consideration (Scheduling I).

6.2. Discussion

An optimal solution for minimizing the number of workstations and maximizing the similarity degree of working load (denoted as Scheduling II) was compared with the energy-saving optimal solution (denoted as Solution I). Table 5 and Figure 7 show the comparison of the results. The comparison shows that the total energy consumption was minimal for Scheduling I, while the maximum similarity degree of working load and minimum idle energy consumption were obtained for Scheduling II. Considering energy consumption, there was a 12.96% energy saving in non-disassembly operations (direction change and tool change) compared to considering only the cost of the disassembly line and similarity degree of working load.

Table 5. Comparison of the optimized scheduling of the DLBP with and without an energy saving consideration.

		Optimal Solution of DLBP	
		Scheduling I	**Scheduling II**
f_1: Number of workstations		7	7
f_2: Similarity degree of working load		0.911	0.923
f_3: Energy consumption/J	Idle	5200.2	4800
	Disassembly	81,249.5	81,249.5
	Direction change	1350.0	1050.0
	Tool change	5100.0	6000.0
	Total	92,899.7	94,342.2

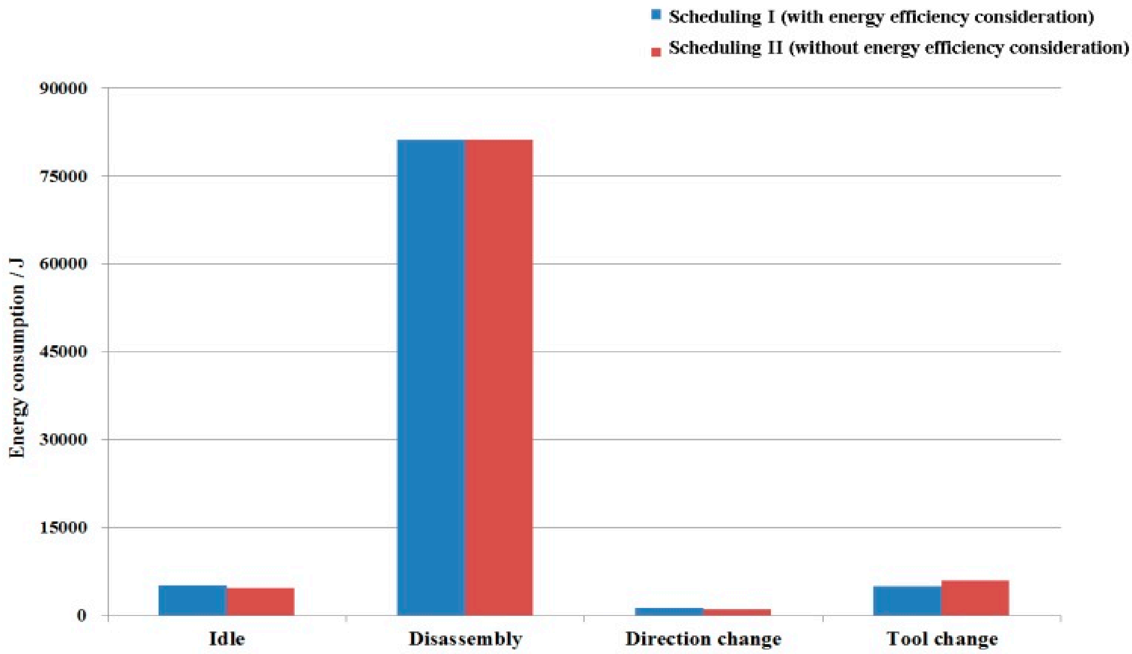


Figure 7. Comparison of Scheduling I and Scheduling II.

Figure 8 lists the disassembly schedule of Scheduling II in form of a Gant chart. Comparing it with Figure 6, it can be seen that the times of direction change and tool change in solution II were greater than the times in Scheduling I. It was observed that a reduction in the time of direction change and tool change reduced energy consumption but increased the energy consumption of idling. Namely, cutting down non-disassembly operations can decrease the total energy consumption, but can make working loads unbalanced.

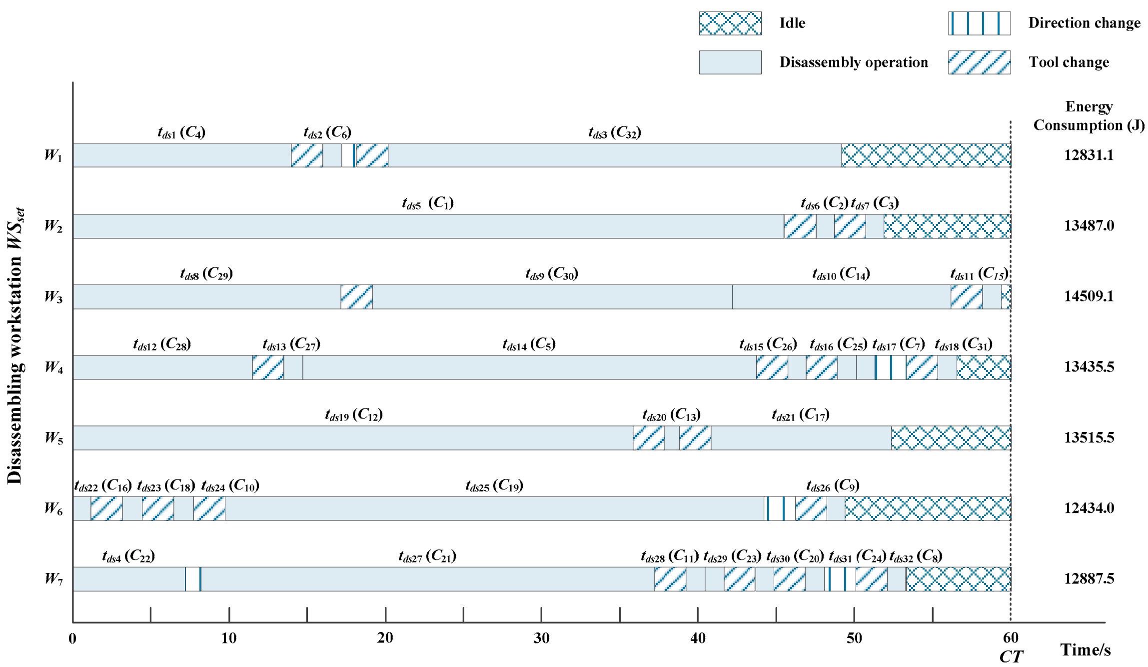
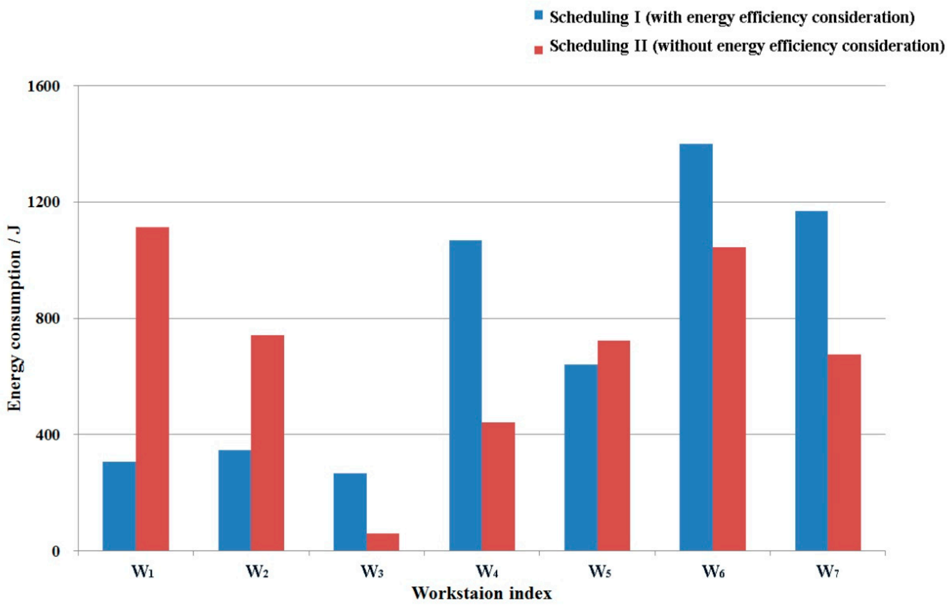
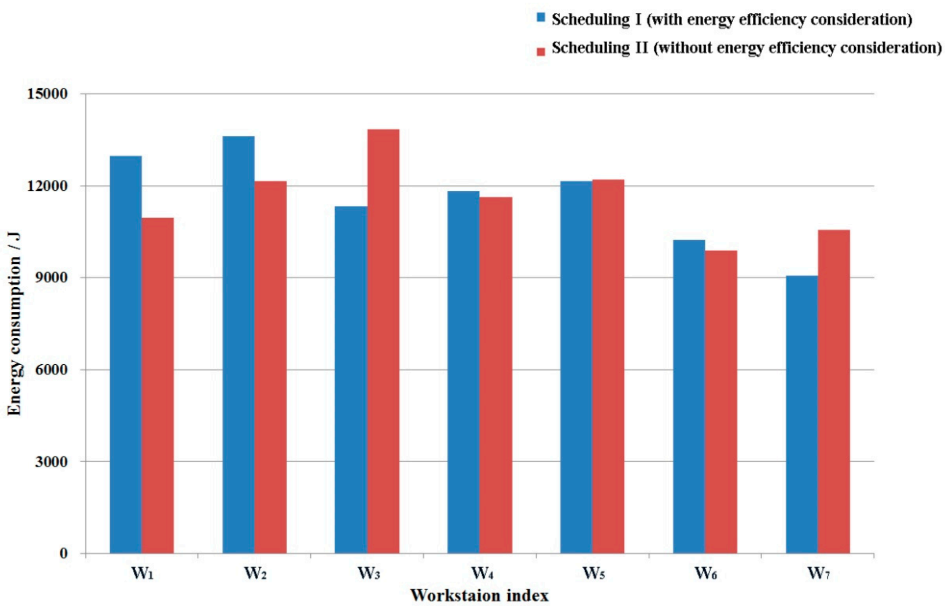


Figure 8. Optimal solution of the DLBP without an energy saving consideration (Scheduling II).

Figure 9 shows a comparison of the energy consumption of idling, disassembling, direction changing, and tool changing of each workstation in the optimal solutions of Scheduling I and Scheduling II. As shown in Figure 9, one can see that total energy consumption of a workstation may not decrease when the energy consumption of idling reduces. For example, there is less total energy consumed in Scheduling I than Scheduling II, while energy consumption of idling in Scheduling II is more than Scheduling I. This suggests that an appropriate selection of workstations and disassembly sequences that cut down unnecessary operations of direction and tool change in a disassembly line would save more energy. This makes the disassembly line more energy-efficient under the proposed schedule.

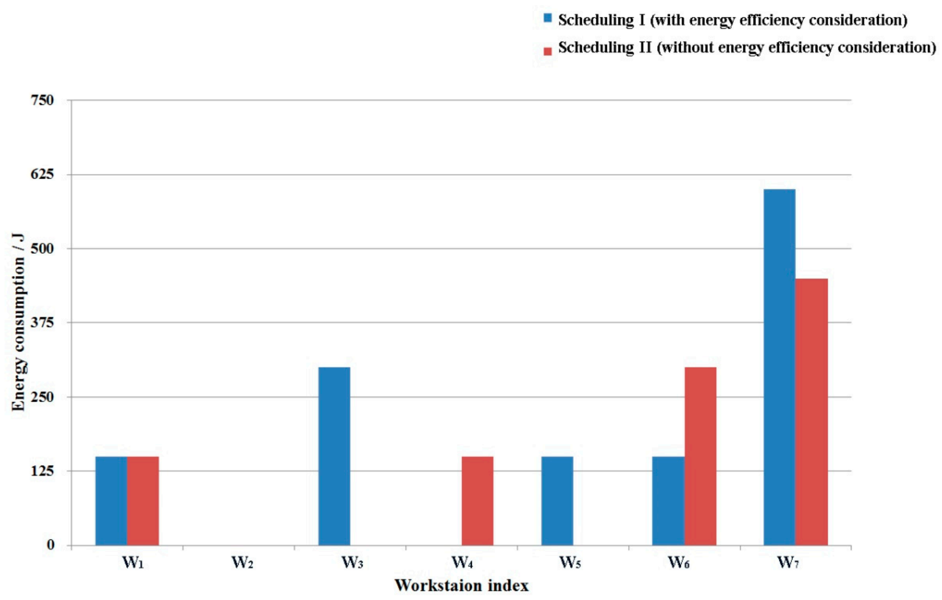


(**a**)

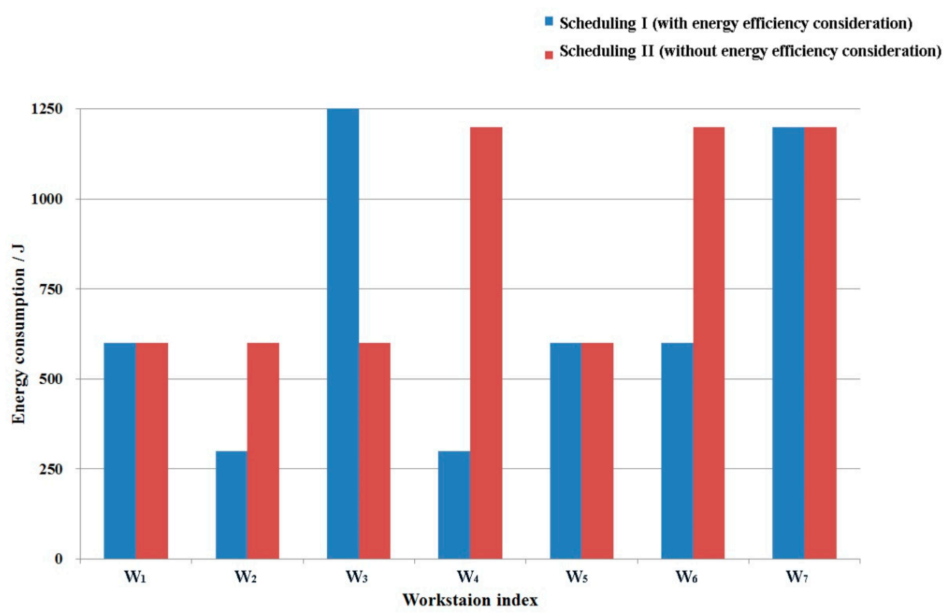


(**b**)

Figure 9. *Cont.*



(**c**)



(**d**)

Figure 9. Comparison of optimal solution of Scheduling I and Scheduling II. (**a**) Comparison of energy consumption of idling; (**b**) comparison of energy consumption of disassembly; (**c**) comparison of energy consumption of direction change; (**d**) comparison of energy consumption of tool change.

7. Conclusions

This paper proposes an energy-efficient optimization method to solve the DLBP with an energy saving consideration. The energy consumption of a disassembly line was analyzed. A mathematical model of the DLBP with an energy saving consideration was formulated, and the energy consumption was considered that took into account the cost and working load in order to design and balance a disassembly line. By applying the proposed model to the DLBP with an energy saving consideration, it is possible to find the optimal solution for a disassembly schedule of workstation selection and disassembly sequence which achieves a lower energy consumption and cost with a higher level of balance degree of load. The studied results show that integrating energy consumption increases the energy savings and sustainability of a disassembly line when comparing only the cost and balance objectives. The idle energy consumptions of disassembly lines can be reduced by appropriately selecting workstations and optimizing the disassembly operation sequence. This is useful for decision-making regarding energy-savings when designing or balancing a disassembly line.

A continuation of this work intends to investigate more realistic situations, where the energy consumptions consider other kinds of impacts obtained by more elaborate models. Another further work would involve an investigation of a sensitivity analysis regarding the decision parameters of a disassembly line.

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Nomenclature

CT	The cycle time.
E_i	Energy consumption of W_i.
$E_{\mathrm{sb}i}$	Energy consumption of the standby of W_i.
$E_{\mathrm{idle}i}$	Energy consumption of the idling of the W_i.
$E_{\mathrm{ds}ij}$	Energy consumption of the disassembling of C_j in W_i.
$E_{\mathrm{dc}ij}$	Energy consumption of the direction changing of C_j in W_i.
$E_{\mathrm{tc}ij}$	Energy consumption of the tool changing of C_j in W_i.
$E_{\mathrm{MTC}i}$	Energy consumption of the manual tool change of W_i.
$E_{\mathrm{ATC}ij}$	Energy consumption of the automatic tool change of C_j in W_i.
$n_{\mathrm{ne}j}$	The normalized execution time of C_j.
$n_{\mathrm{dc}j}$	The times of direction changing (1 if the included angle of C_j and C_k is $\pm 90°$; 2 if the included angle is $\pm 180°$; 0 otherwise).
P_{0i}	The idle power of W_i.
$P_{\mathrm{dc}i}$	The direction changing power of W_i.
$P_{\mathrm{ds}i}$	The disassembling power of W_i.
$P_{\mathrm{sb}ij}$	The standby power of W_i.
$P_{\mathrm{tc}i}$	The tool changing power of W_i.
t_{loading}	The average automatic loading time.
$t_{\mathrm{unloading}}$	The average automatic unloading time.
$t_{\mathrm{claming}i}$	The average clamping time of one EOL product of W_i.
$t_{\mathrm{idle}i}$	The idle time for the next operation of W_i.
$t_{\mathrm{nd}j}$	The normalized disassembly time of C_j.
$t_{\mathrm{dc}0}$	The average direction changing time.
t_{MTC}	The average manual tool changing time.
t_{fix}	The fixed time during one tool change cycle.
$t_{\mathrm{tc}0}$	The time required for the magazine to rotate through one station.
$t_{\mathrm{da}i}$	The additional time of W_i corresponding to precedence constraints.
$t_{\mathrm{dc}i}$	The direction changing time of W_i.
$t_{\mathrm{tc}i}$	The tool changing time of W_i.
Δpos_j	The number of stations rotated from the tool of C_j to that of the next.
M	The number of components.
N	The number of workstations.
i	Workstation index, $i = 1, 2, \ldots, N$.
j,l	Component index, $j, l = 1, 2, \ldots, M$.

k	Disassembly operation index, $k = 1, 2, \ldots, M$.
x_{jk}	Binary variable (1 if C_j is removed as the k-th disassembly operation in the disassembly sequence; 0 otherwise).
y_{ik}	Binary variable (1 if the k-th disassembly operation is assigned to W_i; 0 otherwise).
pl_{jl}	Binary variable (1 if disassembly of C_j can precede disassembly of C_l).
dc_{jl}	Binary variable (1, if the direction of disassembly operations of C_j and C_l are different; 0 otherwise).
tc_{jl}	Binary variable (1, if the disassembly operations of C_j and C_l use different tools; 0 otherwise).

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