Modeling and Optimization of U-shaped Sequence-dependent Disassembly Line Balancing Problem

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Abstract. Disassembly line is the most suitable way for enterprises to disassemble large-scale waste products. However, the disassembly process is complex. It is hard to balance the workload among workstations of line, so designing and balancing the disassembly line is important. Besides, in disassembly process some precedence free parts may interfere with each other. Whenever precedence free tasks interact, their task times will be influenced based on the order in which they are performed. Therefore, in this paper, a multi-objective mathematical model is constructed for U-shaped Sequence-dependent Disassembly Line Balancing Problem (USDDLBP). From efficiency, economic and environmental concerns, the number of open workstations, the smoothing index, and the early disassembly of hazardous and high-demand parts are considered in the disassembly process. The artificial bee colony algorithm is used to solve the problem. The performance of U-shaped and linear disassembly lines is evaluated by benchmark examples, and the calculation results prove the rationality and effectiveness of the presented model for the USDDLBP.

Keywords: Disassembly Line Balancing; Optimization; U-shaped Disassembly Line; Sequence-dependent

1 Introduction

The deterioration of the ecological environment and resource scarcity have prompted enterprises to recycle and remanufacture waste products in order to reduce environmental pollution and achieve resource recycling. According to the United Nations, more than 50 million tons of e-waste are generated worldwide each year, and less than 20% of the e-waste is recycled. The recycling and remanufacturing of scrap vehicles has recently attracted more and more attention with the number of scrap vehicles in china. To achieve higher productivity levels and reduce labor costs, the disassembly line is the best choice for automated disassembly of scrap vehicles on a large scale. Aiming at protecting the environment, boosting development of the

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recycling economy, a new regulation on the recycling of scrapped vehicles was implemented in June 2019, which removes provisions that the five major components of a motor vehicle are reqired to be melted down. Instead, it encourages them to be remanufactured, and this can improve the recycling value of scrapped vehicles. The characteristics of scrap vehicles are large volume, various types and high pollution. It is easy to cause the unbalanced assignment of tasks on the disassembly line, and this will affect disassembly efficiency, as well as the labor, equipment and environmental costs. Therefore, the disassembly line for scrap vehicles should be designed and balanced so that it can work as efficiently as possible.

For large-scale scrap products, in order to improve the disassembly efficiency, disassembly line has is the best choice[1]. When dismantling the scrap products on the disassembly line, there will be an imbalance in workstation task distribution. To address this problem, Gupta and Gungor [2,3] first proposed the disassembly line balancing problem (DLBP). DLBP is considered to assign the disassembly tasks of scrap products among workstations to optimize some measures of effectiveness while satisfacting disassembly constraints. Since DLBP is an NP-complete problem [4], more and more researchers applied intelligent algorithms such as Soft Actor-Critic algorithm [5], Balanced Quantum-inspired Evolutionary algorithm [6], Enumerative Search algorithm [7], Ant Colony Optimization algorithm [8] to deal with DLBP in order to obtain a satisfactory solution.

The DLBPs studied above are all for products operating in a linear layout disassembly line. However, when facing the disassembly of products with variable number of recoveries and varieties, the disassembly line is more efficient with a U-shaped layout. For multi-product mixed-flow disassembly with uncertain disassembly time, Li et al. [9] have studied multi-objective U-shaped DLBP. For some structurally complex products, some parts do not have disassembly priority relationships, but they also interfere with each other. This kind of problem is defined as the sequence-dependence problem. Kalayci and Gupta [10] first introduced the sequence-dependent disassembly line balancing problem (SDDLBP).

Driven by the rapid innovation of information technology, the recycling of scrap products faces the dual challenges of volume volatility and structural complexity. Therefore, the U-shaped line with more flexible allocation and higher efficiency is more suitable for disassembly. This paper constructs a multi-objective U-shaped sequence-dependent disassembly line balancing problem (USDDLBP) model, considering the priority and sequence-dependent constraints between tasks in the disassembly process, and solves it by using Artificial Bee Colony algorithm.

2 Problem Definition

Figure 1 shows a task relationship diagram containing 8 parts of the product. The number in the circle indicates the part (task) number and the number outside the circle corresponds to the operating time of the part. The solid arrow is the priority relationship between the parts in the disassembly process, and the nodes with gray background indicates the hazardous parts. The dotted arrow is the mutual interference between parts, and the number on the dotted line is the interference time increment. In this figure, we can see that there is no disassembly priority relationship between parts 2/3 and 6/7 but there is a sequential dependency relationship. Take part 6/7 as an example, if part 6 is disassembled before part 7, part 7 will interfere with the operation of part 6, resulting in the actual disassembly operation time of part 6 increasing to 8+1=9s (seconds), with an increment of 1s. On the contrary, if part 7 is disassembled before part 6, its operation time will increase by 5s.

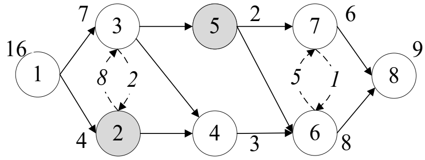


Fig. 1. Product Task Relationship

The U-shaped disassembly line is a more compact and flexible layout in which the workstations are arranged in a U-shape, as shown in Figure 2. The entrance and exit of the U-shape line are at the same direction, so that the tasks can be assigned to the workstations from the front, backward, or in both directions when satisfying the constraints of the priority relationship in the disassembly process. Compared with the linear type, the assignment of tasks on the U-shaped line is more flexible and the disassembly solutions of the scrapped products are more.

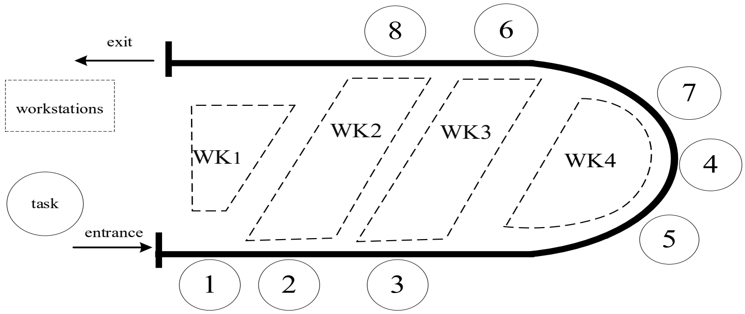


Fig. 2. U-shaped disassembly line

3 Proposed Mathematical Model

The USDDLBP proposed in this paper is to consider the priority relationship and sequence dependency between parts when disassembling products, and to balance the assignment of work tasks of all parts to the workstations opened by the U-shaped line under the condition of satisfying the cycle time to realize the related target requirements. According to the different degrees of importance of the objectives, the following four objectives are considered in descending order:

(1) Minimize the number of workstations opened. The fewer the number of workstations required in the disassembly process, the lower the fixed cost of disassembly will be.

$$\min\ f_1 = \sum_{k=1}^{M} z_k \tag{1}$$

where z_k is a 0-1 variable indicating whether workstation k is opened.

(2) Minimize the smoothing index to ensure the balance of workload among each workstation. The idle time of each workstation should not differ significantly, so the smooth index should be minimized.

$$\min\ f_2 = \sum_{k=1}^{M} \left(IT_k\right)^2 \cdot z_k \tag{2}$$

$IT_k = CT - ST_k$ denotes the workstation k idle time. CT is the cycle time. $ST_k = \sum_{i=1}^{N}\left(t_i + \sum_{j=1}^{N} sd_{ji} \cdot y_{ji}\right) \cdot x_{ik}$ is the total disassembly time of the task assigned on workstation k, in which t_i is the disassembly time of task i, sd_{ji} denotes the time increment of task i caused by the obstruction of task j, and y_{ji} denotes the priority order of assignment of tasks i and j. If task i is assigned prior to j, then y_{ji}=1, otherwise, y_{ji}=0; and x_{ik} is a 0-1 variable to denote whether or not task i is assigned on workstation k.

(3) Minimize hazards by removing hazardous parts as early as possible so as to reduce environmental pollution.

$$\min\ f_3 = \sum_{l=1}^{N} \left(l \cdot h_{PS_l}\right) \tag{3}$$

PS_l denotes the part number corresponding to the lth position in the disassembly sequence, e.g., sequence {1,5,2,3,6,7,4}, the 2nd position PS_2=5. h_i is the hazard of part i. If the part is hazardous then h_i=1, otherwise h_i=0.

(4) Remove high-demand parts as early as possible to satisfy market demand.

$$\min\ f_4 = \sum_{l=1}^{N} \left(l \cdot d_{PS_l}\right) \tag{4}$$

d_i is the demand for part i.

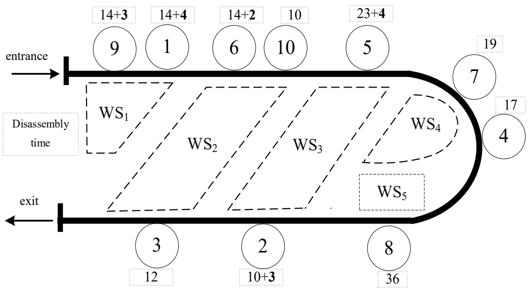
4 Illustrative Examples

In this section, P10 and P25 instances are utilized to explain how the proposed model works for solving USDDLBP. The P10 product containing 10 parts and the P25 disassembly example with 25 parts are disassembled in U-shaped and linear disassembly lines, respectively. To obtain the optimal disassembly solution, P10 and P25 instances are solved by the artificial bee colony algorithm.

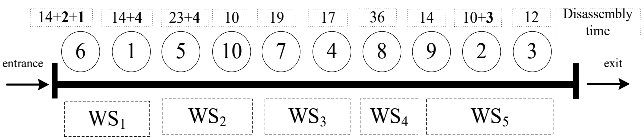
For the P10 instance, the optimal solution of the problem can be searched: f_1=5, f_2=61, f_3=6, f_4=8880. The disassembly sequence corresponding to this optimal solution is shown in Table 1. Figure 3(a) shows the assignment of tasks to each workstation on the U-shaped line for this disassembly scheme. In this disassembly process, 9, 1, 5, 6, and 2 interfered by the task 6, 4, 4, 5 and 3 respectively, which results in an increase in the disassembly time of tasks 9, 1, 5, 6, and 2 by 3s, 4s, 4s, 2s, and 3s, respectively. For the P25 instance, the ABC algorithm can find the optimal solution within the specified 100s: f_1=10, f_2=9, f_3=76, f_4=909, and the corresponding disassembly sequence is shown in Table 1. Table 1 shows the comparison of the optimal solutions for P10 and P25 in both linear and U-shaped layouts. The U-shaped layout outperforms the linear layout in terms of smoothing index, hazard index and demand index, except for the P10 example, where the hazard index increases by 1 comparing the U-shaped layout with the linear layout. Figure 3 shows a comparison of the optimal task assignments under the two disassembly line layout modes for the P10 instance. It can be seen that the U-shaped line layout is designed to be more flexible, which allows the disassembly tasks to be assigned more flexibly on the workstations.

Table 1. Comparison of U-shaped and linear layout results

instances	model	objective function				Optimal disassembly sequence
		f_1	f_2	f_3	f_4	
P10	U-shaped	5	61	6	8880	9,1,-3,6,10,-2,5,-8,-4,-7
	Linear	5	67	5	9605	6,1,5,10,7,4,8,9,2,3
P25	U-shaped	10	9	76	909	2,1,5,4,-24,10,3,-25,-23,-22,-21,-20,-17,-19,-14,11,-13,12,-18,-15,9,6,7,-16,8
	Linear	10	9	80	925	2,1,5,4,10,11,3,9,6,7,12,8,15,18,13,14,17,16,19,20,21,22,25,23,24



(a) U-shaped disassembly line



(b) Linear disassembly line

Fig. 3. Distribution of P10 product tasks in two different layout disassembly lines

5 Conclusions

In the disassembly process, there will be mutual interference between some precedence free parts, which will lead to an increase in disassembly time, and thus it will affect the balance of the disassembly line. Therefore, this paper establishes a U-shaped SDDLBP multi-objective optimization model. Through the comparison of two examples, the U-shaped disassembly line is more flexible than the linear layout, which can make the disassembly tasks more reasonably distributed.

Due to the uncertainty of operation time during disassembly, future research can consider bilateral disassembly of large products and mixed disassembly of multiple product types. The research of DLBP is not only an optimization problem in industrial engineering, but also a technical path to achieve carbon neutrality and circular economy. With the breakthrough of digital twin, AI and flexible robot technology, the disassembly line will accelerate the evolution of intelligence and adaptive direction.

Acknowledgements

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