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Integrated Disassembly and Assembly Model for Heavy Duty Equipment Maintenance

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Abstract

This paper investigates a multi-period integrated decision-making model for the heavy duty equipment maintenance involving disassembly, inspection and assembly with uncertain numbers of replaced parts within a time horizon. There are large numbers of subways cars exported from other countries and the maintenance is difficult to be conducted in Hong Kong (HK) due to the limited spaces, machinery and technical supporting team. Thus, the efficient maintenance planning is required to ensure the quality of transportation services. To resolve the problem, a deterministic mixed integer optimization model is developed to achieve integrated optimization of disassembly and assembly. The model minimizes the total operation cost consisting of purchasing cost and repair cost, subject to capacity constraints. A real-life case study from Mass Transit Railway (MTR) Hong Kong is presented to verify the proposed model.

Keywords: Heavy duty equipment maintenance; Integrated planning; Disassembly and assembly.

1. Introduction

Maintenance services are critical support activities that extend life length and improve performance of the equipment [1]. Even though maintenance is not a value adding activity, it does improve the circularity of material and part use, which reduces capital investment. In some industrial sectors with high capital investment, the equipment is highly valuable and heavy, and called heavy duty equipment, such as subway cars in the metropolitan transportation industry, mining machinery in the mining industry, and airplanes in the airline industry [2]. Such equipment requires not only regularly maintenance but also complete maintenance at regulated intervals.

Complete maintenance aims to keep the equipment in serviceable condition by preventing all kinds of critical damage [3]. Compared to regular maintenance, complete maintenance is completed in order of disassembly, inspection and repair, and assembly, and takes longer maintenance time due to involving many procedures. However, for heavy duty equipment, complete maintenance is cost-effective and reduces labour cost, because replacement of worn parts is more cost effective than purchasing new equipment and less time consuming than replacing one part each time [4]. Due to the large involvement of components, the complete maintenance is usually divided into several procedures with a series of tasks which have designated time and standard quality control [5]. Take Mass Transit Railway (MTR) in Hong Kong for example, there are total 152 railway stations where hundreds of heavy-duty trains are running through the public transport network. The maintenance for MTR includes the infrastructures like railways, electronic and electrical facilities alone the railways, as well as subway cars. The maintenance of subway cars plays a significant role in supporting the whole MTR transportation system since there are large numbers of subways cars exported from other countries and the maintenance is difficult to be conducted in Hong Kong (HK) due to the limited resources,

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Table 1. Related references

Reference	Problem	Objective	Factors	Linear/Nonlinear	Solution method	Solver	Case
[6]	Design disassembly line (Stochastic disassembly line balancing problem)	Maximize the line profit	Under uncertainty of task times; Partial disassembly;	Stochastic mixed binary programing	Monte Carlo sampling based solution method	MS VC++ 2008 & CPLEX 12.5	7 instances
[7]	Design disassembly line	Maximize the profit	Under variability of the end-of-life product quality	Binary integer programing			The remanufacturing of mechatronic parts in the automotive industry
[8]	The capacitated disassembly scheduling problem	Minimize the sum of purchase, inventory holding and disassembly operation costs	Subject to capacity restriction	Integer programing		CPLEX 6.5	End-of-life treatment of inkjet printers
[9]	Disassembly sequencing optimization				A selective disassembly methodology		The example of washing machine
[10]	The integration of assembly and disassembly.						
[11]	Optimization of products life cycles	Define the process for management of life cycle with a focus on assembly, service and disassembly of capital intensive products	The potentials of product services in all phases of each product's life				
[12]	Design and performance analysis of a flexible assembly system and disassembly system with dual kanban	Maximize the throughput for minimum WIP		Mixed integer programing	Petri net model	Integrated Net Analyzer & LINGO	A small case
[13]	Optimization of the disassembly, remanufacturing and assembly system	Minimize inventory holding cost, remanufacturing cost, disposal cost, purchasing cost and backlogging cost	Stochastic lead time and quality of remanufactured components	Stochastic programing	Genetic algorithm		Numerical study (two-level components)
[14]	Design a modular product platform configuration model	Minimize the number of assembly stations and cycle time		Mixed integer programing		AMPL programming language, & CPLEX solver	The base module of the modular phone

such as spaces, machinery and technical supporting team. Thus, there are only few depots where can support the maintenance operations which are commonly regarded as disassembly and assembly problems from the literature for optimization purposes.

There are many research papers from literature talking about the disassembly and assembly of heavy-duty equipment. Table 1 summarizes some typical articles by considering the focused problems, objective functions, factors, problem categories (linear or nonlinear), solutions, solver, and practical cases. It could be observed that most of the research focuses on the maximization of profit. Integer programming is typically treated as the category from Table 1. However, there is a research gap that few studies took the maintenance procedures as a whole to investigate the total cost. In order to fulfil this research gap, this paper presents a deterministic mixed integer optimization model by considering the total operational costs such as purchasing cost and repair cost. A case study from HK MTR is demonstrated to validate the proposed model.

The rest of this paper is organized as follows. Section 2 gives the problem description from the real-world problem given the case from HK MTR. Section 3 talks about the model formulation with the notifications and a deterministic mixed integer optimization model considering the total costs. Section 4 illustrates a case study from a real-life company in HK. Section 5 concludes this paper by giving the key observations and future research directions.

2. Problem Description

In the real-world problem, the increasing number of subway cars puts pressure on the company to optimize the maintenance operation due to the limited resources on maintenance shops. Figure 1 illustrates the key processes of subway car maintenance operation, which is mainly divided into three phases: (i) disassembly; (ii) inspection; and (iii) assembly. Generally, such maintenance operation must be done for each subway car on a 5 or 6 year cycle. Subway cars are then disassembled completely so as to conduct a full inspection and diagnosis. The maintenance planner decides on how many subway cars can be maintained at each period under capacity limits. However, the current maintenance planning is isolated without considering the actual progress of the next two phases, which leads to infeasible decisions due to limited resources maintenance shops.

The dismantled key parts such as wheels, trucks, axles, etc are delivered for inspection and diagnosis. Technicians use diagnostic equipment and inspect machines, such as calibration devices, computerized test equipment and vibration test equipment, to diagnose part defects and classify the disassembled parts into three categories. The first category is reusable items that can be directly reused and reassembled (called type I). The second is defective parts that can be reused and reassembled after repairing or repolishing (type II). And the type III is those should be replaced. For type III, sourcing spare parts could result in assembly schedule delay, because the lead time of spare parts might be longer than the takt time that could be 2 or 3 days for maintaining a subway. Setting a high inventory level for all spare parts is a feasible solution, but this approach is not suitable for our motivated case company due to the limited warehouse space.

Once inspection is completed, type II parts are repaired and assembly plan will be executed to replace type III parts and assemble subway cars. In such case, assembly can be completed without any delays of all required parts. Therefore, the integrated decision-making plays an important role in ensuring the final assembly.

The major challenge faced by the company is the limited storage space for inventory. This paper develops an integrated strategy that combines disassembly and assembly planning into a single mathematical model. Inspection phase will be omitted in this paper using fixed time horizon for presentation. The number of required spare parts is regarded as uncertainty sets that are calculated based on historical data. Hence, a robust counterpart of the single mathematical model is developed by a robust optimization framework to minimize the total operation cost consisting of purchasing cost and repair cost.

The novelties of this paper include: (i) most research focuses on continuous maintenance [15], prescriptive maintenance [16], opportunistic maintenance [17], and preventative maintenance, while little research pays attention to complete maintenance; (ii) an integrated strategy is proposed to consider all phases when complete maintenance planning is made.

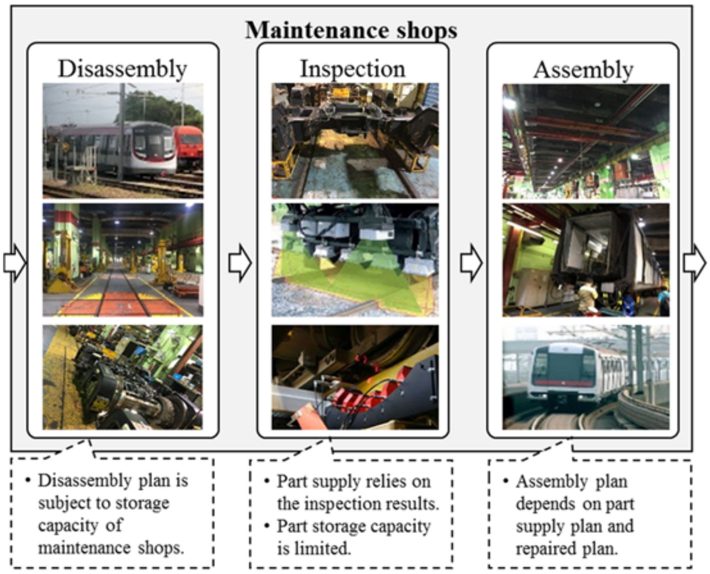

Fig.1. The maintenance operation of subway cars

3. Model Formulation

In this section, a formulation of the disassembly and assembly model for heavy duty equipment is developed. Disassembly planning and assembly planning are usually made separately and sequentially. This method could lead to ineffective planning due to the conflict of disassembly planning and assembly planning; or cause unnecessary waste, such as inventory waste and storage waste. In order to solve these challenges, this paper aims to develop an integrated model of disassembly and assembly to calculate a globally optimal solution for heavy duty equipment maintenance. This model adopts the zero inventory strategy to manage inventory.

The parameters and variables are presented as follows:

$i \in I$: The index of equipment, where I is the set of equipment;

$j \in J$: The index of part, where J is the set of parts;

$t \in T$: The index of time period, where T is the set of time periods within the planning horizon.

Our model includes the following parameters and sets:

D_t: Disassembly capacity at period t;

A_t: Assembly capacity at period t;

n^{ij}: The number of part j needed to assemble equipment i;

m_t^j: The number of part j disposed at period t;

u_t^j: The number of part j that can be reused at period t;

c_t^j: Unit cost of obtaining part j from disassembly lines at period t;

p_t^j: Unit cost of purchasing part j at period t;

Our formulation includes the following decision variables:

x_t^i: 1, if equipment i is disassembled at period t; 0, otherwise;

y_t^i: 1, if equipment i is assembled at period t; 0, otherwise;

q_t^j: The quantity of part j purchased at period t.

The formulation is as follows:

$$\min \psi = \sum_{t=1}^{T} \sum_{j=1}^{J} \left(u_t^j c_t^j + q_t^j p_t^j\right) \quad (1)$$

subject to

$$\sum_{t=1}^{T} x_t^i = 1, \forall i \in I \quad (2)$$

$$\sum_{t=1}^{T} y_t^i = 1, \forall i \in I \quad (3)$$

$$0 \le \sum_{t'=1}^{t-1} x_{t'}^i \le y_t^i, \forall i \in I \quad (4)$$

$$\sum_{i=1}^{I} x_t^i \le D_t, \forall t \in T \quad (5)$$

$$\sum_{i=1}^{I} y_t^i \le A_t, \forall t \in T \quad (6)$$

$$\sum_{i=1}^{I} n^{ij} x_t^i = m_t^j + u_t^j, \forall t \in T, j \in J \quad (7)$$

$$\sum_{i=1}^{I} n^{ij} y_t^i = q_t^j + u_t^j, \forall t \in T, j \in J \quad (8)$$

$$q_t^j \ge 0, \forall t \in T, j \in J \quad (9)$$

$$x_t^i, y_t^i \in \{0,1\}, \forall t \in T, i \in I \quad (10)$$

$$q_t^j \in \mathbb{Z}, \forall t \in T, j \in J \quad (11)$$

The objective (1) is to minimize the total cost including purchasing cost and repair cost. Constraint (2) ensures a disassemble line can only be used to disassemble a piece of equipment at any time. Constraint (3) ensures an assembly line can only be used to assemble a piece of equipment at any time. Constraint (4) guarantees a piece of equipment is disassembled firstly and then assembled. Constraint (5) and (6) show the capacity constraints for disassembly and assembly respectively. Constraint (7) represents the material balance of disassembled equipment. Constraint (8) indicates the material balance of parts at any periods. Constraint (9), (10) and (11) present the decision variables and their constraints.

4. A Case Study

4.1. Case introduction

The case company comes from MTR HK that is a public transport network including heavy rail, light trial, and feeder bus services. There are several maintenance depots at Kowloon Bay, Tsuen Wan, Chai Wan, and Tseung Kwan O. They are responsible for maintaining all MTR subway cars in HK. Each depot has facilities for stabling, cleaning, preventive and corrective maintenance, as well as cranes and jacking facilities for replacement of heavy equipment (mtr.com.hk). MTR Kowloon Bay depot is one of the oldest (dated to 1970s) and biggest facility for 5 MTR lines and 13 and 22 subway cars from Korean and Mainland China respectively. There are total 14 parallel lanes for heavy-duty subway cars maintenance operations such as disassembly, inspection, and assembly.

Firstly, all trains come into the Kowloon Bay depot will be disassembled completely. Then, some major components such as wheels, large springs and truck will be delivered to inspection areas. Some parts such as air-conditioning facilities will be moved to washing areas. Some items such as screws or damaged parts will be disposed. Secondly, the inspected components such as wheels will be sent to repairing areas if they are able to be reused after specific processing such as lathing of the surface. Finally, all the inspected, purchased new components and washed items will be delivered for the final assembly. Specifically, all components from a subway car should be assembled into the same one due to strict requirements and safety & reliability standards.

Cost is one of the critical consideration when Kowloon Bay depot considering the subway cars maintenance due to the limited space and high manpower cost. In this case, two costs are concerned from the practical case. They are purchasing cost and repair cost. The following section gives the results and discussions from the case. For simplicity without losing generality, the experiment uses 7 subway cars, 4 time periods, and 3 types of components for validating this model.

4.2. Results and discussions

The size parameters for the experiment are $|I| = 7$, $|J| = 3$ and $|T| = 4$, where $|I|$, $|J|$ and $|T|$ represent the number of equipment, the number of types of parts, and the total number of periods respectively. The experiment was conducted using MATLAB R2014b. For easy simplicity without losing generality, subway cars are the same type, so they have the same demand for three categories of parts. Thus, $n^{i1} = 20$, $n^{i2} = 25$, $n^{i3} = 15$, where n^{i1}, n^{i2} and n^{i3} indicate the number of part 1, 2 and 3 that are required in each subway car. In maintenance shops, there are only 4 maintenance lines that can be used to disassemble and assemble subway cars. The main data of the experiment is provided in Table 2 and Table 3. Table 2 shows the disassembly and assembly capacity information, and related cost information. Note that unit of cost instead of any specific currency is considered in this case. And Table 3 shows the number of each type of parts that are required to be disposed in each subway car.

Table 2. Input parameters

Input data	t			
	1	2	3	4
D_t	4	3	1	0
A_t	0	1	3	4
c_t^1	3	3	2	4
c_t^2	6	5	3	4
c_t^3	3	4	3	3
p_t^1	10	11	10	11
p_t^2	15	12	13	17
p_t^3	13	12	16	17

Table 3. The number of each type of parts disposed in each subway car

J	I						
	E1	E2	E3	E4	E5	E6	E7
P1	1	2	3	1	3	2	1
P2	2	3	1	2	3	3	4
P3	2	3	1	3	2	1	5

The detailed disassembly and assembly planning is shown in Table 4, where capital letter D denotes disassembly and capital letter A denotes assembly. Table 5 shows the detailed number of each type of parts that are required to be reused and procured. The total cost is 2040.

Table 4. The disassembly and assembly plan

t	I						
	E1	E2	E3	E4	E5	E6	E7
1	D				D	D	
2		D		D			D
3			D	A	A	A	
4	A	A	A				A

Table 5. The number of each type of parts procured and resused at each period

t	q_t^j			u_t^j		
	P1	P2	P3	P1	P2	P3
1	6	8	5	54	67	40
2	4	9	11	56	66	34
3	3	1	1	17	24	14
4	0	0	0	0	0	0

From Table 3, it could be observed that it is not necessary to assemble a subway car after it is disassembled. For most of subway cars, there is a time interval between disassembly and assembly processes, except subway car 3 and 4. The phenomenon is caused by purchasing cost and repair cost.

5. Conclusion

This paper is motivated from a real-life company – MTR Hong Kong where maintenance operations are conducted in one of its largest depot in Kowloon Bay. Two costs are paid attention to including purchasing cost and repair cost. A deterministic mixed integer optimization model is established to minimize the total cost. Several contributions are highlighted in this paper. First of all, an entire view of heavy-duty equipment maintenance was presented by considering three stages: disassembly, inspection, and assembly. Secondly, by considering the costs, this research introduces a model with objective function for minimizing the cost from practice concerns.

Future research directions will be conducted in the following aspects. On one hand, the above two costs will be considered in different scenarios with different weights. How to extend this proposed model for facing more generic situations will be further investigated. On the other hand, this model could be integrated into some decision-making systems such as production planning and scheduling. That will be implemented in the near future. Finally, the inventory holding cost is not considered in this paper as it is one of the significant factors which should be concerned due to the limited space for holding required components. For practical concern, this is with great merit due to the large volume of components from subway cars so that the space requirement for holding these parts such as trucks and wheels are necessarily considered in the future.

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