Production Planning and Inventory Control in a Remanufacturing Production System

Swee S. Kuik*, Toshiya Kaihara, Nobutada Fujii, Daisuke Kokuryo

Grauate School of System Informatics, Kobe University, 1-1 Rokkodai, Nada, Kobe, Hyogo 657-8501, Japan

*Corresponding Author: Swee.Kuik@outlook.com

Abstract

The management of production and inventory control associated activities in remanufacturing production system has received attention by practitioners in the last two decades. This is due to the increased productivity, limited supply of virgin materials, stringent environmental requirements for product disposal and treatment as well as substantial change in global sustainability regulations. In order to constantly attain the supply chain cost savings for manufacturing operations, an integrated production planning model in remanufacturing by considering component obsolescence is developed. The aim of this developed model is to minimise an overall costs for production with remanufacturing operations. A numerical application is demonstrated to show its practical usefulness and flexibility in a remanufacturing production plan by considering different obsolete time periods for used components from returns streams. Finally, the contributions of this study and future works are discussed.

Keywords: Remanufacturing operations, reverse supply chain management, sustainable manufacturing, product recovery, component obsolescence.

1. Introduction

Supply chains is commonly known as logistical system that is to plan and organise the procurement of raw materials for manufacturing and distributing to their final consumers. [1-3] To reduce the used product landfill potential, manufacturers are now considering various remanufacturing operations as parts of their strategic planning towards sustainability [4-8]. Staiko et al [9] emphasised that manufacturers must be responsible for managing product returns and recovery operations. Currently, there is lacking on the appropriate production planning for the consideration of

component obsolescence [1, 2, 4, 5]. Furthermore, the production and inventory with remanufactured components is very difficult to manage due to the large variation of technological lifecycle and consumer demands. In particular, some used component may not able to be remanufactured for other secondary markets [10-12]. In this research study, we consider the complex scenario of production planning and inventory control with remanufacturing operations. A new optimisation model in remanufacturing is developed by analysing and utilising used components for production and minimising disposal related treatment costs in a supply chain.

In addition, there is also a lack of discussion and review on the remanufactured component obsolescence scenario where the returned products and components are to be disassembled and utilised [10, 11, 13-15]. In this article, we discuss remanufacturing production planning and inventory control by varying used component obsolescence. Section 2 discusses the reverse supply chain management and product recovery operations. A gap in current literature for production planning in remanufacturing is presented. In Section 3, the mathematical formulation is then presented and objective function is formulated for this study. Section 4 presents the numerical application to show the practical usefulness of the proposed model. In Section 5, we present the results and analysis based on varying used component obsolescence time periods. A comparative study is analysed and discussed. Finally, the significant contributions and our future works are also discussed.

2. Product Recovery

2.1 End of Life strategies

To increase global competitiveness among supply chain networks, the considerations of end-of-life (EOL) strategies has recently become an alternative solution to generate

additional profits for manufacturers [16, 17]. Prices for acquiring virgin materials for production are now getting higher and the environmental regulations has been revised regularly to meet current market needs [2, 4]. Therefore, there is an increase of total associated costs for used product disposal and treatment upon product returns.

The traditional supply chain always aims for optimising the operational costs effectiveness and improving product order fulfilment and distribution to their end users. In reverse supply chain management, the obsolescence issue is one of the critical aspects for manufacturers to be considered for recovery operations as parts of their business processes [6-8]. This is due to the rapid change in technology lifecycle in which the used components may need to be disposed partly and/or entirely and unable to disassemble for other purpose or remanufacturing processes.

Although there is an increased number of research literature that focuses on the importance of component obsolescence and technology lifecycle in remanufacturing, current optimisation modelling for production planning with obsolescence is still lacking due to complexity of product returns and recovery operations.

2.2 Remanufacturing operations

In views of today's short lifecycle of new and innovative products, the remanufacturing strategy is now considered as one of the compromising ways to minimise large amount of product disposal for landfill [2, 3, 5]. This has become an important research focus to help manufacturers to cope with the higher costs of waste treatment and increased burdens. There are various important factors and aspects that need to be examined for the technical feasibilities and lifecycle constraints including technology life and wear-out life [1-4]. Currently, there are numerous optimisation models for production planning for remanufacturing operations but those models exclude the component obsolescence issues. In fact, this is one of the major bottlenecks for manufacturers to overcome this constraint [10, 17].

In today's markets, there are many remanufactured products that are currently available for consumers including single-use camera, mechanical machinery with components, laptop, automotive rebuilt parts and/or components [16, 17]. In addition, for achieving full financial sustainability, global manufacturers are also now working more on product returns and recovery operations improvement including production planning and inventory control to increase profitability of the organisation.

2.3 Product Returns Management

Kuik et al. [2, 4] also emphasised on the importance of improving product returns and remanufacturing operations as manufacturers can generate significant cost savings by implementing the effective and efficient handling processes. For example, the returned product can be disassembled into multiple subassemblies for secondary markets and for other remanufacturing processes [2, 3].

In recent years, the used component obsolescence issue is one of the upmost problems in recovery operations [2, 6]. For effective production planning in remanufacturing operations, the reduction of operational improvement programmes by minimising the inventory holding costs of those obsolete used components can actually improve the profitability of the organisation. Therefore, there is a need for developing integrated optimisation model for production planning in remanufacturing by incorporating obsolescence issue and minimising the total associated costs for production and inventory control.

3. Mathematical Modelling

The optimisation model is developed to examine various remanufacturing cost effective management in production planning. The developed model aims to minimise an overall associated costs for the remanufacturing operations and inventory holding including the collection returned costs.

Table 1. Model parameters

Description	
N	Number of remanufactured product i , where $i = 1, 2, 3, \dots, N$
J	Number of component j , where $j = 1, 2, 3, \dots, J$
T	Planning horizon comprising of time period t , where $t = 1, 2, 3, \dots, T$
f	Time period f , upon receiving component j ,
$(R + Q)_i$	Unit cost of returned and remanufactured product i
C_j	Unit cost of component j
U_i	Inventory holding unit cost for remanufactured product i
H_j	Inventory holding unit cost for component j
A_i	Fixed set-up cost for remanufactured product i
G_j	Fixed ordering cost for component j
V_i	Production capacity for remanufactured product i
M_j	Ordering capacity for component j
α_j	Disposal treatment unit cost for component j
S_j	Order lot size ordering for component j
O_j	Order lead-time for component j

The detailed formation for this optimisation model is presented in the following section. The model parameters and decision variables used for this formulation is tabulated in Table 1 and 2. The assumption made in this study is summarised as below:

- Demands are deterministic;
- Remanufactured product and components are known;
- Remanufacturing capacity and ordering are deterministic and constant;
- Reliability and quality aspects are excluded.

Table 2. Model variables

Description	
X_{it}	Quantity of i produced in t period
I_{it}	Quantity of inventory i in t period
y_{jt}	Quantity of j ordered in t period
L_{jt}	Quantity of inventory j in t period
L_{jtf}	Quantity of inventory in t period upon receiving j at the end of f period
β_j	Quantity of disposal treatment j
γ_{jtf}	Quantity of usage in t period upon receiving j at the end of f period
D_{it}	Demand i in t period
B_{ji}	Bill of Material (BOM) with j of i
e_j	Obsolescence with j lifecycle
a_{it}	Fixed setup-up of i in t period (binary)
P_{jt}	Fixed (scheduled) ordering of j in t period (binary)
p_{jt}	Fixed ordering of j in t period (binary)

3.1 MIP Model Development

This section discusses the mathematical formulation for a MIP optimisation model to examine remanufactured production planning scenario by considering remanufactured component obsolescence issue.

Using the above derived model parameters, an objective function is then formulated based on the costs associated with production planning and inventory control in a remanufacturing production system as shown in Eq. (1). Term 1-4 are the primary cost associated with producing a remanufactured product with used components in production and inventory. Term 5 is the production setup-up associated costs in time period planning horizon. Terms 6 and 7 are related to the cost associated with ordering used components for production. Term 8 is known as the inventory cost

associated with used components in production planning at the end of obsolete time period. Finally, term 9 is used to estimate the disposal cost needed for obsolete inventory holding in production.

$$\begin{aligned}
 \text{Min } Z = & \sum_i \sum_t (R + Q)_i X_{it} \\
 & + \sum_j \sum_t C_j y_{jt} \\
 & + \sum_j \sum_t C_j Y_{jt} + \sum_i \sum_t U_i I_{it} \\
 & + \sum_i \sum_t A_i a_{it} + \sum_i \sum_t RR_j P_{jt} \\
 & + \sum_j \sum_t G_j p_{jt} \\
 & + \sum_j \sum_t \sum_f H_j L_{jtf} + \sum_j \alpha_j \beta_j
 \end{aligned} \tag{1}$$

The following specific constraints are used for deriving the objective function.

$$I_{it} = I_{i,t-1} + X_{it} - D_{it}, \forall t, j \tag{2}$$

$$\sum_f L_{jtf} = L_{j0} + S_j Y_{jt} - \sum_i B_{ji} X_{it}, t = 1, \forall t, j, r \tag{3}$$

$$\begin{aligned}
 \sum_f L_{jtf} = & \sum_f L_{j,t-1,f} + S_j Y_{jt} - \sum_i B_{ji} X_{it} \\
 & 1 < t < e_j, t \geq e_j, \forall t, j
 \end{aligned} \tag{4}$$

$$\begin{aligned}
 \sum_{f=t+1-e_j}^t L_{jtf} = & \sum_{f=t+1-e_j}^{t-1} L_{j,t-1,f} + S_j Y_{jt} - \sum_i B_{ji} X_{it} \\
 & t \geq e_j, t \geq o_j, \forall t, j
 \end{aligned} \tag{5}$$

$$\begin{aligned}
 \sum_f L_{jtf} = & \sum_f L_{j,t-1,f} + S_j y_{jt} - \sum_i B_{ji} X_{it} \\
 & 1 < t < e_j, t \geq o_j, \forall t, j
 \end{aligned} \tag{6}$$

$$\begin{aligned}
 \sum_{f=t+1-e_j}^t L_{jtf} = & \sum_{f=t+1-e_j}^{t-1} L_{j,t-1,f} + S_j y_{jt} - \sum_i B_{ji} X_{it}, \\
 & t \geq e_j, t \geq o_j, \forall t, j
 \end{aligned} \tag{7}$$

$$\sum_i B_{ji} X_{it} = \sum_f \gamma_{jft} \tag{8}$$

$$\begin{aligned}
 \sum_i B_{ji} X_{it} = & \sum_{f=t+1-e_j} \gamma_{jft} \\
 & 1 \leq t < e_j, \forall t, j, r
 \end{aligned} \tag{9}$$

$$L_{jtf} = S_j Y_{jt} - \gamma_{jft} \tag{10}$$

$$L_{jtf} = S_j y_{jt} - \gamma_{jft} \quad f = t, t \leq o_j, \forall t, j, r \quad (11)$$

$$L_{jtf} = L_{j,t-1,f} - \gamma_{jft} \quad f = t, t \leq o_j, \forall t, j, r \quad (12)$$

$$\beta_j = \sum_{t=o_j-1} \gamma_{j,t,t+1-o_j} \quad \forall t, j \quad (13)$$

$$X_{it} \leq V_i, y_{jt} \leq M_j \quad \forall t, j \quad (14)$$

$$y_{jt} \leq W P_{jt}, X_{it} \leq W a_{it}, Y_{jt} \leq W p_{jt} \quad \forall t, i \quad (15)$$

$$X_{it}, y_{jt}, Y_{jt}, I_{it}, L_{jtf}, \gamma_{jft}, \beta_j \geq 0 \quad \forall t, i, j, f \quad (16)$$

$$a_{it}, P_{jt}, p_{jt} \in (0,1) \quad (17)$$

Eq. (2) is considered as the balance of inventory holding in production that must be satisfied with the demand request. Eqs (3) – (7) are classified as each remanufacturing order is corresponding with the scheduled production. Eqs. (8) and (9) is related to the remanufacturing production usage at each period with the obsolete used components. Eqs. (10) – (12) are used for inventory control for product and used component at each period. Eq. (13) is used for the excessive components to be disposed at the end of its obsolete period. Furthermore, the remanufacturing capacity constraints are formulated as shown in Eq. (14). Eq. (15) is known as the decision variable in binary form. Under the condition, these variables of y_{jt} , P_{jt} , and p_{jt} are known as one, where W is represented as a large positive number. Finally, Eqs. (16) and (17) are the continuous and binary decision variables used in study. For solving this optimization model with obsolete used component scenario as shown in Eqs. (1), a CPLEX mixed integer optimization solver is used.

4. Numerical Example

This section discusses the numerical example used in remanufacturing production system. In this study, we set the planning horizon of 12 periods. In this model, there are three types of remanufactured products (i.e. RP1, RP2, and RP3) to be assembled by four separate components (i.e. CP1, CP2, CP3, CP4). These separate components have different time-period for obsolescence from returned collection. In the following, Table 3 shows the important parameters used for remanufactured product in the modeling. Table 4 shows that the related parameters for used components in the modeling.

Table 3. Parameters used product i for modelling

	<i>PT1</i>	<i>PT2</i>	<i>PT3</i>
V_i	300	700	700
$(R + Q)_i$	115	100	230
U_i	56	48	77
A_i	530	780	840

Table 4. Parameters used component j for modelling

	<i>CP1</i>	<i>CP2</i>	<i>CP3</i>	<i>CP4</i>
S_j	4500	4500	10000	10000
M_j	60	30	6	8
C_j	7500	22000	35000	23000
L_{jt}	4	5	5	3
α_j	6	8	9	6
G_j	420	540	680	460
O_j	30000	22000	5000	0

Fig. 1. A summary of total associated costs for producing 3 product types with 4 components

In this study, we consider 6 months for CP1, 3 months for CP2, 4 months for CP3, 3 months for CP4. We develop the optimisation model and solve it using Cplex optimisation solver. In addition, in this study, we also consider the practical scenario by considering the increase of 5%, 10% and 15% of obsolescence time-period for each separate components. Results obtained showed an overall minimum

costs for remanufacturing production planning was approximately \$6,029,983 with linear relaxation of approximately \$5,528,876.

5. Discussion

Due to rapid change in technological development, many reused components are used for a new manufactured products. Furthermore, as mentioned earlier, the product obsolescence management is one of the important issue in remanufacturing operations. In this study, we also compare various obsolete time-period scenario for used components from returned collection. The obtained results revealed that total associated costs in remanufacturing is significantly reduced as illustrated in Figure 2.

Fig. 2. A summary of variation of the obsolescence

Figure 2 illustrates clearly that when there is an increase of 5%, 10% and 15% in terms of the obsolete time-period used components, total associated costs in remanufacturing operations is reduced dramatically. This is primarily due to the significant reduction of production and inventory holding costs for those obsolete used components in production. This implies that if technology lifecycle for a remanufactured product is further extended and longer, the remanufacturing costs for producing a remanufactured product is significantly reduced as well. This study proved that the effect of varying obsolete time period for used component is also one of the crucial factors in remanufacturing production operations.

Conclusion

The proposed optimisation model for production planning has been developed to take into consideration of the

component obsolescence for a remanufacturing production system. Comparisons of the obtained results for used component obsolescence shows that the associated costs for producing a remanufactured product is significantly reduced if the obsolete time of the used components from returned collection is increased from 5% to 15%.

In addition, the contribution of this study is twofolds. Firstly, this optimisation model aims to analyse and examine used component obsolescence issue for production planning and inventory control in remanufacturing from returned collection. Secondly, the proposed optimisation model by incorporating the obsolescence element is developed to tackle and resolve some oversimplifications in numerical optimisation modelling and analysis. For our future works, we also plan to consider the uncertainty of product returns and recovery in reverse supply chain.

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