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# Simulation and Optimisation of a Failure-Prone Disassembly-Reconditioning-Assembly System

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**Abstract:** This paper deals with the simulation and optimisation of disassembly-reconditioning-assembly system (DRAS) taken into account random machines failures and repairs. The proposed system is composed of one disassembly machine, two parallel structures, one assembly machine and stocks to store the used products, components and finished product. In this study a complete disassembly and assembly process in a supply chain is considered, and which allows to acquire used products, disassemble the used products, storing reconditioning components, assemble the components and selling the finished product to reply customers demand. The objective is to determine the optimal acquisition quantity of used products that maximises the total profit. A mathematical model is formulated on the basis of discrete flow model that allows to express the behaviour of the system. The proposed model is then simulated and the optimal acquisition quantity is determined. Numerical results are presented to discuss the optimal acquisition quantity and the lost profit risk.

*Keywords:* Disassembly-assembly system, Reconditioned products, Random repairs and failures.

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## 1. INTRODUCTION

Throughout the last decades, research on circular economy and environment has acquired significant momentum in industrial engineering and academia. In this framework, the reverse logistic Turki et al. (2018) has a strong relationship with the circular economy regarding the closed loop product life-cycle and which consists recovering and reconditioning used products Julianelli et al. (2020); Turki and Rezg (2018). Most of the reverse supply chain systems are formed by including disassembly and assembly activities with the reconditioning of components. Several research papers in the literature have dealt with disassembly-assembly systems. Ketzenberg et al. (2003) have considered the problem of designing a mixed assembly and disassembly line for remanufacturing activities. As the components from the disassembly and repair of used products can be used to build new products. Slama et al. (2020b,a, 2021b,a) have proposed an optimisation methods for disassembly lot-sizing stochastic problem under ran-

dom lead time. The authors have considered one type of used product that is disassembled to satisfy a dynamic and known demand of parts over a planning horizon. Most of the existing works have neglect same important characteristics of the manufacturing systems such as the machines failures. In fact, when a machine is down, a production timeout accrues that perturbs the production activities and may causes delays and shortages. Thus, the consideration of random machines failures in disassembly-assembly system, certainly has in impact on the different disassembly and assembly activities and their process. In the literature, Guiras et al. (2019) have considered corrective maintenance period in two-level assembly system. The authors have determined optimal order release dates for the different components at level 2 and the optimal preventive maintenance plan. The authors have proposed a system which is composed of single machine and produces one product. However, in practice the disassembly and assembly systems are usually composed of more than one machine and produce more than one products. To fill this

gap, we will consider a system which is composed of one disassembly machine, two parallel reconditioning machines and one assembly machine. Furthermore, as in practice, we will consider that all machines are independently subject to random repairs and failures, and also the interactions between the events of machines and stores complicates the system study, as it shall consider all possible scenarios. The reconditioning machines are parallel but not identical. Each machine is assigned to reconditioning one type of component. To model such system, we adapt discrete flow model (Turki and Rezg, 2019) which is regarded as the most realistic model. In the literature, we found many studies used discrete flow model for the design and the optimal control (Rezig et al., 2020; Turki et al., 2020). For the simulation, the discrete flow model takes into account all events and their interactions. In addition, the simulation of a discrete flow model is easy, especially for disassembly and assembly system simulation. Thus, we will develop a mathematical model based on discrete flow model that considers all events system (Ben-Ammar and Dolgui, 2018; Ben-Ammar et al., 2020), such as store levels, machines failures and repairs, machines blocked and lost sales. The proposed model is simulated to determine the total profit and the objective is to find the optimal acquisition quantity of used products that maximises the total profit. Finally, the contribution of this work, is to consider a real life disassembly and assembly process in a supply chain, and which acquires used products, disassembles the used products, storing reconditioning components, assemble the components and selling the finished product. Furthermore, to make our system more realistic, we integer in the simulation, random machines repairs and failures periods and random demands. Indeed, to consider random machines repairs and failures in such system, makes the problem more complex compared to published works that neglect the repair time.

This paper is organised as follows: in section 2, the disassembly-reconditioning-assembly- system is presented as well as the mathematical model with different assumptions are presented. Section 3 is denoted by numerical results and analyses. Finally, in the section 4, we conclude and we will give perspectives.

## 2. DISASSEMBLY-RECONDITIONING -ASSEMBLY SYSTEM

### 2.1 Notation

#### Parameters

$i$	index of items, $i = 0, \dots, n$
$t$	instant time
$\Delta t$	length of the time period
$H$	total of the simulation time
$\mathcal{D}$	set of disassembled components
$\mathcal{R}$	set of reconditioned components
$Id_{it}$	inventory level of disassembled $i$ at $t$ , $i \in \mathcal{D} \cup \{0\}$
$Ir_{it}$	inventory level of reconditioned $i$ at $t$ , $i \in \mathcal{R}$
$I_{nt}$	inventory level of finished product (selling stock) at $t$
$dr_t$	disassemble rate of the disassembly machine at $t$
$U$	maximum value of $dr_t$
$ir_t$	inspection rate of disassembled components at $t$
$gi_t$	number of disassembled components $i$ with good quality at $t$ , $\forall i \in \mathcal{D}$

$q_i$	percentage of components $i$ with good quality, $\forall i \in \mathcal{D}$
$\bar{g}_t$	number of disassembled components with bad quality at $t$
$pr_{it}^r$	production rate of reconditioning machine of component $i$ at $t$ , $\forall i \in \mathcal{D}$
$P_i$	maximum production rate of reconditioning machine of component $i$ , $\forall i \in \mathcal{D}$
$ar_t$	assembly rate of the assembly machine at $t$
$A$	maximum assembly rate of the assembly machine
$d_t$	demand on finished product at $t$
$x_t$	number of finished product sold at $t$
$v_t$	number of unsatisfied demand at $t$
$y_t^d$	state of the disassembly machine at $t$
$y_t^a$	state of the assembly machine at $t$
$y_{it}^r$	state of the reconditioning machine of $i$ at $t$ , $\forall i \in \mathcal{D}$
$\Phi^d$	mean time between failures for the disassembly machine
$\Phi^a$	mean time between failures for the assembly machine
$\Phi_i^r$	mean time between failures for the reconditioning machine of component $i$ , $\forall i \in \mathcal{D}$
$R^d$	mean time to repair the disassembly machine
$R^a$	mean time to repair the assembly machine.
$R_i^r$	mean time to repair the reconditioning machine of component $i$ , $\forall i \in \mathcal{D}$
$cs_i$	unit storage cost of $i$ , $\forall i = 0, \dots, n$
$cd$	unit disassembling cost of one used product
$ci$	unit cost inspection of one component
$di$	unit disposal cost of one component with bad quality
$cr_i$	unit reconditioning cost of $i$ , $\forall i \in \mathcal{D}$
$ca$	unit assembling cost
$pu$	unit price of one used product
$sp$	unit selling price for one finished product
$cl$	unit lost sales cost for finished product
$l_t$	number of lost sales of finished product at $t$
$W$	total profit function
$Q^*$	optimal acquisition quantity of used products.

#### Decision variables

$Q$	acquisition quantity of used products
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Table 1. Notations.

### 2.2 System description

The proposed reconditioning system represents a disassembly -assembly process that allows to transform used products to reconditioned ones (see Fig. 1). The proposed DRAS receives from the supplier used products that will be stored in the stock  $cs_0$ . A disassemble machine is available to to dismantle each used product into several components  $i \in \mathcal{D}$  that will be next inspected in an inspection centre, and then sorted according to their condition. The component with bad condition, will be disposed or recycled. The inventory level of each component with good condition is  $Id_{it}$  for all  $i \in \mathcal{D}$  at each period  $t$ . Several parallel reconditioning machines ensure the reconditioning of the components. Thus, the inventory level of each reconditioned component is  $Ir_{it}$  for all  $i \in \mathcal{R}$ . Each assembly machine is supplied simultaneously from the stocks  $Ir_{it}$  and assemble components  $i \in \mathcal{R}$  to obtain the finished reconditioned product. The inventory level of the latter is stored in the selling stock  $I_{nt}$  to satisfy a random demand  $d_t$ .

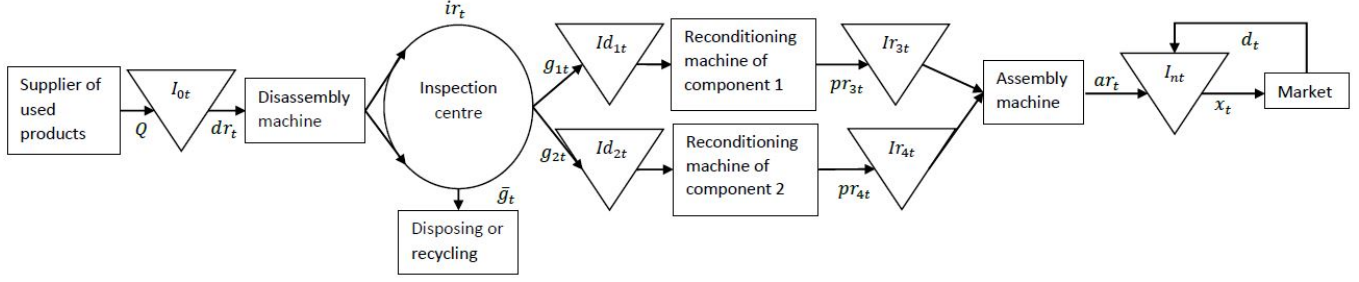


Fig. 1. Disassembly-reconditioning-assembly system

As it mentioned in introduction that we consider a real system, thus, as in practice, we consider that all machines are independently subject to random repairs and failures. Furthermore, we consider that the assembly machine will be blocked when the stock of a single reconditioned component  $i$  is empty for all  $i \in \mathcal{R}$ , also the disassembly machine will be blocked when the stock  $cs_0$  is empty. Moreover, we propose the following assumptions:

- For building the stocks and to avoid having always unsatisfied demands, we assume that the maximum rate of each machine allows satisfying the demand (i.e.  $U > d_t, P_i > d_t$  for all  $i \in \mathcal{D}$ , and  $A > d_t$ ).
- When  $d_t$  is not satisfied, it supposed that it is lost and lost sales costs occur.
- The disassembly of one used product gives a number of  $i$  components where  $i \in \mathcal{D}$ .
- The assembly of the reconditioned components gives a finished product.
- We assume the case of unlimited capacity of the stocks.
- We assume the case of one type of finished product.

### 2.3 Model formulation

In this subsection, a mathematical model in form of equations is present to describe the proposed system. The equations are formulated on the basis of discrete flow model that allows to express the behaviour of the system. In the end of this subsection, we present the total profit that is the objective function.

In this study, we consider the system failures which occur randomly. Thus we will consider all failure sources in the system. The state of the disassembly machine can be either down or up, thus the state of the disassembly machine at  $t$  is given by:

$$y_t^d = \begin{cases} 1 & \text{if disassembly machine is up} \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Also the state of the reconditioning machines and assembly machine can be either down or up. In what follow, we present the different states: The state of the reconditioning machine of component  $i \in \mathcal{D}$  is given by:

$$y_{it}^r = \begin{cases} 1 & \text{if reconditioning machine of } i \text{ is up} \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

The state of the assembly machine is given by:

$$y_t^a = \begin{cases} 1 & \text{assembly machine is up} \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

The stock level of used products ( $I_{0t}^d$ ) at time  $t$  is equal to its level in the previous period, plus the quantity of

used products received from the supplier ( $Q$ ), minus the number of used products outgoing from this stock. This last corresponds the number of used products that are disassembled by the disassembly machine in the previous period ( $dr_{t-\Delta_t}$ ). Thus, the stock level of used products at  $t$  is  $I_{0t}^d = I_{0t-\Delta_t}^d + Q - dr_{t-\Delta_t}$ .

The disassembling rate of the disassembly machine corresponds to the number of used products that are disassembled per unit time. As it mentioned previously that we consider the machine failure that means when the disassembly machine is down, the disassemble rate is null. When the machine is up, it disassembles the used products at its maximum if there are enough used products in  $cs_0$  (i.e  $dr_t = U$  if  $I_{0t}^d \geq U$ ). Thus, the disassemble rate depends of the machine state and the stock level of used products and which is given by:

$$dr_t = \begin{cases} U & \text{if } y_t^d = 1 \text{ and } I_{0t}^d \geq U \\ I_{0t}^d & \text{if } y_t^d = 1 \text{ and } I_{0t}^d < U \\ 0 & \text{if } y_t^d = 0 \end{cases} \quad (4)$$

The inspection rate of the inspection centre corresponds to the number of components that are inspected per unit time. As the disassembling of one used product gives  $|\mathcal{D}|$  components, thus the number of inspected components equals to  $|\mathcal{D}|$  multiplied by the number of disassembled used products. Therefore, the inspection rate depends on the disassembly machine rate and which is given by  $ir_t = |\mathcal{D}| \cdot dr_t$ .

The number of disassembled components  $i \in \mathcal{D}$  with good quality is represented by a percentage ( $q_i$ ) of the inspected components  $i$  ( $ir_t/|\mathcal{D}|$ ). The number of disassembled components  $i$  with good quality at  $t$  is  $g_{it} = q_i \cdot ir_t/|\mathcal{D}|$ .

The number of disassembled components with bad quality is equal to the inspected components minus the components with good quality. The number of disassembled components with bad quality at  $t$  is given by:

$$\bar{g}_t = ir_t \cdot (1 - \sum_{i \in \mathcal{D}} q_i/|\mathcal{D}|) \quad (5)$$

The stock level of components  $i \in \mathcal{D}$  with good quality at  $t$  ( $Id_{it}$ ) is equal to its level in the previous period, plus the number of disassembled components  $i \in \mathcal{D}$  with good quality ( $g_{it}$ ), minus reconditioning rate at time  $t$ . This last corresponds the number of components  $i$  that are reconditioned by the reconditioning machine in the previous period ( $pr_{it-\Delta_t}$ ). Thus, stock level of components  $i \in \mathcal{D}$  with good quality at  $t$  is given by:

$$Id_{it} = Id_{it-\Delta_t} + g_{it} - pr_{it-\Delta_t} \quad (6)$$

The reconditioning machine  $i \in \mathcal{R}$  rate corresponds to the number of components  $i \in \mathcal{R}$  that are reconditioned per unit time. When the reconditioning machine  $i$  is down, the reconditioning rate is null. When the machine is up, it reconditions the components  $i$  at its maximum if there are enough parts in stock (i.e  $I_{it}^r \geq 0$  and  $pr_{it} = P_i$  if  $Id_{it} \geq P_i$ ). Thus, the reconditioning machine  $i$  rate depends of the machine state and the stock level  $I_{it}^r$  and which is given by:

$$pr_{it} = \begin{cases} U & \text{if } y_{it}^r = 1 \text{ and } Id_{it} \geq P_i \\ Id_{it} & \text{if } y_{it}^r = 1 \text{ and } Id_{it} < P_i \\ 0 & \text{if } y_{it}^r = 0 \end{cases} \quad (7)$$

The stock level of each reconditioned component  $i \in \mathcal{R}$  at  $t$  ( $I_{it}$ ) is equal to its level in the previous period, plus the number of reconditioned component  $i$  ( $pr_{it}$ ), minus assembling rate. Thus, the stock level of reconditioned components  $i$  at  $t$  is given by:

$$I_{it} = I_{it-\Delta_t} + pr_{it} - pr_{it-\Delta_t} \quad (8)$$

The assembling rate of the assembly machine corresponds to the number of finished product unit time. When the assembly machine is down, the assembling rate is null. When the machine is up, it assembles the components  $i \in \mathcal{D}$  at its maximum if the inventory level  $I_{jt}$  of reconditioned components  $j \in \mathcal{R}$  is non null (i.e  $ar_t = A$  if  $Id_{it} \geq A$  and  $Id_{it} \geq A$ ). Thus, the assembling rate depends of the machine state and the stock levels  $I_{jt}$ . It is given as follows:

$$ar_t = \begin{cases} A & \text{if } y_t^a = 1 \text{ and } I_{jt} \geq A \\ I_{jt} & \text{if } y_t^a = 1, I_{jt} < A \text{ and } \\ & I_{kt} \geq I_{jt} \quad \forall k \neq j \\ 0 & \text{if } y_t^a = 0 \end{cases} \quad (9)$$

The stock level of finished product at  $t$  ( $I_{nt}$ ) is equal to its level in the previous period, plus the number of assembled components 1 and 2, minus number of finished product sold at  $t$ . Thus, the stock level of finished product at  $t$  is given by  $I_{nt} = I_{nt-\Delta_t} + ar_t - x_{t-\Delta_t}$ .

The numbers of finished product sold at  $t$  expressed by:

$$x_t = \begin{cases} d_t & \text{if } d_t \leq I_{nt-\Delta_t} \\ I_{nt-\Delta_t} & \text{otherwise} \end{cases} \quad (10)$$

The number of lost sales of finished product at  $t$  expressed by  $l_t = d_t - x_t$ .

The total profit function over the horizon  $[0, H]$ , is the difference between the total sales of finished product revenues and the total costs over the horizon. The total costs include: the total acquisition cost of used products, the total disassembly and assembly costs, the total inspection cost, the total reconditioning costs, the lost sales costs and the storage costs. Finally, the total profit function over the horizon  $[0, H]$  is expressed by:

$$\begin{aligned} W(H) = & \sum_{t=0}^H (sp \cdot x_t - pu \cdot Q - cs_0 \cdot Id_{0t} - cd \cdot dr_t) \\ & - \sum_{i \in \mathcal{D}} cs_i \cdot Id_{it} - \sum_{i \in \mathcal{R}} cs_i \cdot Ir_{it} - di \cdot \bar{g}_t \\ & - ci \cdot ir_t - \sum_{i \in \mathcal{R}} cr_i \cdot pr_{it} - ca \cdot ar_t - cl \cdot l_t - s \cdot I_{nt} \end{aligned} \quad (11)$$

In the next section, the proposed mathematical model will be simulated and the acquisition quantity of used products will be determined.

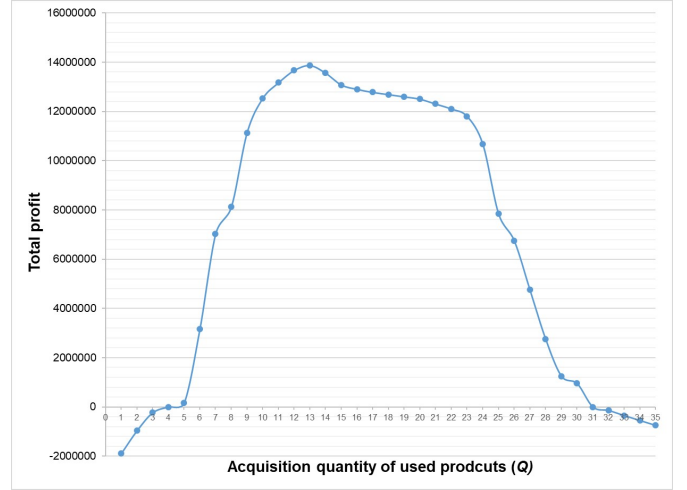


Fig. 2. Total profit in function of the acquisition quantity of used products

### 3. EXPERIMENTAL RESULTS AND ANALYSIS

In this section, we aim to determine the optimal acquisition quantity  $Q^*$  of used products that maximizes the profit.

#### 3.1 Optimal acquisition quantity

Based on simulation, we simulated the profit for the different values acquisition quantity  $Q[1, 35]$ , and the optimal acquisition quantity  $Q^*$  which corresponds to the maximum profit. The specification of this simulation that can treats all possible scenarios of the machines states, such as random repairs and failures events, and the stores levels. Furthermore, interactions between the events of machines and stores are considered in all scenarios, such as for example, that one machine can be blocked in the case when the upstream store is empty.

In what follows, the parameters that are used in the simulation are presented:  $H = 105$  unit times,  $U = 15$  parts /unit time,  $g_1 = 85\%$ ,  $g_2 = 78\%$ ,  $P_1 = 10$  parts /unit time,  $P_2 = 10$  parts /unit time,  $A = 10$  parts /unit time,  $\Phi^d = 12$  unit times,  $R^d = 3$  unit times,  $\Phi^a = 10$  unit times,  $R^a = 2$  unit times,  $\Phi_1^r = 11$  unit times,  $R_1^r = 2$  unit times,  $\Phi_2^r = 12$  unit times,  $R_2^r = 2$  unit times,  $pu = 10$  monetary units,  $cs_0 = 1$  monetary unit,  $cd = 5$  monetary units,  $ci = 2$  monetary units,  $cs_1 = 1$  monetary unit,  $cs_2 = 1$  monetary unit,  $cd = 1$  monetary unit,  $cr_1 = 7$  monetary units,  $cr_2 = 8$  monetary units,  $cs_3 = 1$  monetary unit,  $cs_4 = 1$  monetary unit,  $ca = 15$  monetary units,  $cs_0 = 2$  monetary units,  $sp = 250$  monetary units,  $cl = 1000$  monetary units.

We note that the demand  $d_t$  is generated by truncated normal distribution with average = 7 and standard deviation = 4. The distribution for the failures and repairs are generated by the exponential distribution.

In the following figure, we present the total profit in function of the acquisition quantity of used products. As it observed, the maximum total profit corresponds to the value of 13. Thus the optimal acquisition quantity of used products  $Q^*$  is equal to 13. Furthermore, we

can observe from the figure, that when  $Q \leq 4$ , the total profit is negative. This is explained by the fact when the number of used products that are received from supplier is low, the number of finished product also is low, as from used products, we obtain components to produce finished product. Thus the lost sales cost become high and then the total profit becomes very low. In addition, when  $Q$  exceeds 31 parts, the total profit becomes negative. This is explained by the fact when the number of used products that are received from supplier is high, the total storage cost becomes high, as it shall to store the used products, the disassembled components, the reconditioned components and the finished product. Thus, when  $Q$  becomes high, the storage cost becomes very high comparing to the sales revenues, and then the total profit decreases until becomes negative. Besides, from this study we can interpret the lost profit risk related to the acquisition quantity of used products. Indeed, when  $4 < Q < 31$  the total profit stills positive. Finally, in practice, this study can serve as a decision support to a leader of disassembly-reconditioning-assembling system, it provides the optimal acquisition quantity of used products and the limits values of acquisition quantity that causes the lost profit.

#### 4. CONCLUSIONS AND PERSPECTIVES

In this work, we have studied and simulated disassembly-reconditioning-assembling system taken into account random machines failures and repairs and different uncertainties sources such as machines failures and random demands. Numerical results are presented to discuss the optimal acquisition quantity that maximizes the total profit. Furthermore, we have studied the lost profit risk related to the acquisition quantity of used products.

This work has potential future perspectives: we will propose an optimal design of the system, then will determine acquisition, disassembling, reconditioning and assembling planning. Finally, we will integrate the carbon emissions reduction.

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