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PERFORMANCE EVALUATION OF CENTRALIZED MAINTENANCE WORKSHOP IN THE CIRCULAR ECONOMY CONTEXT

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ABSTRACT: *The availability of production equipment is crucial to the life of manufacturers. When these high capital assets are heavy and require a significant set of resources, the company groups all the maintenance activities together in a centralized maintenance workshop (CMW). The circular economy, by integrating remanufacturing, is a way to support industrial development. Once integrated into the maintenance workshops model, the remanufacturing allows the recovery of irreparable components from failed equipment. Thus, the decision regarding the initial stock level and the remanufacturing rate has to be made. This paper proposes a new form of organization of the CMW allowing to take into account the different actions which contribute to sustainable development. Thus, depending on the condition of the defective equipment which can come from various production workshops, three options are available: repair, replacement with new equipment, or reconditioning/remanufacturing. A CMW model based on queuing networks is proposed as well as a simulation evaluation of performance indicators.*

KEYWORDS: *Centralized Maintenance Workshop, Circular economy, Remanufacturing, Industrial maintenance, Systems modelling, Performance management*

1 INTRODUCTION

The promotion of sustainable industries is one of the greatest challenges of the coming decades. For example, waste from industrial activities can be reduced by extending the life cycle of products, thereby increasing productivity and reducing environmental issues. Increasing productivity performance requires extending the operational availability of equipment. This is already being done through research and development of maintenance strategies. Maintenance strategies have automatically become crucial for critical systems, whose failures significantly affect equipment availability and staff safety. Over time, maintenance has progressively taken an important place as a core activity in companies depending on the availability of expensive assets to provide their services or to manufacture their products (Driessen et al., 2020).

Centralized maintenance workshops (CMW) aim to gather and to provide all the tools required for preventive and corrective maintenance processes (Simeu-Abazi et al., 2014). The recent models of CMW proposed in the literature focus on corrective maintenance of equipment, where malfunctioned parts or components are replaced by ready-for-use spares. Once the repair of the failed components is finished, they are forwarded back to stock “as-good-as-new.” (Sleptchenko et al., 2019). However, one of the main assumptions of these models is that all equipment or components arriving at the CMW are

repairable. Some extensions of the model proposed in the literature deal with the purchase of components to replace irreparable components that are discarded (Li et al., 2013). Remanufacturing is an approach that allows the recovery of parts from irreparable components and the production of other components as good as new (Potting et al., 2017).

This paper aims to extend the works presented in (Simeu-Abazi et al., 2014) and (Li et al., 2013) by proposing a model of CMW embedding the purchase of spare parts and the remanufacturing of components. So, one interesting research question is: how can we improve the CMW model by integrating remanufacturing? To answer this question, this article is structured into six sections, including the present introduction section. Section 2 is dedicated to the context and motivation of this work. Section 3 is dedicated to the description of the CMW. Section 4 describes the model of CMW and the way to evaluate its performance by simulation. Based on the developed method, we determine the optimal parameters of the proposed CMW embedding the management of irreparable components. The last section contains our conclusion and future developments.

2 CONTEXT AND MOTIVATION

In almost all the manufacturing companies, maintenance operations involve huge costs that can represent between 15% and 70% of the total production budget. It is the case of non-military equipment, which spent more than

\$9 billion from a turnover generated by the component repairs in 2015 (Sleptchenko et al., 2018). Besides, the last decades lead to the increasing changes in maintenance activities and associated budget (Simeu-Abazi et al., 2012). In the aircraft field, the high availability of fleet is crucial for airline operator profitability. Maintenance consists of replacing defective components by components in good condition rather than repair inside the aircraft. The failed component is then repaired separately allowing the reduction of TAT (repair turnaround times) by the operators (van Jaarsveld et al., 2015). In the high-speed railway locomotive field, we have the same approach with the presence of interchangeable component inventory where purchased or repaired components are waiting for assembly (Li et al., 2013). However, the recent model of Centralized Maintenance workshops did not take into account the irreparable components from failed pieces of equipment, which are assumed discarded. With the evolution of "Industry 4.0" one of the objectives of maintenance workshops is to be more sustainable and the Circular Economy is one of the recent and promising solutions for that. Remanufacturing technologies appear as the most appropriate strategies to deal with the recovery of irreparable components.

3 DESCRIPTION OF CENTRAL MAINTENANCE WORKSHOP

A CMW is designed first, to find the origin of the failure of the equipment in the production workshop, and second, to repair it (Simeu-Abazi et al., 2014). Depending on the nature of the failure, equipment is repaired on different stations, centralized or decentralized. In the case of Centralized Maintenance Workshops, all the process of repairing the equipment is inside the CMW.

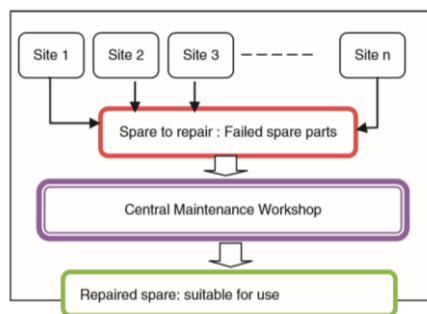


Figure 1: Organization of Maintenance

Coming from different production workshops as presented in Fig. 1, failed pieces of equipment arrive at the centralized maintenance workshop to be repaired and, after finishing the maintenance process, they are returned to the production line.

A maintenance process including the remanufacturing with Initial inventory is presented in Fig. 2. It consists of a set of stations for equipment diagnosis, disassembly, repair and assembly. The failed equipment reaching

CMW is composed of two parts: the main one, that we will go on calling "equipment", and a component. We assume that only the component can fail, and that the main part of the equipment is always in good condition. Thus, after the diagnosis and the disassembly, we only have one component that is failed. The remaining part of the equipment is transferred directly to the assembly station, in a buffer, where it will wait for a component in good condition to be assembled with. If the failed component is respectively repairable, or irreparable, or discarded, then it is respectively transferred toward the repair station or the remanufacturing station or for the purchase of a new component.

If a defective component is not yet recovered but the remaining part of the equipment is already available at the assembly station, then a component from the initial inventory (and then a component from the other inventories: repaired, remanufactured or new components) replaces the defective component for the assembly of the equipment.

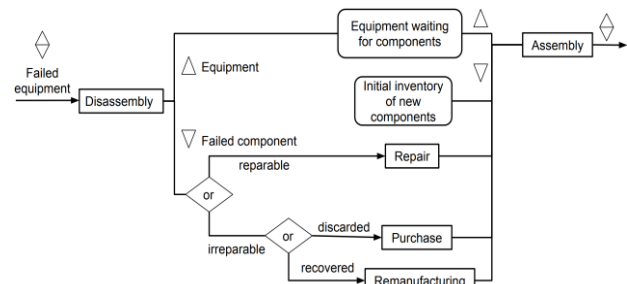


Figure 2: Organization of the CMW under study

The goal is to minimize the average TAT (turn-around times) defined as the spending time of a failed piece of equipment throughout the maintenance process, from disassembly to assembly. Thus, we have taken the methodology of the queuing network used in (Simeu-Abazi et al., 2014) to evaluate the CMW performance

4 MODELLING AND PERFORMANCE EVALUATION

A simulation, based on Queuing Network modelling, has been conducted to evaluate the CMW performance using the software Matlab_Simulink. Some assumptions are necessary to simplify the model and obtain the first interesting results.

- 1) Each CMW station is composed of 6 parallel servers
- 2) All the buffers have unlimited capacity. There is thus no blocking.
- 3) Pieces of equipment arrive at the CMW according to a homogeneous Poisson process with rate λ .
- 4) Disassembly lead times for all pieces of equipment follow an exponential distribution with rate μ_{ds} .

- 5) Assembly lead times for all pieces of equipment follow an exponential distribution with rate μ_{as} .
- 6) Repair lead times for all the components follow an exponential distribution with rate μ_{rp} .
- 7) Remanufacturing lead times for all irreparable components follow an exponential distribution with rate μ_{rm} .
- 8) When an irreparable component is not remanufactured, a purchase order is sent for a new component
- 9) We do not consider the transfer time from any stage to its downstream ones

4.1 Model description

After simplifying the model of CMW, we can obtain the queuing network representation composed by queues and servers connected as presented in Fig. 3. The resulting system is characterized by some important parameters:

- λ : equipment arrival rate (pieces of equipment/month)
- i : proportion of irreparable components ($[0,1]$)
- r : proportion of remanufactured components ($[0,1]$)
- B : Initial Inventory Level for the new components
- μ_{ds} : service rate of the disassembly station (pieces of equip/month)
- μ_{ti} : service rate of the reparability test station (pieces of equip/month)
- μ_{tr} : service rate of the remanufacturing test station (pieces of equip/month)
- μ_{rp} : service rate of the repair station (pieces of equip/month)
- μ_{rm} : service rate of the remanufacturing station (pieces of equip/month)
- μ_{nw} : service rate of the purchasing station (pieces of equip/month)
- μ_{as} : service rate of the disassembly station (pieces of equip/month)

- N_{rm} : total number of pieces of equipment with remanufactured components at the departure of the CMW
- N_{rp} : total number of pieces of equipment with repaired components at the departure of the CMW
- N_{nw} : total number of pieces of equipment with new components at the departure of the CMW
- S_{rm} : buffer of the remanufactured components
- S_{nw} : buffer of the new components
- S_{rp} : buffer of the repaired components
- For the simulation, the service rate of the test stations μ_{ti} et μ_{tr} are supposed to be very high compared to all the other service rates of CMW stations. Thus, the service time is considered negligible for these two stations.

4.2 The decision variables of CMW

Remanufacturing aims to reduce the scraps from the maintenance process by recovering irreparable components. It can be realized by, either the OEM (Original Equipment Manufacturer), or by local remanufacturers (Kleber et al., 2011). In our model, we assume that CMW only has to decide on how many irreparable components must be provided to the remanufacturer for optimal costs and quality. Besides, we have to find the minimal Initial Inventory Level satisfying both the minimal TAT and the minimal costs. So we consider the following decision variables:

- r : remanufacturing rate
- B : Initial Component Inventory Level

4.3 Performance indicators for CMW

The maintenance process of each failed equipment reaching the CMW requires a set of resources (time, operators, tools and spare parts) until its departure. The main performance indicators of CMW are:

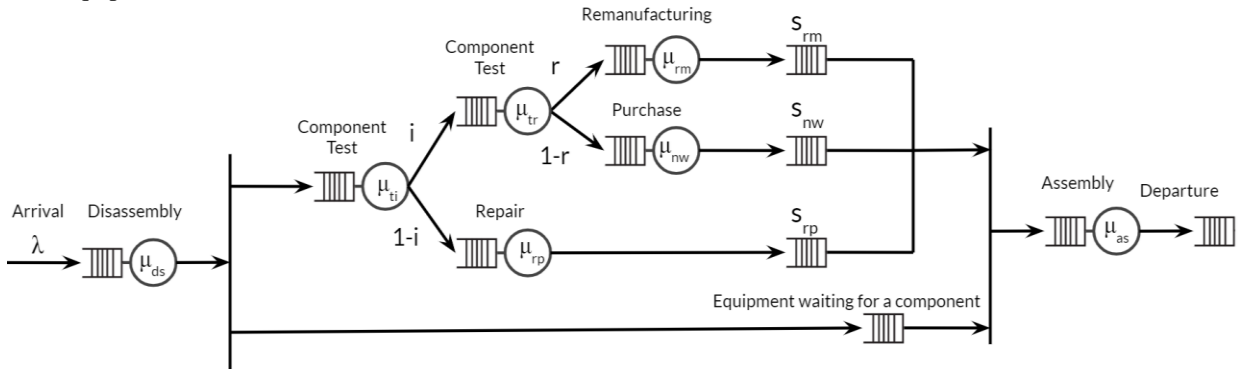


Figure 3: Queuing Network model of CMW

- $\square\square\square$: average time spent by the equipment throughout the maintenance process
- Total cost: evaluation of all the costs generated by the maintenance activities

4.4 Simulation experiments

Matlab_simulink is the software used to simulate the CMW model based on real benchmark data from high-speed railway locomotive fields, taken from (Li et al, 2012), and adapted to include the remanufacturing and the purchase of new parts. Using the simEvents library,

many experiments have been carried out to get an overview of the influence of CMW parameters (B, r) and the service rates (μ_{rp} , μ_{rm} , μ_{nw}) on the performance indicators.

Real data: $\lambda = 6$, $\mu_{ds} = \mu_{as} = 6$, $\mu_{rp} = 2$, $\mu_{rp} > \mu_{rm} > \mu_{nw}$

The first series of experiments were performed by varying the rate of irreparable components, i, and the rate of components to be remanufactured, r, from 0 to 1. 15 configurations of CMW stations were obtained by simulating different values of service rates μ_{rp} , μ_{rm} , μ_{nw} combined to 5 configurations of Initial Inventory Level with B=10, 15, 20, 25, 30. Then we have:

- Group 1: $\mu_{rm} = 1.9$, with $\mu_{nw} = 1.7, 1.3, 1, 0.5, 0.3$
- Group 2: $\mu_{rm} = 1.7$, with $\mu_{nw} = 1.3, 1, 0.5, 0.3$
- Group 3: $\mu_{rm} = 1.3$, with $\mu_{nw} = 1, 0.5, 0.3$
- Group 4: $\mu_{rm} = 1$, with $\mu_{nw} = 0.5, 0.3$
- Group 5: $\mu_{rm} = 0.5$, with $\mu_{nw} = 0.3$

A priority policy for selecting the components from S_{rm} , S_{nw} and S_{rp} inventories for the assembly was used so that new components have a higher priority than remanufactured components which have a higher priority than repaired components (New > Remanufactured > Repaired). We choose this policy to always prioritize the best quality components for assembly.

4.5 Costs evaluation

C_{inv} = Unit storage cost of components inside the CMW (\$/component)

C_{TAT} = Unit cost generated by sojourn time of each failed piece of equipment inside the CMW (\$/day/piece of equip)

C_{Stock} = Unit storage cost of each failed piece of equipment inside the CMW (\$/piece of equip)

C_{nw} = Unit Cost to purchase a new component (\$/component)

C_{rm} = Unit cost for remanufacturing (\$/component)

C_{rp} = Unit cost for repairing (\$/component)

A total cost is composed of the:

□ Immobilization costs which are generated by the non-utilization of the components or the equipment (while being processed or in stock in the CMW)

$$\text{Immobilizat_Cost} = (\text{□□□} \times C_{TAT} + C_{Stock}) \times (N_{rm} + N_{rp} + N_{nw})$$

□ Operation costs which are generated by the maintenance process

$$\text{Operation_Cost} = C_{inv} \times B + N_{rm} \times C_{rm} + N_{nw} \times C_{nw} + N_{rp} \times C_{rp}$$

$$\text{Total Cost} = \text{Imobilizat_Cost} + \text{Operation_Cost}$$

From benchmark data, we have $C_{TAT} = 20$, $C_{inv} = 20$, $C_{Stock} = 20$ and $0 < C_{rp} < C_{rm} < C_{nw}$. Thus, proportionally

to the value of C_{rp} , we obtained 6 different cost configurations:

Group 1: $C_{nw} = 3 \times C_{rp}$, with $C_{rm} = 2.5 \times C_{rp}, 2 \times C_{rp}, 1.5 \times C_{rp}$

Group 2: $C_{nw} = 2.5 \times C_{rp}$, with $C_{rm} = 2 \times C_{rp}, 1.5 \times C_{rp}$

Group 3: $C_{nw} = 2 \times C_{rp}$, with $C_{rm} = 1.5 \times C_{rp}$

The investment cost of remanufacturing is consider to be zero, assuming that it is managed by the company that manufactures the new components (OEM). In this case, the OEM sells the remanufacturing services to the CMW at the unit cost C_{rm} .

5 SIMULATION RESULTS

Based on the instances presented in the previous section, the simulation leads to 1875 configurations of CMW with different parameters. To obtain the optimal combination (B,r) for each case we study the variation of the $\square\square\square$ and the Total Cost considering $C_{rp}=1$.

5.1 Average TAT

We studied the average waiting time of equipment in the system, considering different scenarios consisting of 5 groups of service rates for the operations (as it is explained in section 4.4) and different combinations of i, r and B. Table 1 shows the different values of i, r and B which are used in the study.

Service rate	i	r	B
Group n (n: 1, ..., 5)	0, 0.2, ..., 1	0, 0.2, ..., 1	0, 10, 20, 30

Table 1: Combination of variables

For all initial inventory levels, the decrease of μ_{rm} and μ_{nw} led to an increase in the $\square\square\square$ value. Figure 4 indicates the variation of $\square\square\square$ for different values of parameter B and rate μ_{rm} , for $\mu_{nw} = 0.3$, $i = 0.4$ and $r = 0.6$.

As It is shown in figure 4, the increase of B from 0 to 20 has a positive effect on $\square\square\square$ and leads to a significant decrease in it. But changing B from 20 to 30 has no impact on $\square\square\square$. Studying all possible service rate values, it is obtained that the initial inventory level of 20 is the most time-efficient option in general.

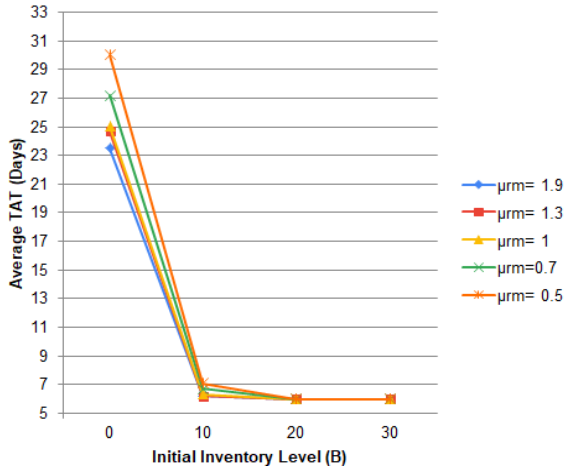


Figure 4: Relevance between average TAT and initial inventory level of components

5.2 Impact of total number of irreparable components on the total cost

In this section, we observe the total cost for each combination of (B,r) obtained by taking many values of parameter i , with fixed parameters $\mu_{rm} = 1.9$, $\mu_{nw} = 1.3$, $C_{nw} = 3 * C_{rp}$, and $C_{rm} = 2.5 * C_{rp}$.

We observe that the cost globally increases with the increase of i . The optimal Initial inventory is $B=20$ represented by the plots red and blue of the figure 5. The optimal remanufacturing rate satisfying the minimal costs are different depending on the value of i . For $i=0.2$ we obtain $r=0.2$, for $i=0.4$ we obtain $r=1$ and for $i=0.6$ we obtain $r=0.8$. If the Initial inventory level is equal to 0, $B=0$ in Figure 6, all the costs are the highest and decrease with the increase of the remanufacturing rate r and the decrease of the irreparable rate i .

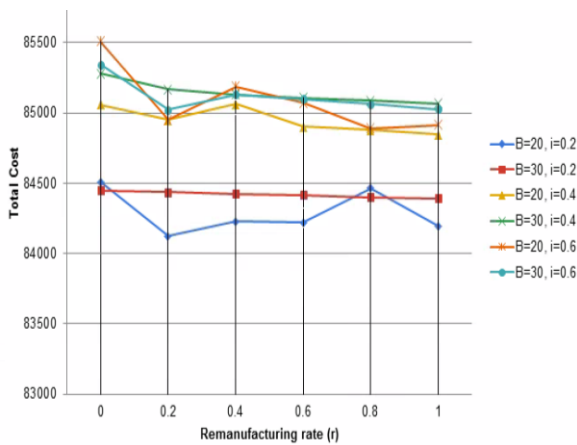


Figure 5: Total cost versus remanufacturing rate and Initial Inventory level for $i=0.2$ and $i=0.4$

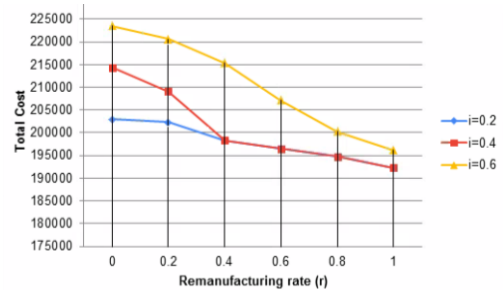


Figure 6: Total cost versus remanufacturing rate for $B=0$

5.3 Impact of the stations service rate

We take the following values: $i = 0.2$, $C_{nw} = 3 * C_{rp}$, and $C_{rm} = 2.5 * C_{rp}$ and observe that the service rate of the stations μ_{rm} and μ_{nw} have effects on the optimal costs until $r=0.4$ as shown in figure 7. For example when $\mu_{rm} = 1.9$, $\mu_{nw} = 1$ the optimal $(B, r)^*$ is $(10, 0.4)$. $\mu_{rm} = 1.9$, $\mu_{nw} = 0.7$ lead to a new $(B, r)^* = (20, 0.2)$; $\mu_{rm} = 1.3$, $\mu_{nw} = 0.3$ lead to $(B, r)^* = (20, 0.2)$ and $\mu_{rm} = 1.3$, $\mu_{nw} = 0.3$ lead to $(B, r)^* = (20, 0.4)$.

Globally from $r=0.4$ the service rate of the stations μ_{rm} and μ_{nw} no longer have much effects on the costs

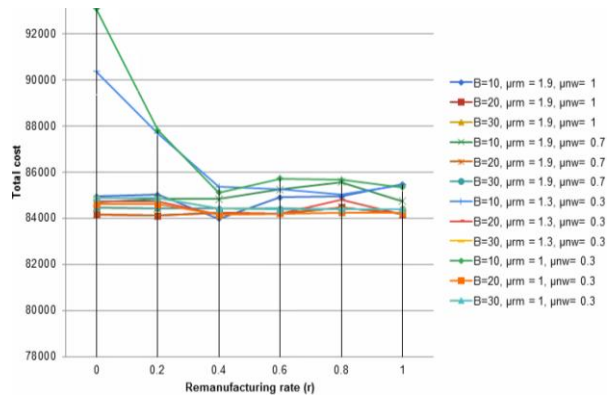


Figure 7: Total cost versus remanufacturing rate and Initial Inventory level with the variation of μ_{nw} and μ_{rm}

5.4 Unit costs

$i = 0.2$, $\mu_{rm} = 1.9$, $\mu_{nw} = 1.3$

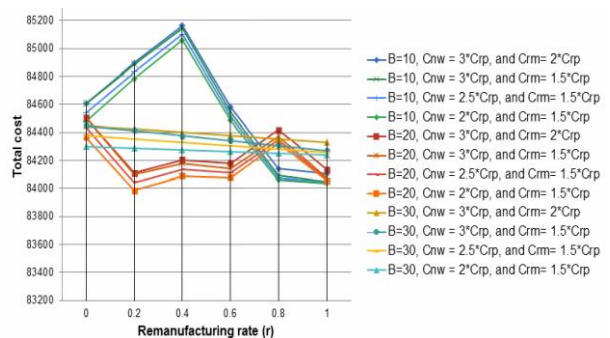


Figure 8: Total cost versus remanufacturing rate and Initial Inventory level with the variation of C_{nw} and C_{rm}

Globally as presented in figure 8, the variation of the unit costs C_{nw} and C_{rm} does not have effects on the shape of the plots whatever the values of B. Besides, regardless of the unit cost values, for respectively B=10, B=20 and B=30 we have respectively the optimal remanufacturing rate $r=1$, $r=0.2$ and $r=1$.

In general, for all the scenarios initial inventories B=0 and B=30 are never suitable for optimal costs. The choice is between B=10 and B=20. In the majority of cases, B=20 is the optimal inventory level.

□ 6 CONCLUSION

In this study, we evaluated the costs and the average waiting time of failed equipment in a CMW integrating the remanufacturing of irreparable components. From the existing model, we proposed to explore the effects of variation of initial inventory level and remanufacturing rate of components. It suggests using remanufactured components may create value by affecting the total cost and average TAT, positively. The main results can be summarized as follows:

- Average TAT decreases significantly by increasing initial inventory level.
- Initial inventory level of 20 is the best option in terms of cost and time for the CMW with the defined number of servers and equipment arrival rate in this study. Regardless of the irreparable rate and the remanufacturing rate of the components the optimal value of B is the same.
- The optimal remanufacturing rate depends mainly on the irreparable rate of the components whatever the service rate of the stations or the unit costs of the maintenance process.
- There is a trade off between average TAT and initial inventory level for some combination of C_{rm} and C_{nw} . Initial inventory level of 20 is the most time efficient option that will assure the high service level of CMW. But considering the total costs in some combinations of C_{rm} and C_{nw} , initial inventory level of 10 is the most cost efficient option compared to B equal to 20. It is noteworthy that the difference is too low. According to the policies of a company one of these options may be selected.

Future research based on this article can be to extend the CMW model embedding the variation of the equipment arrival rate. A closed-loop system can be studied considering the fact that each equipment reaches CMW several times throughout its life cycle.

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