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PERFORMANCE EVALUATION OF A CENTRALIZED MAINTENANCE WORKSHOP WITH REMANUFACTURING

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***Abstract* – Having a Centralized Maintenance Workshop (CMW) allows companies to centralize their resources to assure production equipment availability. The introduction of Circular products and remanufacturing processes helps industry players avoid excessive raw material consumption. In a CMW, the remanufacturing process, besides repairing and purchasing new components, recovers a portion of parts that are not repairable. This paper proposes a closed-loop model considering the lifetime of components, which well represents the real-life components' flow through the CMW. Adding the remanufacturing process to the system has some impacts on the performance of the CMW. Main indicators like the waiting time of equipment in CMW and maintenance cost must be studied to be able to evaluate the performances. To this purpose, a new CMW organization is proposed based on a real case in the automotive industry. Considering different possible simulation scenarios is crucial to get reliable results from the proposed closed-loop queuing network model. Several simulations are conducted to evaluate the CMW performance and find the optimal combinations of decision variables.**

***Keywords* – Centralized maintenance workshop, Closed-loop queuing network, Circular economy, Remanufacturing, Performance evaluation, System modelling, Optimization, Arena simulation.**

1 INTRODUCTION

In recent years, circular products absorbed more attention from industry players. Companies try to implement sustainability strategies, and the aim is to reduce the waste and environmental effects and maximize the productivity and efficiency of raw material consumption (Popa et al., 2016).

Maintenance is a process to maintain the functionality of a part of a facility, which is required in production sites. Traditionally, the maintenance process was limited to repairing a failed component or its replacement by a new one.

Centralized maintenance workshops permit companies to gather all required resources to perform maintenance. The goal is to achieve maximum operational availability of the production lines (Simeu-Abazi et al., 2014). Therefore, maintenance efficiency directly impacts a manufacturing line's capacity and service level and the product's final cost (Driessen et al., 2020). All these factors can affect customer satisfaction, which is the final goal of every business unit.

Knowing the importance of the maintenance in customer satisfaction and the company's global performance, evaluation and optimization of CMW became an essential need of the companies.

In the literature, the main focus of the CMW is on the corrective maintenance and periodic overhauls by replacing the malfunctioned parts with the existing spare parts. All the repaired components are considered to have the same quality as the new ones (Sleptchenko et al., 2019). However, one of these models' main assumptions is that the failed units visiting the CMW are always repairable. In the literature, some models consider that a portion of the components entering the CMW are not repairable (Li et al., 2013).

There are different processes in the CMW to make a failed unit usable (Djeunang Mezafack et al., 2020). Repairing the failed unit, replacing it with a new one are traditional processes. In addition to these two methods, the remanufacturing process can help to extend the product's life (Kleber et al., 2011).

Depending on the maintenance process, the equipment's failure rate will be different and they will return to the CMW at different times even if they leave it simultaneously.

Therefore, to have more realistic outputs, the quality of maintained equipment should be considered. The lifetime of equipment in the production site is a suitable parameter to indicate the quality of the maintenance process. To be able to differentiate between maintenance processes from the lifetime perspective and track it, it is needed to have a closed-loop of equipment flow. This approach well represents real-life equipment flow through the CMW (Assadi et al., 2018).

This study, which is inspired by a real case in the automotive industry, extends the works of (Simeu-Abazi et al., 2014) and (Djeunang Mezafack et al., 2020) in two ways:

- Considering a closed-loop flow between the production line and CMW, therefore the components visit the CMW more than once,
- Taking into account the lifetime of the components leaving the CMW.

The study's main objective is to evaluate the CMW's performance in the presence of remanufacturing and new component purchasing. To achieve this goal, we have

structured this study into six sections. Section 1 contains the introduction and a short explanation of the objectives. Problem description and the organization of the CMW are presented in section 2. Section 3 gives more details about the constructed model properties, queuing network of the system, and the decision variables. A detailed explanation of the experiments and the critical indicators of the CMW's performance are represented in section 4. Several simulations are performed to obtain the results. They are well discussed in section 5. Finally, section 6 is dedicated to the conclusion and further research opportunities.

2 PROBLEM DESCRIPTION

A CMW is designed first to find the origin of the equipment's failure in the production workshop and second to repair it (Simeu-Abazi et al., 2014). Depending on the nature of the failure, severity of the failure, and experts' recognition, different processes are defined in CMW. According to the required procedures, failed units are directed to the stations with varying service time and costs.

Serving different production lines by a CMW makes it necessary to trace the failed units. It is more crucial when there is a closed-loop system where the equipment visits the CMW more than once during its life cycle.

In this study, the failed unit is a spindle of the machining center used to mass production of main engine parts in the automotive industry. It is composed of 2 parts; one is the rotating union shown in Figure 1, and the other is the rest of the spindle. From now on, we will call them "component" and "equipment," respectively. The rotating union provides high pressure through spindle coolant liquid during the machining process. It is necessary for high precision machining of automotive parts to reach high surface quality.

The CMW supports different production lines with 100 identical machining centres in total. It is assumed that only components fail, and the equipment is reusable without any further action.

The case study is taken from a private Iranian company that is active in automotive aluminium engine parts' mass production. The company is one of the leaders in its sector with significant market share.

The organization of CMW is shown in Figure 2. After failed unit diagnosis and disassembly, the equipment waits for component arrival in a buffer before the assembly station.

There are different possible paths through the CMW regarding components' last number of visits to CMW and their condition. In case the component is repairable, the tracing system checks the component's previous visits and sends them to one of the three repairing stations. Each component can be repaired a maximum of 3 times. Repair 1, 2, and 3 in Figure 2 are the stations for a first, second, and third time repairing, respectively.

If the component is not repairable, either because of its condition, or because it reaches the maximum three times repair, it may transfer to the remanufacturing station or be replaced by a new component in the station called NC Purchase.

Remanufacturing is a process in which all wearable components have been replaced and mechanical tolerances have been restored to their original standards.

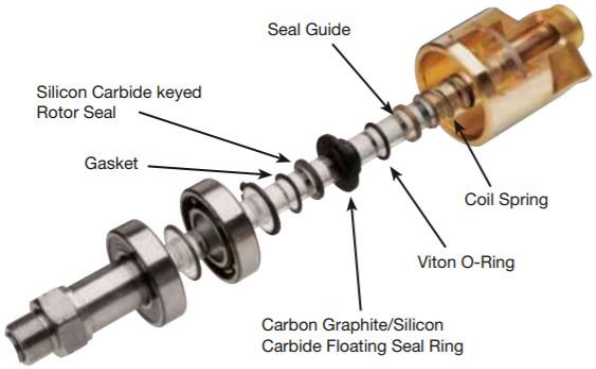


Figure 1. Rotating union[1]

Waiting equipment is always assembled with the first available component, which can be repaired, remanufactured, or new. If all types of components are available, the priority of use will be 1- new component, 2- remanufactured, 3- first-time repair, 4- second-time repair, 5- third-time repair.

The goal is to evaluate the system's performance under different conditions and scenarios and identify the situation that leads to the best system performance. The system

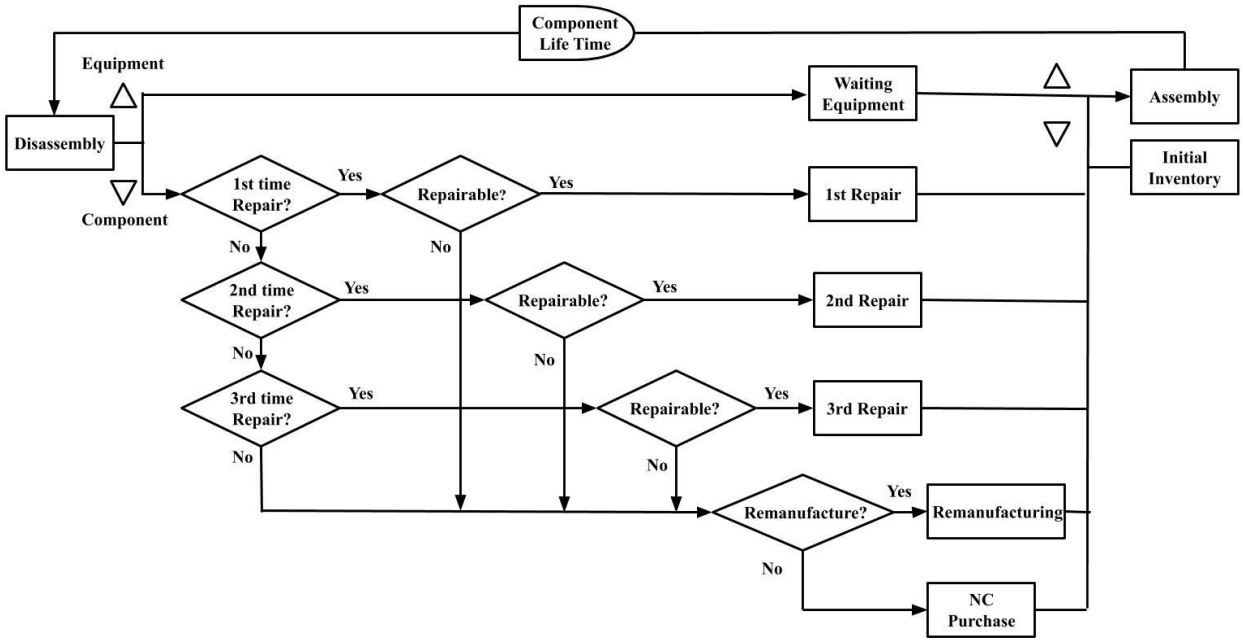


Figure 2. CMW organization

[1]https://www.deublin.eu/rotating-unions

performance's key indicators are the average waiting time of the system's equipment and average maintenance cost per machine in 10 years. Thus, we have taken the methodology of the queuing network used in (Simeu-Abazi et al., 2014) to evaluate the CMW performance.

3 SIMULATION MODELING

3.1 Model properties

Based on queuing network modelling, a simulation model in Arena is conducted to study the system performance under different conditions. General properties of the system are as follows:

- The total number of machines that are supported by the CMW is 100,
- Each component can be repaired a maximum of 3 times, which means more than one visit is possible.
- At the beginning of the simulation, it is assumed that all machines are equipped with new components.
- Assembly and disassembly are single server stations (components processed one by one).
- There is no blocking in the system thanks to unlimited buffer capacities.
- There are two common servers for all three repairing stations (Two equipment can be repaired at the same time).
- NC purchase and remanufacturing stations have infinite servers. It means there is no restriction in supplying remanufactured and new components, and the suppliers have enough capacity.
- Classification and test stations are very rapid with little service time.
- First arrival of 100 failed units from different production lines follow a Poisson distribution with a rate of λ.
- All operational stations follow an exponential distribution with rates shown in Table 1.

Table 1. Service rates of the stations

Station		Service rate
disassembly		μ_{ds}
1st repair		μ_{rp1}
2nd repair		μ_{rp2}
3rd repair		μ_{rp3}
remanufacturing		μ_{rm}
NC purchase		μ_{nw}
assembly		μ_{as}
Component life cycle	1st repair	μ_{L1}
	2^{nd} repair	μ_{L2}
	3rd repair	μ_{L3}
	remanufacturing	μ_{L4}
	NC purchase	μ_{L5}

3.2 Queuing network representation

Figure 3 represents the queuing network of understudy CMW considering all the mentioned properties in the previous section. In addition to parameters in Table 1, the following parameters are used to characterize the system:

- r: proportion of remanufacturing components $\in [0, 1]$,
- r_{p1}, $r_{p2,}$ and r_{p3}: proportion of repairable components for the first, second, and third times, respectively $\in [0, 1]$,
- B: initial inventory safety stock
- λ: first arrival rate of 100 failed units from different production lines,
- μ_{cl}: classification station service rate,
- μ_{tr1}: service rate of the first-time repairability test stations,
- μ_{tr2}: service rate of the second-time repairability test stations,
- μ_{tr3}: service rate of the third-time repairability test stations,
- N_{rp1}: number of components that are repaired for the first time,
- N_{rp2}: number of components that are repaired for the second time,
- N_{rp3}: number of components that are repaired for the third time,
- N_{rm}: number of remanufactured components,
- N_{nw}: number of purchased components,
- s_{rp1}: buffer of the first time repaired components,
- s_{rp2}: buffer of the second time repaired components,
- s_{rp3}: buffer of the third time repaired components,
- s_{rm}: buffer of remanufactured components,
- s_{nw}: buffer of purchased components.

3.3 Decision variables and key indicators

This study aimed at studying the CMW performance based on two main indicators of time and cost. From the time point of view, the system's agility in providing the required service to the failed units is evaluated by measuring the equipment's average waiting time (T_w). To assess the cost, the best indicator that can measure the system's efficiency is the average cost spent to maintain production line machines. The last indicator can be calculated by dividing the total CMW cost by the number of machines, 100 in this study.

Defined indicators must be studied under different scenarios and with various values of decision variables. Repairability rate (r_{p1}, r_{p2}, r_{p3}), remanufacturing rate (r), maximum allowed number of repairing for each component, and initial inventory level (B) are considered as decision variables. Various combinations of these variables will enable us to evaluate CMW's performance under different circumstances.

4 EXPERIMENTS

Experiments have been conducted based on the data from the automotive industry. We used the Arena simulation tool to study the CMW performance by analysing the variation of key indicators. Obviously to study the system accurately, the simulation length was crucial. The length of simulation is 2400 days, which is equal to almost 10 years to obtain reliable and accurate results. Using several combinations of decision variables leads to a more accurate evaluation of system behaviours and performances.

To validate the proposed model, we ran a simplified version of current model to compare its output with the results reported by (Djeunang Mezafack et al., 2020) for an open-loop CMW. The same results were obtained which validates the accuracy and efficiency of the current model.

4.1 Experiments' characteristics

We have considered three different groups of repairability rate, which is shown in Table 2. In Group 1, 90 percent of components visiting the repairing station for the first time, are

repairable. 70 percent of components which have been repaired one time, are repairable. 50 percent of parts with two times previous repairs, can be repaired for third time. The remaining components can be processed in other stations (NC purchase or remanufacturing). The repairing rates of Group2 are 80, 60, and 40 percent for first, second, and third time repairs, respectively. The repairing rates for Group 3 are 70, 50 and 30 percent.

For each group in Table 2 we performed several experiments by changing the value of remanufacturing rate (r: 0, 0.1, 0.2, 0.4, 0.6, 0.8, 1).

Table 2. Repairability rate

	Repairability rate (r_{p1}, r_{p2}, r_{p3})
Group 1	(0.9, 0.7, 0.5)
Group 2	(0.8, 0.6, 0.4)
Group 3	(0.7, 0.5, 0.3)

Various initial inventory level (B) is considered to analyse the influence of this variable on the CMW performance efficiency:
B: 0, 2, 5, 10, 15, 20, 25

We defined three scenarios for the repairing process:

1. Scenario 1: each component can be repaired a maximum of three times,
2. Scenario 2: each component can be repaired a maximum of two times,
3. Scenario 3: each component can be repaired one time.

In case all types of components are available, the priority of use will be 1- new component, 2- remanufactured, 3- first-time repair, 4- second-time repair, 5- third-time repair.

We performed 441 simulations to study all possible combinations of the variables.

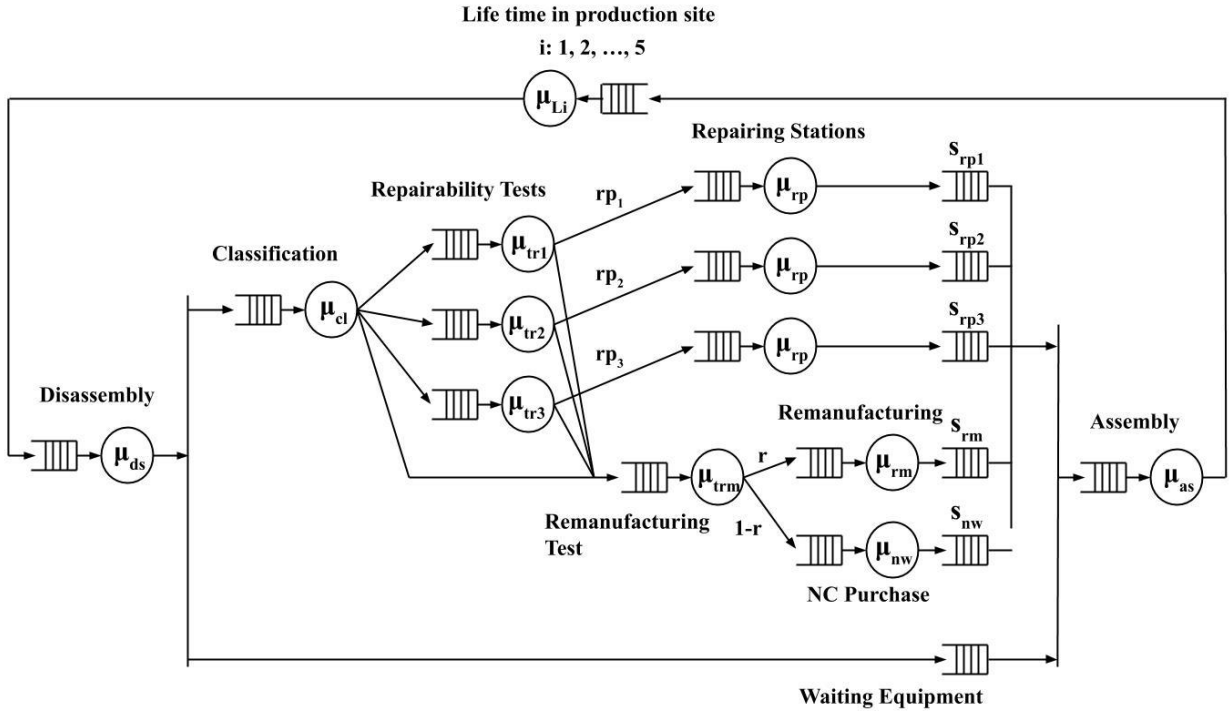
The components' first visit follows a Poisson distribution with rate (λ) of 1 equipment per week (5 days).

Other stations service times are as follows:

- $T_{ds} = T_{as} = 1$ day
- $T_{rp1} = T_{rp2} = T_{rp3} = 5$ days (1 week)
- $T_{rm} = 30$ days (6 weeks)
- $T_{nw} = 40$ days (8 weeks)

Based on a real case in the automotive industry, the lifetime of components processed in different stations are reported as follows:

- $T_{L1} = 160$ days
- $T_{L2} = 120$ days
- $T_{L3} = 80$ days
- $T_{L4} = 360$ days
- $T_{L5} = 480$ days



4.2 Cost function

One of the key indicators of the CMW is the average cost spent on maintenance of each machine over a period of time. To be able to calculate the key indicator, the total cost of the CMW must be calculated. Different methods can be used to calculate the cost. In this study, Total cost is the sum of the waiting cost of the equipment in the CMW and the operational cost of the CMW itself.

$C_{total} = C_{waiting} + C_{operation}$

$C_{waiting} = T_w * C_{ew} * (N_{rp1} + N_{rp2} + N_{rp3} + N_{rm} + N_{nw})$

C_{ew} represents the cost of waiting equipment per day, which can be calculated with different methods. One most common practice is to consider the opportunity cost. We assumed that the presence of a failed unit in CMW is the same as the absence of a machining centre in the production line. Thus, C_{ew} will be equal to the revenue that the producer gains in a day when they use their machine in the production line, and it is 12 EUR/day.

Operational cost can be calculated by:

$C_{operation} = C_{rp1} * N_{rp1} + C_{rp2} * N_{rp2} + C_{rp3} * N_{rp3} + C_{rm} * N_{rm} + C_{nw} * N_{nw}$

where:

- C_{rp1}: First time repairing unit cost (200$)
- C_{rp2}: Second time repairing unit cost (250$)
- C_{rp3}: Third time repairing unit cost (300$)
- C_{rm}: Remanufactured component unit price (600$)
- C_{nw}: New component unit price (900$)

The costs were estimated based on our real case in the automotive industry.
Since the components are small and do not take a lot of space in the warehouse, the inventory cost has been neglected.

5 RESULTS

Having our model constructed, we simulated 441 different combinations of the decision variables to precisely study the performance of the CMW for ten years. By analysing the key indicators, we can obtain the optimum combination of the decision variables introduced in section 3.

5.1 Average waiting time of equipment (T_w)

Average waiting time as a key indicator represents the agility of the CMW in processing the visiting failed units. We measured the variation of T_w under various scenarios by choosing several combinations of variables explained in detail in section 4.
Globally we found that T_w decreases as we increase the initial inventory level up to B equal to 20. As it is shown in Figure 4, the deduction rate of T_w decreases while the value of B increases. Increasing the initial inventory level from 20 to 25 has no impact on the amount of T_w. This trend is true for all other combinations of the decision variables.

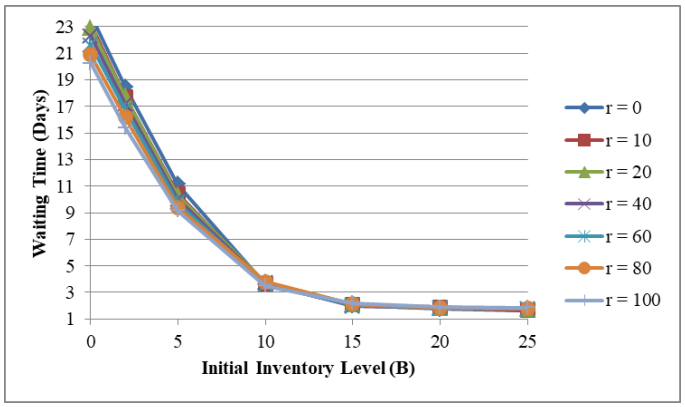


Figure 4. T_w versus B for Group 2 and maximum two times repairing

For the initial inventory level of 20, the simulation results of all combinations of the maximum allowed number of repairing and repairability rates show that the 1-time repair is the most time-efficient option. Therefore, from time point of view, it is better to repair the components only once and in future visits the failed components should be processed in the remanufacturing or NC purchase stations.

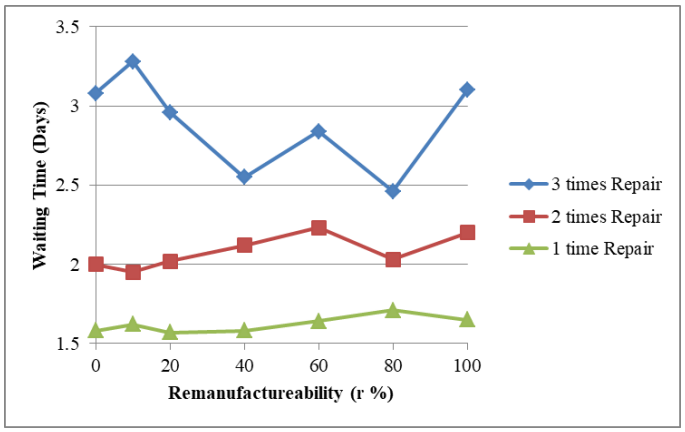


Figure 5. T_w versus r for Group 1 and B = 20

Depending on the repairability rate, the optimum value for remanufacturing is different. In Figure 5, it is shown that for group 1, the optimum remanufacturing rate is 0.2.
For other combinations of repairability rates, the optimum values of r are 0.1 for group 2 and 0.4 for group 3. According to Figures 6 and 7, after the optimum point, the increase of remanufacturing rate increases the T_w.

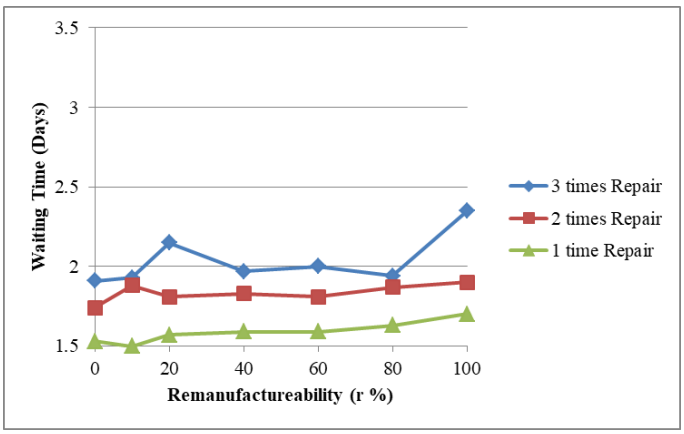


Figure 6. T_w versus r for Group 2 and B = 20

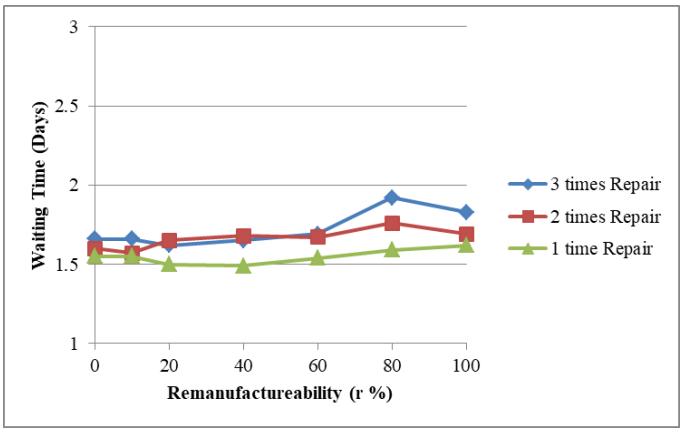


Figure 7. T_w versus r for Group 3 and B = 20

5.2 10-year maintenance cost per machine (C_{10})

10-year maintenance cost per machine as a key indicator represents the cost efficiency of the CMW in processing the visiting failed units. We measured the variation of C_{10} under various scenarios by choosing several combinations of variables that are explained in detail in section 4.

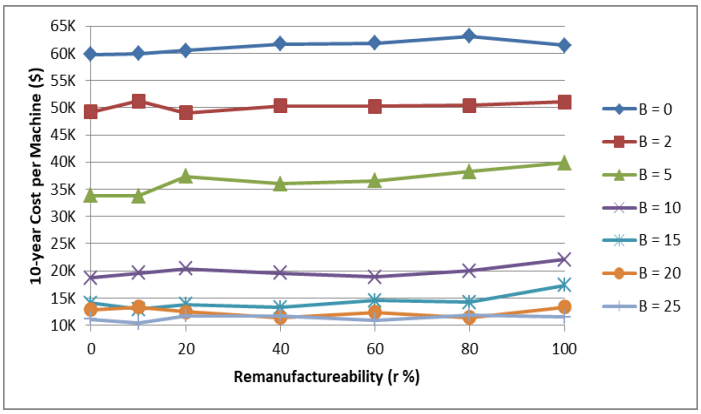


Figure 8. C_{10} versus r for Group 1 and maximum three times repairing

The number of components in the initial inventory has a significant impact on the maintenance cost per machine.
Generally, C_{10} decreases by an increase in the initial inventory level. Figure 8 indicates how the value of C_{10} changes versus the remanufacturing rates for different initial inventory levels.
For groups 2 and 3 and other maximum allowed number of repairing, the same variation trend is observed.
The deduction rate of C_{10} decreases while the value of B increases. The deduction rate of C10 is the slope of the curve shown in Figure 9.

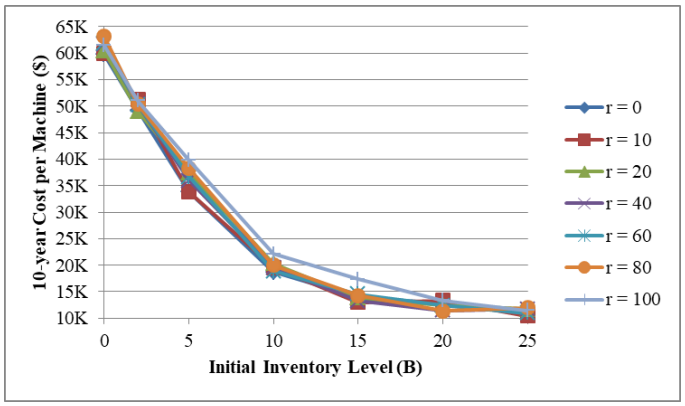


Figure 9. C_{10} versus B for Group 1 and maximum three times repairing

Top figures show that CMW is the most cost-efficient when the initial inventory level is 25. Analyzing the simulation results for B = 25 indicates that the system is more cost-efficient if the component is repaired only once. Figure 10 shows the variation of C_{10} versus remanufacturing rate (r) when B is equal to 20, and only one-time repair is allowed. Different curves in the figure indicate different repairability rates (Group1, 2, and 3).

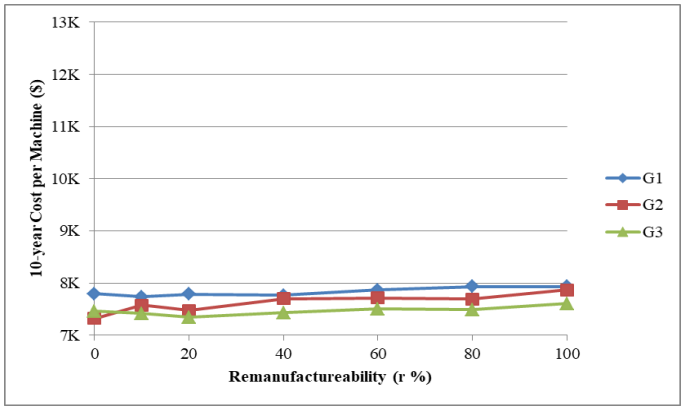


Figure 10. C_{10} versus r for one-time repair and B = 20

For Group 1, the optimum remanufacturing rate is 0.1. Remanufacturing is not cost-efficient for Group 2, which means that the optimum value of r is equal to 0. A remanufacturing rate of 0.2 is the optimum point for Group 3.

6 Conclusion

In this study, we measured the performance of CMW by evaluating the average waiting time of equipment in the system and 10-year maintenance cost per machine.
The impact of various combinations of initial inventory level, maximum allowed number of repairing, remanufacturing, and repairing rates were studied.
It is concluded that using the remanufacturing process can positively affect the CMW performances from the time and cost perspectives.
We also found that there is not a unique point that we can optimize both indicators of the system. But the trends of the variation of the indicators were similar because T_w had a significant effect on the cost function. The simulation results show that, although the optimum point for Tw and C_{10} are not the same, if a company chooses one of these options, it can be sure that the other indicator is in an acceptable range not far from the optimal.
The impact of an increase in initial inventory level is more in the lower values of B. For the more significant amounts of B, the initial inventory level's growth has less impact on CMW performance.
For an initial inventory level of less than 10, a maximum of the three-time repair was the optimal option. By increasing the value of B, the maximum one time repair became more efficient.
The repairing rate of the stations has a significant effect on the optimal remanufacturing rate. Also, the maximum number of allowed repairs had a considerable impact on the optimal remanufacturing rate.
For further research, different cost calculation scenarios can be considered. The transportation time between the production lines and the CMW can be taken into account. The priority of the components according to the maintenance process can be studied.

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