Journal of Optimization in Industrial Engineering,
Vol.15, Issue 2, Summer & Autumn 2022, 75- 86
DOI: 10.22094/joie.2022.1951658.1934

Research Article

Performance Analysis of Remanufacturing System Considering Inspection & Grading Policies, Sourcing Policies and Resource Policies

Magdalene Andrew-Munot [a,*] , Shirley Jonathan Tanjong [a]

[a] *Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), 94300 Kota Samarahan, Sarawak, Malaysia*

Received February 03 2022; Revised 13 March 2022; Accepted 15 March 2022

Abstract

The aim of this study was to investigate the effect three factors (inspection & grading, sourcing policies and resource policies) on the cycle-time performance of a remanufacturing system under three different quality scenarios. The objectives were to analyse (i) the main effect of factors on the remanufacturing cycle-time under the given three quality scenarios, (ii) the interaction effect between these factors on the remanufacturing cycle-time under the given three quality scenarios; and (iii) the factors and corresponding levels that lead to shortest remanufacturing cycle-time. Simulation technique was used to model and simulate the remanufacturing system. Design of experiment method was used to design a mixed two-level and three-level full factorial for running the simulation experiments. Analysis of variance (ANOVA) was used to analyse the output results from the simulation experiments. The ANOVA results show all three factors have significant effect on the remanufacturing cycle-time, regardless of the quality scenarios. The ANOVA results also suggest that sourcing policies has the most predominant effect when the quality scenario is average. Despite the different quality scenarios, the interaction between sourcing policies and resource policies have significant effects on the remanufacturing cycle-time, with predominant effect when the quality scenario is average. The implications for remanufacturing industry are there must be (i) inspection & grading policies, (ii) sourcing policies and (iii) resource policies, as these factors affect the remanuafacturing cycle-time. This work is novel because it considers three factors simultaneously and carries out the research by using simulation, design of experiment and ANOVA.

***Keywords*:** Remanufacturing; Used-Products; Simulation; Inspection; Grading

1. Introduction

Remanufacturing is defined as an activity in which used-products or some of its components are repaired and transformed into a like-new condition (Haziri and Sundin, 2019; Matsumoto and Ijomah, 2013). It is also the process of restoring non-functioning, discarded, or traded-in products (cores) to like-new performance (Lund and Hauser, 2010). Examples of companies that are actively engaged in remanufacturing programs are Caterpillar (Caterpillar, 2019), VolvoTruck (Swanberg, 2018), Fuji Xerox (Fuji Xerox Australia, 2020), and HP (HP, 2020). During this process, used-products passes through inspection, cleaning, disassembly, reprocessing, reassembly and final testing to ensure it meets the desired product standards (Sundin, 2019). For remanufacturing companies, surviving the competitive remanufacturing industry is important (Graham, et. al., 2015) and this requires optimizing the remanufacturing process steps (Butzer et. al, 2016).

Unlike normal manufacturing activities, several factors complicate remanufacturing activities. As reported in Golinska-Dawson, Kosacka and Nowak (2015), Zhang, Ong and Nee (2015) and Zikopoulos (2017), these factors are (i) used-products with uncertain quality conditions and quantities (ii) uncertain inspection yield, (iii) uncertain disassembly yield, (iv) uncertain repair effort for constituent components, (v) multiple types of constituents components, (vi) reassembly of original components into final product, and (vii) balancing customer demand with used-products supply. These factors and their interactions make remanufacturing planning and control activities more challenging. As stated by Matsumoto et.al., (2016), Priyono, Lage Junior and Godinho Filho (2016), and Andrew-Munot et. al., (2018) these factors and their interactions must be considered when modelling and analysing any remanufacturing systems to ensure efficient and effective remanufacturing systems.

Graham et al. (2015) established that the performance of any remanufacturing system could be measured through work in progress, as well as the cycle time (total time from the beginning to end of remanufacturing process). Specially, the authors also establish that the common performance measure for remanufacturing wind turbine gearbox and automotive engine are work in progress and cycle time, despite the slight different in remanufacturing process.

The recently emerging sustainable development goals (SDG) aim to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030 (GA,

Corresponding Author Email Address: ammagdal@unimas.my

2015). Remanufacturing contributes to achieveing SDG 12 by taking back used-products and reprocessing them to products with as good as new conditions. This leads to promoting recycling culture, thus reducing natural resources usage and waste. In addition remanufacturing also contribute to achieving SDG 13 by reducing greenhouse gas emission as remanufacturing activity consume less energy compared to normal manufacturing activity.
This paper is organised as follows. The engineering framework and related literature is presented in Section 2. Section 3, provides the system and problem descriptions, Section 4 describes the methodology, Section 5 presents and discusses the results and Section 6 concludes the work reported in this paper.

2. Engineering Framework and Related Literature

2.1 Engineering framework

This work is grounded on the remanufacturing concept inspired by Lund (1984) and shown in Figure 1 (Appendix). As shown in Figure 1, remanufacturing process normally starts with acquiring used-products, which are then inspected & graded to determine the quality conditions. After inspection & grading, used-products are disassembled into corresponding constituent components, which are then reprocessed. Once all constituent components are reprocessed, these are reassembled and tested before sold as remanufactured products. To date, numerous work on remanufacturing highlight several factors that complicate decision-making within the remanufacturing environment; which are (i) used-products with uncertain quality conditions and quantities (ii) uncertain inspection yield, (iii) uncertain disassembly yield, (iv) uncertain repair effort for constituent components, (v) multiple types of constituents components, (vi) reassembly of original components into final product, and (vii) balancing customer demand with used-products supply. Thus, motivated by the need to support SDG 12 & 13 and understand the effect of above factors on the cycle-time performance of remanufacturing, this work primarily focus on studying the effect of uncertain quality conditions of used-products, inspection & grading policies and resource policies on the cycle-time performance of remanufacturing system.
Uncertain quality conditions of used-products complicate decision making on acquisition, production planning & control activities and inventory planning & control activities within the remanufacturing system. Previous research on acquisition of used-products where the quality conditions are uncertain, can be found in Karamouzian, Teimoury and Modarres (2011); Karamouzian, Naini and Mazdeh (2014); Yang, Wang and Ji (2015); Li, Li and Cai (2016); Mutha, Bansal and Guide (2016); Yang et. al. (2016A); Yang et. al. (2016B); Oh and Behdad (2017); Zhou et. al. (2018); Yang, Ma and Talluri (2019). In these work the researchers study the effect of uncertain quality conditions of used-products on the quantity to be purchased.

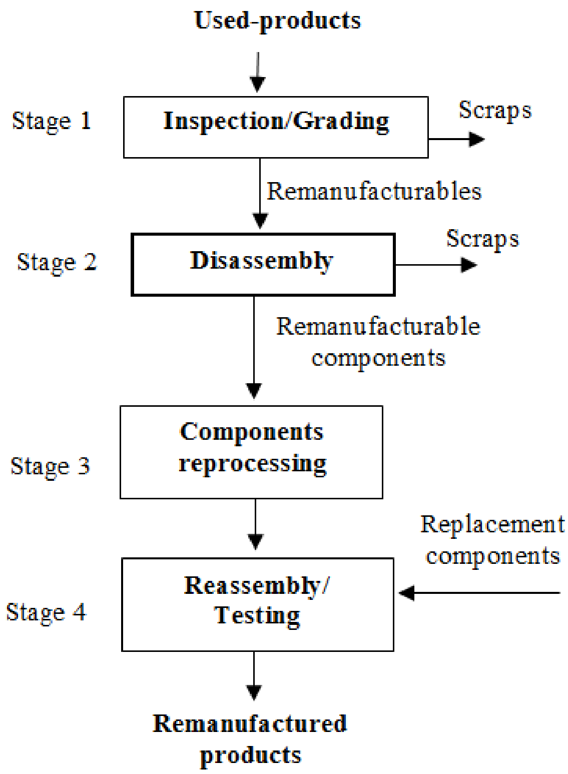


Fig. 1. Key remanufacturing process and material flows (Andrew-Munot et. al., 2018)

2.2. Related literature

In terms of production planning & control the uncertain quality conditions affect the quantity of used-products to remanufactured; related work can be found in Iwao and Kusukawa (2012); Tao, Zhao and Tang (2012); Zikopoulos (2017); Aydin et. al. (2018); Liao, Deng and Shen (2019); Devoto et. al. (2020).
As for inventory planning & control the uncertain quality conditions affect the inventory of used-products, disassembled parts and replacement parts carried in the remanufacturing system. Studies on this have been reported by Zikopoulos (2012); Mashhadi, Esmaeilian and Behdad (2015).
The uncertain quality conditions also requires used-products to be inspected and graded in order to determine the appropriate reprocessing tasks for the different quality groups; thus grading policies is necessary. Several related works are Kang (2013); Mashhadi and Behdad (2017); Farhani, Otieno and Omwando (2020). Furthermore there are researchers that considered grading used-products into multiple quality classes prior to reprocessing; they are Teunter and Flapper (2011); Mezhani and Loukil (2012); Chen et. al., (2018); Yanıkoğlu & Denizel (2020).

As stated, remanufacturing systems consist of several complicating factors, thus requires alternative method to simultaneously study these factors and their interactions. However, from the previous literature, the problems and solutions were mostly studied and proposed using mathematical approaches. Therefore, this is a need to apply alternative method such as simulation to simultaneously study the complicating factors and their interactions. This work fill in this gap by implementing simulation method to analyse the performance of remanufacturing system. Simulation technique is widely used in modelling and analysis of many decision-making models for manufacturing, healthcare and logistics (Sturrock, 2019). This is because simulation enables analyst to view changes in system's performance due to changes in system's parameters (Kelton, Sadowski and Zupick, 2015). Furthermore, simulation is the key technology enabler for the recent progress of fourth industrial revolution (Gunal, 2019; Gunal & Karatas, 2019). However, there were limited remanufacturing research that apply simulation technique; few examples are Gaspari et. al., (2017), Zheng, Zhang and Su (2019), Savaliya & Abdul-Kader (2020). Given that remanufacturing system has complicating factors and simulation enable anyone to analyse the effect of system factors on system performance, this work uses simulation modeling approach combine with design of experiment and analysis of variance (ANOVA); the data used to run the simulation is obtained from previous work (Andrew-Munot et. al., 2018).

This work is novel and contribute in several ways, first there are three factors (inspection & grading policies, sourcing policies and resource policies) that are studied simultaneously where their main and interaction effects on the remanufacturing cycle-time are analysed. Inspection & grading policies are important to avoid costly mistake of processing the wrong grade of used-products; sourcing policies are critical given the uncertain nature of used-product quantities, and resource (facilities) policies are important given the uncertain quantities & quality of used-products to be remanufactured. Secondly this work applies the combination of simulation modeling, design of experiment and analysis of variance (ANOVA) techniques to carryout the research. The simulation technique enables the three factors to be modelled and controlled; design of experiment ensure correct execution of the simulation experiment, and analysis of variance ensure the main and interaction effects of the three factors are properly analysed. Thus simulation technique combine with design of experiment and analysis of variance ensure answering the objective set for this study.

Thus, the motivation for this work was to study three sourcing policies for acquiring used-products, which could be inspected & graded or not and remanufactured using three resource policies under three quality scenarios. The three sourcing policies are to acquire from (i) customer-stream, (ii) 3P-stream, and (iii) mixture of customer & 3P stream. The two inspection & grading policies are (i) to inspect and grade into four quality groups (grade 1 being the highest and grade 4 being the lowest), and (ii) not to inspect & grade. The three resource policies are to remanufacture using (i) dedicated resources, (ii) shared resource, and (iii) switching between resources. Finally, the three quality scenarios for customer-stream used-products are (i) good quality (highest proportion of grade 1 and lowest proportion of grade 4), (ii) average quality (equal proportion of all grades), and (iii) worst quality (highest proportion of grade 4 and lowest proportion of grade 1).

3. System and Problem Description

This work considers a remanufacturing system with the following characteristics. Used-products are acquired according to three possible sourcing policies; (i) policy 1: sourcing from the customer-stream, (ii) policy 2: sourcing from the 3P-stream, (iii) policy 3: sourcing from both customer & 3P streams, i.e. mixed stream. Used-products acquired from the 3P-party-stream are readily available, already inspected at the 3P-center so are in good quality conditions, thus require no inspection & grading and shorter remanufacturing time. Used-products acquired from the customer-stream are those returned by the customers themselves, thus having uncertain quality conditions, require inspection & grading and longer remanufacturing time. The customer-stream used-products are graded into four quality grades with grade 1 being the highest and grade 4 being the lowest. (i.e. inspection & grading policy 1). For policy 2, the customer-stream used-products are not inspected and graded. As stated, the customer-stream used-products, are uncertain in quality conditions, thus considering different quality scenarios is important to reflect this uncertainty. The three quality scenarios are good, average and worst, which differ in terms of the proportion graded into grade 1, grade 2, grade 3, and grade 4. For the good quality scenario, the proportion of used-products graded into grade 1, grade 2, grade 3 and grade 4 are 0.40, 0.30, 0.20 and 0.10 respectively. For the average quality scenario, the proportion for grade 1, grade 2, grade 3 and grade 4 are 0.25, 0.25, 0.25 and 0.25 respectively. As for the worst quality scenario, the proportion for grade 1, grade 2, grade 3 and grade 4 are 0.10, 0.20, 0.30 and 0.40 respectively.

Given the uncertain quantity of used-products, proper allocation of resource is important to ensure optimum operation of the remanufacturing system. For the remanufacturing resource, there are three possible policies to choose from (i) policy 1: dedicated resource for each customer-stream and 3P-stream, (ii) policy 2: one resource shared between the customer-stream and 3P-stream, (iii) policy 3: two resources shared between the customer-stream and 3P-stream where both streams can switch between the resources. Given that there are three factors (inspection & grading policies, sourcing policies and resource policies) with several possible options (three possible sources of used-products, two possible policies for inspection & grading and three possible resource policies), then achieving the three stated objectives would benefit tremendously from simulation technique.

The research questions are (i) which factor(s) (inspection & grading policies, sourcing policies and resource policies) has significant effect on the remanufacturing cycle-time, (ii) which combinations of any two and three factors have a significant effect on the remanufacturing cycle-time, (iii) which combination of the factors leads to the shortest remanufacturing cycle-time. Thus the objectives are to analyse (i) the main effect of factors on the remanufacturing cycle-time under the given three quality scenarios, (ii) the interaction effect between these factors on the remanufacturing cycle-time under the given three quality scenarios; and (iii) the combination of factors and correspong levels that lead to shortest remanufacturing cycle-time.

4. Methodology

4.1. Model development, translation, verification and validation

This work adopts the basic conceptual model established in Andrew-Munot et. al., (2018) and extend this model to include the 3P-stream and also to grade the customer-stream used-products, into four quality grades. The extended conceptual model is translated into the simulation model using the ARENA simulation platform (Rockwell Automation, 2020). The simulation model is verified using the animation technique to make sure the model's assumptions are appropriately programmed (Kelton, Sadowski and Zupick, 2015; Lari & Singh, 2015). The simulation model is validated using the sensitivity analysis adopted by Sarda & Digalwar (2018); which is appropriate when the system under studied not yet exist and no data are available for comparison; this technique allow confirmation of certain data trend against the theory.

In this work, the sensitivity analysis is performed by varying the values of two factors (percentage of customer-stream used-products in the mixed-sourcing policies and inter-arrival time for customer-stream used-products) and observing the effects on the production quantity. As stated, incoming used-products are uncertain in terms of quantity, and this affect the remanufacturing system. Considering the two factors for the sensitivity analysis would reflect the effect on production quantity. As shown in Figure 2 (Appendix), as the % of used-products in the customer-stream increases in the mixed-sourcing policy (i.e. more input into the system), the production quantity also increases. Similarly, as shown in Figure 2 (Appendix), as the inter-arrival time of customer-stream used-products becomes shorter (i.e. more frequent arrival of used-products) then the production quantity increases. Therefore, for both factors there is a linear relationship between these two factors and production quantity; thus the simulation model developed in this work is considered as valid.

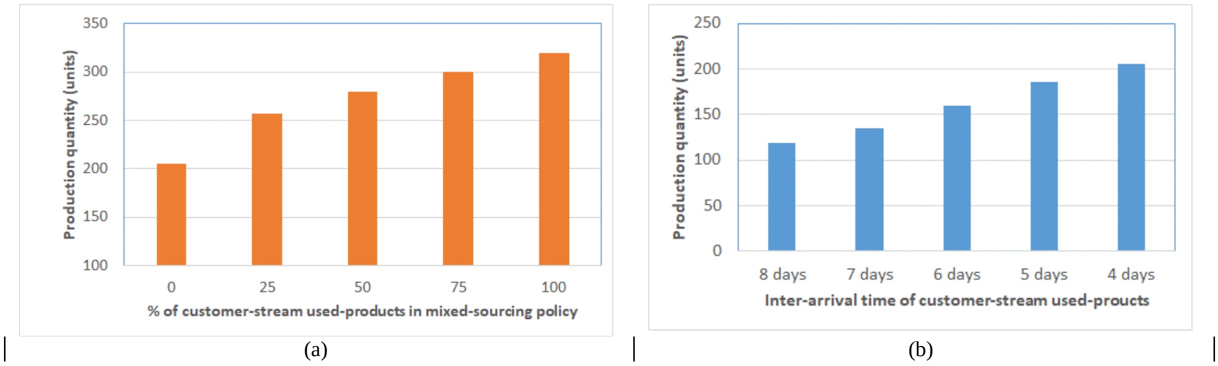


Fig. 2. Variation of production quantity with (a) percentage of customer-stream used-products in mixed-sourcing policy, and (b) inter-arrival time of customer-stream used-products

4.2. System parameters and values

The system parameters and corresponding values are shown in Table 1. As shown in Table 1, the customer-stream used-products are modelled to arrive one unit at a time with exponential distribution to represent uncertain inter-arrival times of the used-products. Also, as indicated in Table 1, the 3P-stream used-products are also modelled to arrive one unit at a time, but with constant distribution inter-arrival time to represent deterministic inter-arrival times. The repair time for customer-stream used-products are modelled according to the uniform distribution with grade 1 with the shortest repair time compared to grade 2, grade 3 and grade 4. The repair time for the 3P-stream is also modelled according to the uniform distribution with time that is shorter than grade 1. There are three quality scenarios with different values for each grade in each scenario.

Table 1.
System Parameters and Values

System parameters		Values	Notes
Inter-arrival time for used-products	Customer-stream	Expo (4) days	Similar to Andrew-Munot et. al. (2018)
	3P-stream	Constant (3) days	Quantities and quality conditions are certain compared to customer-stream used-products
Repair time for customer-stream used-products	Grade 1	unif (3, 4)	Similar to Andrew-Munot et. al. (2018)
	Grade 2	unif (4, 5)	
	Grade 3	unif (5, 6)	
	Grade 4	unif (7, 8)	
Repair time of 3P-stream		unif (2, 3)	Better quality conditions than customers used-products, thus shorter overall remanufacturing time

4.3. Design of Experiment

Referring to Table 2, the three factors considered are inspection & grading policies (A), resource policies (B) and sourcing policies (C), while the dependent variable is remanufacturing cycle-time (RCT). As tabulated in Table 2, Factor A has two levels (1=No inspection & Grading, 2=Inspection & Grading), Factor B has 3 levels (1=100%Customer, 2=50%Customer 50%3P, 3=100%3P), while Factor C has 3 levels (1=Dedicated policy, 2=Sharing policy, 3=Switching policy). The mixed two-level and three-level full factorial design is applied to examine the main effect of factors A, B & C and interaction effects on the remanufacturing cycle-time. Table 3 (Appendix) shows the mixed two and three-level full factorial design consisting of 18 rows corresponding to the 18 experiments and three columns for each factor A, B & C.

Table 2.
Variables Parameters and Levels

			Levels		
Factors	Symbol	Units	1	2	3
Inspection & Grading Policies	A	Dimensionless	No inspection & Grading	Inspection & Grading	-
Sourcing policies	B	%	100%Customer	50%Customers 50%3P	100%3P
Resource Policies	C	Dimensionless	Dedicated	Sharing	Switching

Table 3.
Mixed two-level and three-level full factorial design and simulation results

Experiment Number	Inspection & Grading Policies	Sourcing Policies	Resource Policies	Quality Scenarios		
				Good	Average	Worst
	A	B	C	RCT (days)	RCT (days)	RCT (days)
1	1	1	1	70.02	141.14	193.52
2	1	1	2	4.52	6.16	9.51
3*	1	1	3	2.5	2.50	2.50
4	1	2	1	79.46	126.08	165.43
5	1	2	2	4.74	5.86	7.34
6*	1	2	3	2.5	2.50	2.50
7	1	3	1	70.02	141.14	193.52
8	1	3	2	23.98	59.76	99.39
9*	1	3	3	2.5	2.50	2.50
10	2	1	1	79.46	126.08	165.43
11	2	1	2	28.67	51.88	77.96
12*	2	1	3	2.5	2.50	2.50
13	2	2	1	9.08	19.68	45.32
14	2	2	2	4.8	6.14	7.96
15*	2	2	3	2.5	2.5	2.5
16	2	3	1	9.81	4.06	28.25
17	2	3	2	5	5.89	6.93
18*	2	3	3	2.5	2.5	2.5

Note: '*' denotes experiment run that resulted in the shortest remanufacturing cycle-time.

4.4. Analysis of variance (ANOVA)

The Statistical Package for Social Sciences (SPSS) version 23 is utilised to perform analysis of variance (ANOVA) on the simulation results. The ANOVA is conducted to compare the main effects of factor A, B and C and the interaction effect between factors A & B, A & C and B & C on the remanufacturing cycle-time. For each of the quality scenario, the ANOVA is conducted at a significant level alpha (α) of 0.05 (95% confidence).

5. Experimental Results and Discussions

5.1. Main effect analysis under three quality scenarios

Under the good quality scenario, the main effect analysis results show that for all factors (A, B, C) the effect on remanufacturing cycle-time are statistically significant (Table 4 in Appendix). The main effect of factor A (inspection & grading policies) is found to be statistically significant, F (1,4) = 8.023, p=0.047, partial η2= 0.667. For factor B (sourcing policies) the main effect is found to be statistically significant, F (2,4) = 1020.091, p=0.000, partial η^2=0.998. Finally, the effect of factor C (resource policies) is also found to be statistically significant, F (2, 4) = 320.533, p=0.000, partial η^2=0.994. Thus, amongst the three factors, sourcing policies, B (F=1020.091) has the most predominant effect on remanufacturing cycle-time, followed with resource policies, C (F=320.533) and inspection & grading policies (F=8.023). Graphically the main effects are shown in Fig. 3.

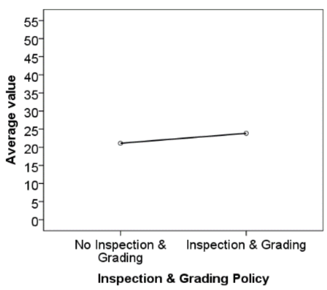
Under the average quality scenario, as tabulated in Table 5 (Appendix), the main effect of all factors (A, B, C) on remanufacturing cycle-time are statistically significant. The main effect of factor A (inspection & grading policies) is statistically significant, F (1,4) = 48.702, p=0.002, partial η2= 0.924. For factor B (sourcing policies) the main effect is found to be statistically significant, F (2,4) = 4050.894, p=0.000, partial η^2=1.000. Finally, the effect of factor C (resource policies) is also statistically significant, F (2, 4) = 1551.043, p=0.000, partial η^2=0.999. Thus, amongst the three factors, sourcing policies, B (F=4050.894) has the most predominant effect on remanufacturing cycle-time, followed with resource policies, C (F=1551.043). Graphically the main effects are shown in Fig. 4.

Table 4.
Results for analysis of variance: good quality scenario

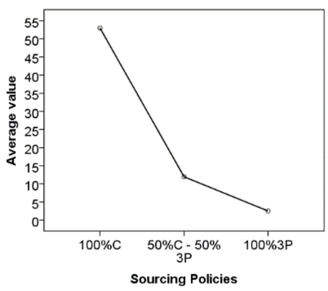
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	15028.628[a]	13	1156.048	272.970	.000	.999
Intercept	9092.488	1	9092.488	2146.949	.000	.998
A	33.977	1	33.977	8.023	.047	.667
B	8640.322	2	4320.161	1020.091	.000	.998
C	2714.958	2	1357.479	320.533	.000	.994
A * B	34.542	2	17.271	4.078	.108	.671
A * C	15.010	2	7.505	1.772	.281	.470
B * C	3589.818	4	897.455	211.910	.000	.995
Error	16.940	4	4.235			
Total	24138.056	18				
Corrected Total	15045.568	17				

Table 5.
Results for analysis of variance: average quality scenario

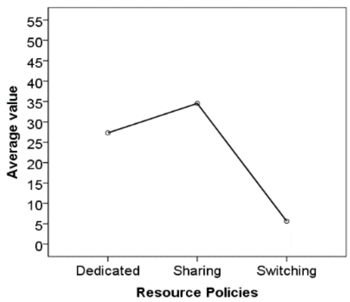
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	50552.381[a]	13	3888.645	1161.786	.000	1.000
Intercept	27916.301	1	27916.301	8340.379	.000	1.000
A	163.013	1	163.013	48.702	.002	.924
B	27117.707	2	13558.853	4050.894	.000	1.000
C	10383.073	2	5191.536	1551.043	.000	.999
A * B	197.592	2	98.796	29.517	.004	.937
A*C	5.968	2	2.984	.891	.478	.308
B*C	12685.029	4	3171.257	947.457	.000	.999
Error	13.389	4	3.347			
Total	78482.070	18				
Corrected Total	50565.769	17				



(a) Main effect of A

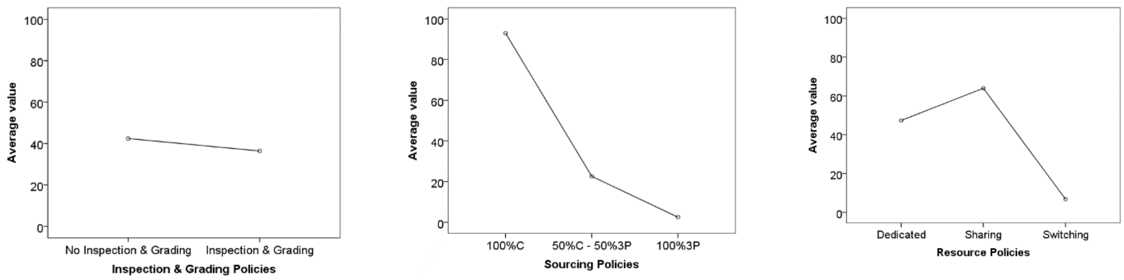


(b) Main effect of B



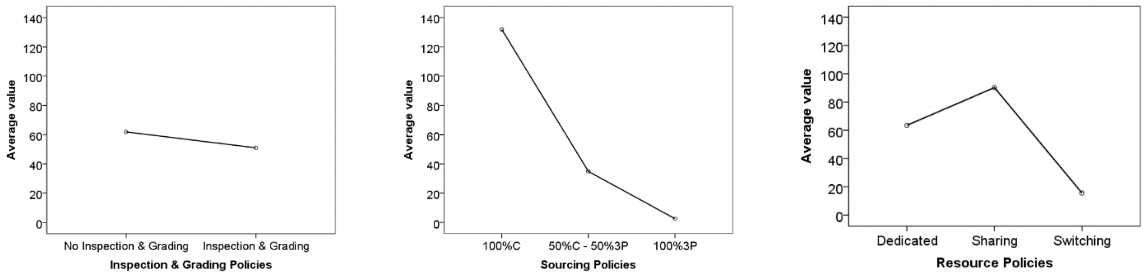
(c) Main effect of C

Fig. 3. Figures of main effects: good quality scenario



(a) Main effect of A (b) Main effect of B (c) Main effect of C

Fig. 4. Figures of main effect for average quality scenario



(a) Main effect of A (b) Main effect of B (c) Main effect of C

Fig. 5. Figures of main effect for poor quality scenario

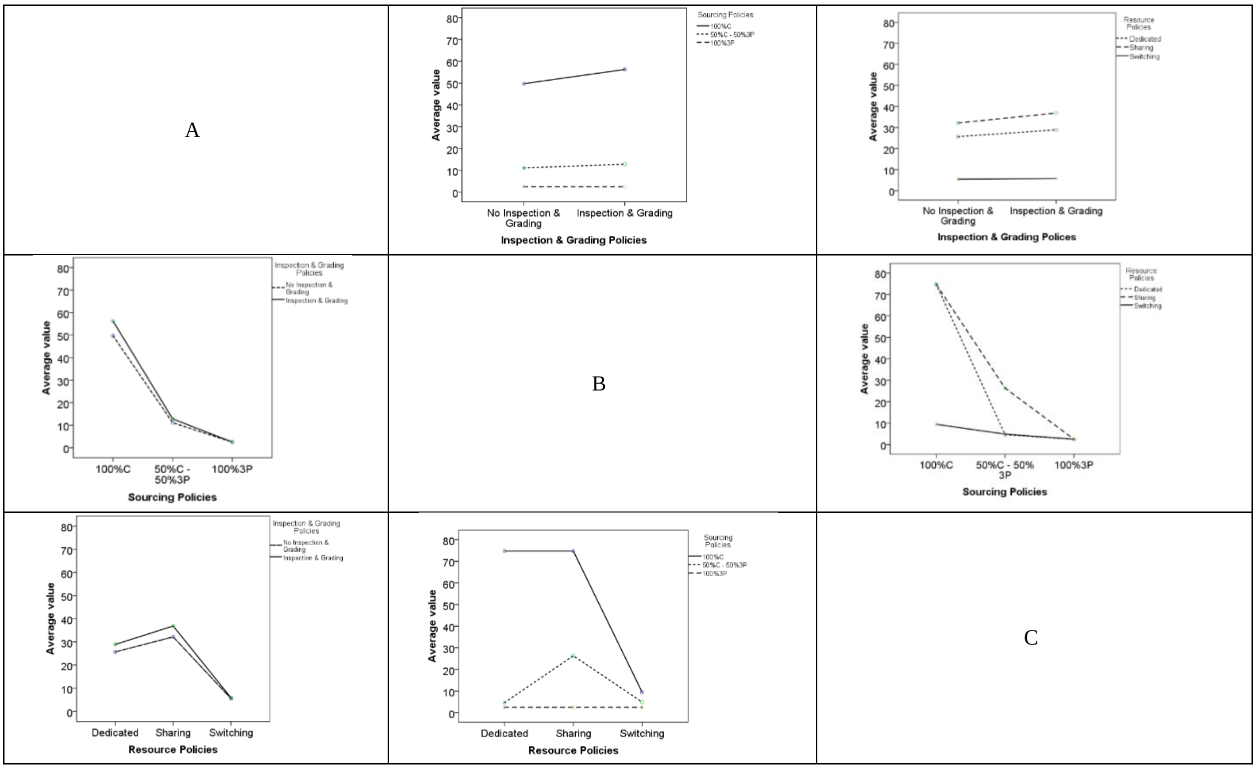


Fig. 6. Figures of interaction effects: good quality scenario

For the poor quality scenario, as shown in Table 6 (Appendix), the main effect of all factors (A, B, C) on remanufacturing cycle-time are statistically significant. The main effect of factor A (inspection & grading policies) is statistically significant, F (1,4) = 24.124, p=0.008, partial η2= 0.858. For factor B (sourcing policies) the main effect is found to be statistically significant, F (2,4) = 1233.481, p=0.000, partial η^2=0.998. Finally, the effect of factor C (resource policies) is also statistically significant, F (2, 4) = 388.860, p=0.000, partial η^2=0.995. Thus, amongst the three factors, sourcing policies, B (F=1233.481) has the most predominant effect on remanufacturing cycle-time, followed with resource policies, C (F=388.860). Graphically the main effects are illustrated in Fig. 5.

5.2. Interaction effects analysis under three quality scenarios

For the good quality scenario, Table 4 (Appendix) shows that the interaction effect between factors (B & C) on remanufacturing cycle-time is statistically significant, F (4,4) =211.910, p=0.000. In other words, the effect of sourcing policies (B) is affected by the presence of resource policies (C). Fig. 6 (Appendix) , show the interaction effects of variable parameters A, B, C.

Table 5 (Appendix) shows that for the average quality scenario, the interaction effect between factors (A & B) on remanufacturing cycle-time is statistically significant, F (2,4) =29.517, p=0.004. The interaction effect between factors (B & C) on remanufacturing cycle-time is also statistically significant, F (4,4) = 947.457, p = 0.000. Fig. 7, show the interaction effects of variable parameters A, B, C. Amongst the interaction effects, the interaction between sourcing policies and resource policies, B*C (F=947.457) has the most predominant effect on remanufacturing cycle-time. In other words, the effect of sourcing policies (B) depends on the presence of resource policies (C).

Finally, for the poor quality scenario, Table 6 (Appendix) shows that the interaction effect between factors (A & B) on remanufacturing cycle-time is statistically significant, F (2,4) 10.497, p=0.026. The interaction effect between factors (B & C) on remanufacturing cycle-time is also statistically significant, F (4,4) = 211.663, p = 0.000. Fig. 8, depicts the interaction effects of factors A, B, C. Amongst the interaction effects, the interaction between sourcing policies and resource policies, B*C (F=211.663) has the most predominant effect on remanufacturing cycle-time. In other words, the effect of sourcing policies (B) depends on the presence of resource policies (C).

Table 6.
Results for analysis of variance: poor quality scenario

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	91349.460[a]	13	7026.882	318.480	.000	.999
Intercept	57297.275	1	57297.275	2596.892	.000	.998
A	532.257	1	532.257	24.124	.008	.858
B	54430.523	2	27215.262	1233.481	.000	.998
C	17159.459	2	8579.730	388.860	.000	.995
A*B	463.203	2	231.601	10.497	.026	.840
A*C	83.688	2	41.844	1.896	.263	.487
B*C	18680.330	4	4670.082	211.663	.000	.995
Error	88.255	4	22.064			
Total	148734.990	18				
Corrected Total	91437.715	17				

Table 7.
Combination of factors and corresponding levels that resulted in the shortest remanufacturing cycle-time

Experiment Number	Inspection & Grading Policies	Sourcing Policies	Resource Policies	Quality Scenarios		
				Good	Average	Worst
	A	B	C	RCT (days)	RCT (days)	RCT (days)
3*	1	1	3	2.5	2.50	2.50
6*	1	2	3	2.5	2.50	2.50
9*	1	3	3	2.5	2.50	2.50
12*	2	1	3	2.5	2.50	2.50
15*	2	2	3	2.5	2.5	2.5
18*	2	3	3	2.5	2.5	2.5

5.3. Combined factors analysis under three quality scenarios

Table 7 (Appendix) tabulates the combination of factors and corresponding levels that resulted in the shortest remanufacturing cycle-time. As shown in Table 7, for all quality scenarios the shortest remanufacturing cycle-time is 2.5 hours, which correspond to six experiment runs that are number 3, 6, 9, 12, 15 and 18. Specifically, as shown in Table 7, no inspection & grading policy (factor A) combined with switching between remanufacturing resources (factor C) under all three sourcing policies resulted in the shortest remanufacturing cycle-time; run number 3, 6 and 9. In other words, whether used-products are sourced from the customer-stream, 3P-stream or both streams, inspection & grading is not required, as long as resource for remanufacturing is always available (switching between dedicated & sharing policies), this would resulted in the shortest remanufacturing cycle-time.

Table 7 also showns that having an inspection & grading policy together with switching resource policy under all three sourcing policies resulted in the shortest remanufacturing cycle-time. In other words, regardless of the sourcing policies for used-products, as long as remanufacturing resource is always available (switching policy), having the used-products inspected & graded still resulted in the shortest remanufacturing cycle-time. This result implies that under the conditions studied in this work, availability of resource is important for achieving short remanufacturing cycle-time, when used-products are sourced from three different streams and whether these used-products are inspected & graded or not.

6. Conclusion and Future Work

This work has studied three factors (inspection & grading policies, sourcing policies and resources policies) that are important for the cycle-time performance of any remanufacturing system. The simulation model has been developed, verified and validated within the ARENA simulation platform. The simulation experiments have been designed using the mixed two-level and three-level full factorial design of experiment. Results from the

simulation experiment were analysed using analysis of variance (ANOVA) to determine the main and interaction effects of the three factors on remanufacturing cycle-time.
Results showed that for the good quality scenario, all factors have significant effect on remanufacturing cycle-time. For the interaction effect, the interaction between sourcing policies and resource policies significantly affects the remanufacturing cycle-time. For the average quality scenario; results show that all factors also have significant effects on the remanufacturing cycle-time, with sourcing policies has the greatest impact. Unlike the good quality scenario, there are two interaction effects that significantly affect the remanufacturing cycle-time; interaction between inspection policies and sourcing policies and the interaction between sourcing policies and resource policies. Finally, for the poor quality scenario, all three factors also have significant effect on the remanufacturing cycle-time. As for the interaction effects, similar to the average quality scenario, there are two interaction effects (between inspection policies & sourcing policies and between sourcing policies & resource policies) that have significant effects on the remanufacturing cycle-time.

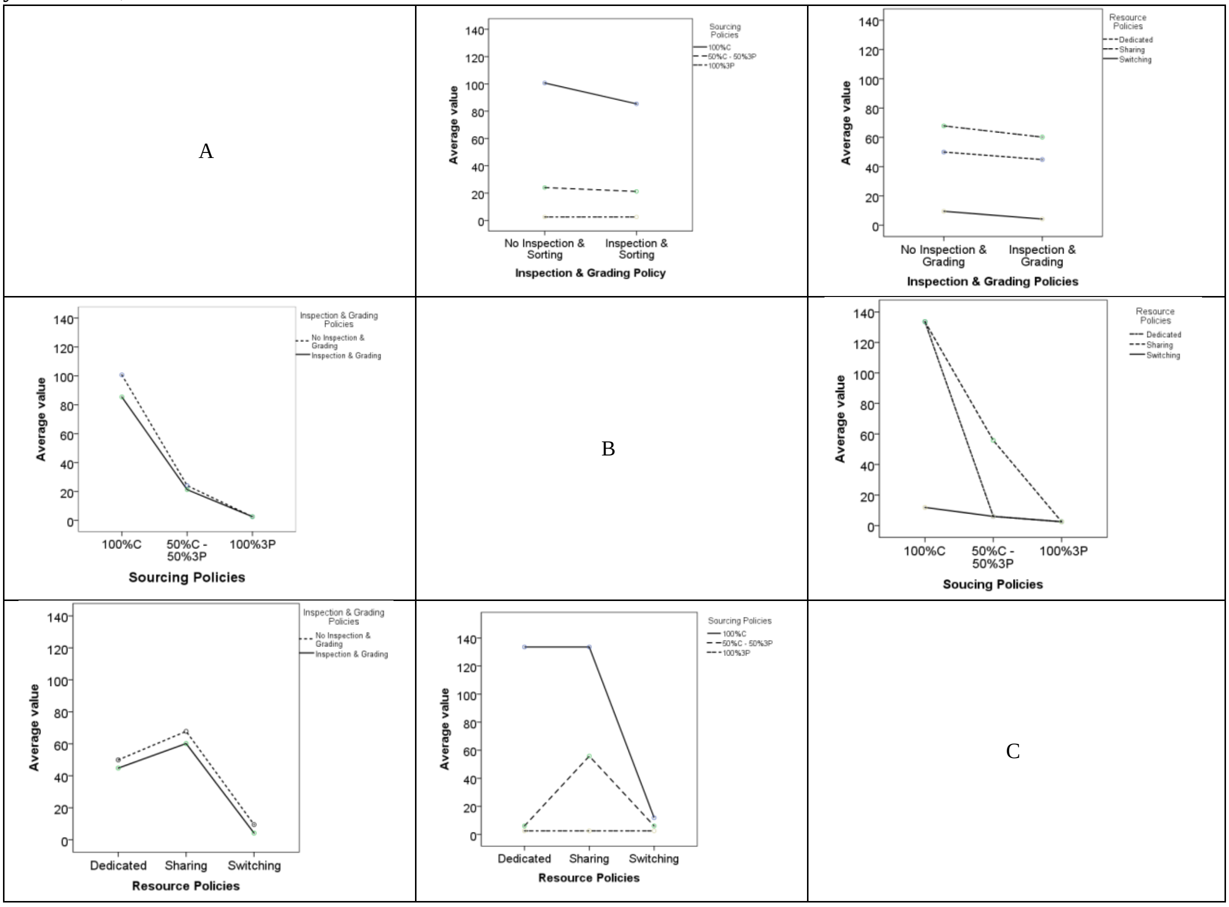


Fig. 7. Figures of interaction effects for average quality scenario

Findings from this study suggest that regardless of the quality scenarios, all three factors have significant effects on remanufacturing cycle-time, with sourcing policies has the most predominant effect when the quality scenario is average. Also, in all quality scenarios simulated, the interaction between sourcing policies and resource policies have significant effects on the remanufacturing cycle-time, with predominant effect when the quality scenario is average. Finally, regardless of the quality scenario, the combination of inspection & grading policies, sourcing policies and resource policies that resulted in the shortest remanufacturing cycle-time are the same. The managerial implications of this study are remanufacturing companies need to, (1) implement inspection & grading strategy to avoid costly error of improper inspection & grading, (2) obtain used-products from multiple sources to avoid shortages of used-products, (3) allocate resource wisely to avoid wasting or insufficient resource, (4) decide resource policy together with sourcing policy. Finally there is a combination of inspection & grading policy, sourcing policy and resource policy that gives the shortest remanufacturing cycle time.
This work has contributed to the study of remanufacturing system, in which simulation technique and ANOVA were used to study the main and interaction effects of inspection & grading policies, sourcing policies and resource policies on remanufacturing cycle-time. This work has also supported the emerging movement on 12 sustainable development goals; specifically towards achieving SDG 12 (responsible consumption and production) and SDG 13 (climate action). This work focuses on optimizing remanufacturing system performance where short cycle-time leads to less greenhouse gas emission. Furthermore, remanufacturing minimize raw materials usage and waste through taking back used-products. The future directions of this work are

to consider (i) different statistical distributions to model the inter-arrival time for used-products from both streams and repair time, (ii) remanufacture-to-order strategy and compare it to present work, and (iii) components' disassembly yield, and (iv) reassembly the same set of components.

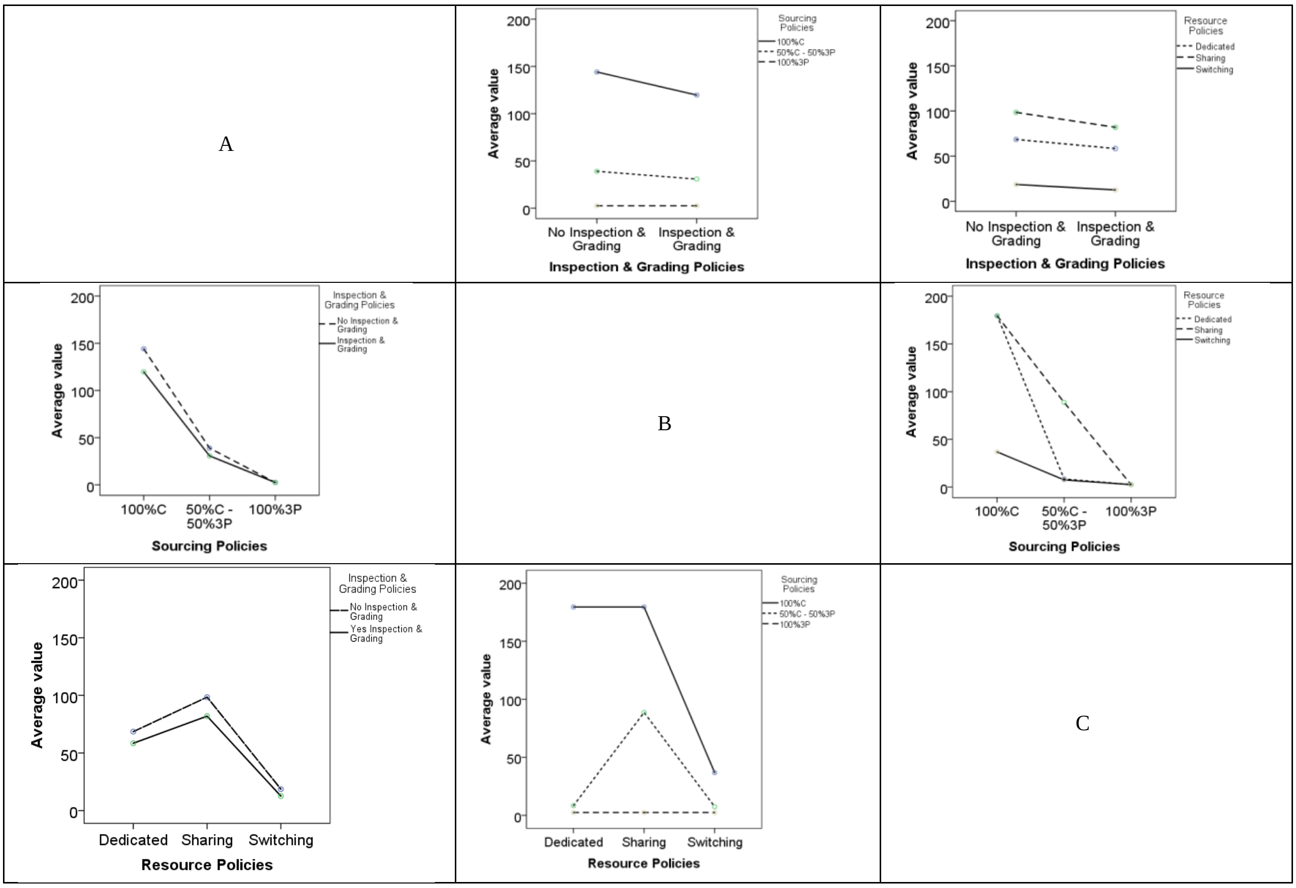


Fig. 8. Figures of interaction effect for worst quality scenario

Conflict of Interest

The authors have no conflict of interest to declare.

Acknowledgment
The author acknowledges the funding support of Universiti Malaysia Sarawak (UNIMAS).

References

Andrew-Munot, M., Yassin, A., Shazali, S. T., Sawawi, M., Tanjong, S. J., & Razali, N. (2018). Analysis of production planning activities in remanufacturing system. *Journal of Mechanical Engineering and Sciences, 12(2),* 3548-3565.

Aydin, R., Kwong, C. K., Geda, M. W., & Okudan Kremer, G. E. (2018). Determining the optimal quantity and quality levels of used product returns for remanufacturing under multi-period and uncertain quality of returns. *The International Journal of Advanced Manufacturing Technology, 94,* 4401-4414.

Butzer, S., Kemp, D., Steinhilper, R., & Schötz, S. (2016). Identification of approaches for remanufacturing 4.0. *IEEE European Technology and Engineering Management Summit (E-TEMS),* 1-6.

Caterpillar, (2019), 2019 Annual Report, [Online] Available: https://reports.caterpillar.com/ar/2019_Caterpillar_Annual_Report.pdf (February 10, 2020)

Chen, W., Wang, Y., Zhang, P., & Chen, X. (2018). Effects of an Inaccurate Sorting Procedure on Optimal Procurement and Production Decisions in a Remanufacturing System. *Engineering Management Journal, 30(2),* 117-127.

Devoto, C., Fernández, E., & Piñeyro, P. (2020). The economic lot-sizing problem with remanufacturing and inspection for grading heterogeneous returns. *Journal of Remanufacturing*, 1-17.

Fuji Xerox Australia, (2020), Eco Manufacturing Centre and Product Stewardship Program Information, [Online] Available: https://www.fujixerox.com.au/en/Sustainability/Eco-Manufacturing-Centre (March 15, 2020)

Farahani, S., Otieno, W., & Omwando, T. (2020). The optimal disposition policy for remanufacturing systems with variable quality returns. *Computers & Industrial Engineering, 140,* 106-218.

Gaspari, L., Colucci, L., Butzer, S., Colledani, M., & Steinhilper, R. (2017). Modularization in material flow simulation for managing production releases in remanufacturing. *Journal of Remanufacturing, 7(2-3),* 139-157.

GA, U. (2015). Transforming our world: the 2030 Agenda for Sustainable Development. Division for Sustainable Development Goals: New York, NY, USA.

Graham, I., Goodall, P., Peng, Y., Palmer, C., West, A., Conway, P., Mascolo, J. E., & Dettmer, F. U. (2015). Performance measurement and KPIs for remanufacturing. *Journal of Remanufacturing,* 5-10.

Golinska-Dawson, P, Kosacka, M, & Nowak, A. (2015). Automotive Parts Remanufacturing–Experience of Polish Small Companies. *CMUJ NS Special Issue on Logistics and Supply Chain*, *14,* 415-430.

Gunal M.M. (2019) Simulation and the Fourth Industrial Revolution. In: Gunal M. (eds) Simulation for Industry 4.0. Springer Series in Advanced Manufacturing. (pp.1-17). Springer, Cham.

Gunal, M. M., & Karatas, M. (2019). Industry 4.0, Digitisation in Manufacturing, and Simulation: A Review of the Literature. In Gunal M. (eds) Simulation for Industry 4.0. Springer Series in Advanced Manufacturing. (pp.19-37). Springer, Cham.

HP, (2020), Remanufactured Hardware, [Online] Available: https://www8.hp.com/us/en/hp-information/environment/refurbished-products.html (March 22, 2020)

Haziri, L. L., & Sundin, E. (2019). Supporting design for remanufacturing-A framework for implementing information feedback from remanufacturing to product design.*Journal of Remanufacturing*, 1-20.

Iwao, M. & Kusukawa, M. (2012). Optimal production planning for remanufacturing with uncertainty in quality of returns and classification error in quality grading. *Proceedings of the Asia Pacific Industrial Engineering & Management Systems Conference Osaka*

Jin, X., Ni., J, & Koren, Y. (2011). Optimal control of reassembly with variable quality returns in a product remanufacturing system. *CIRP Annals*, *60*,25-28.

Kang, T. (2013). Balancing Acquisition and Sorting Policies Of Remanufacturing. https://rc.library.uta.edu/uta-ir/handle/10106/23941 (February 21, 2020).

Karamouzian, A., Naini, S.G.J. & Mazdeh, M.M. (2014). Management of returned products to a remanufacturing facility considering arrival uncertainty and priority processing. *International Journal of Operational Research*, *20*, 331-340.

Karamouzian, A., Teimoury, E., Modarres, M. (2011). A model for admission control of returned products in a remanufacturing facility using queuing theory. The International *Journal of Advanced Manufacturing Technology*, *54*, 403-412.

Kelton, W., Sadowski, R., & Zupick, N. (2015). Simulation with Arena. 6th ed. Singapore

Lage Junior, M., & Godinho Filho, M. (2016). Production planning and control for remanufacturing: exploring characteristics and difficulties with case studies. *Production Planning and Control, 27(3),* 212-225.

Lari, O, & Singh, H. (2015). Basics of Modelling and Simulation. S. K. Kataria & Sons

Liao, H., Deng, Q., & Shen, N. (2019). Optimal remanufacture-up-to strategy with uncertainties in acquisition quality, quantity, and market demand. *Journal of Cleaner Production*, *206*, 987-1003.

Li, X., Li, Y., & Cai, X. (2016). On Core Sorting in RMTS and RMTO Systems: A Newsvendor Framework. *Decision Sciences*, *47,* 60-93.

Lund, R. T., & Hauser, W. M. (2010). Remanufacturing-an American perspective.

Mashhadi, A. R., Esmaeilian, B., & Behdad, S. (2015). Uncertainty Management in Remanufacturing Decisions: A Consideration of Uncertainties in Market Demand, Quantity, and Quality of Returns. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering, 1(2)*.

Mashhadi, A. R., & Behdad, S. (2017). Optimal sorting policies in remanufacturing systems: Application of product life-cycle data in quality grading and end-of-use recovery. *Journal of Manufacturing Systems, 43(1)*, 15-24.

Matsumoto, M., & Ijomah, W. (2013). Remanufacturing. In Handbook of sustainable engineering (pp. 389-408). Springer Netherlands.

Matsumoto, M., Yang, S., Martinsen, K., & Kainuma, Y. (2016). Trends and research challenges in remanufacturing. *International Journal of Precision Engineering and Manufacturing-Green Technology, 3,* 129-142.

Mezghani M, & Loukil T. (2012). Remanufacturing planning with imprecise quality inputs through the goal programming and the satisfaction functions. *International Journal of Multicriteria Decision Making*, *2*, 379-390.

Mutha, A., Bansal, S., & Guide, V. D. R. (2016). Managing demand uncertainty through core acquisition in remanufacturing. *Production and Operations Management*, *25*, 1449-1464.

Oh, Y., & Behdad, S. (2017). Simultaneous reassembly and procurement planning in assemble-to-order remanufacturing systems. *International Journal of Production Economics, 184*, 168-178.

Priyono, A., Ijomah, W., & Bititci, U. (2016) Disassembly for remanufacturing: A systematic literature review, new model development and future research needs. *Journal of Industrial Engineering and Management, 9,* 899-932.

Rockwell Automation (2020) Arena simulation software. 16 ed.

Sarda, A., & Digalwar, A. K. (2018). Performance analysis of vehicle assembly line using discrete event simulation modelling. *International Journal of Business Excellence, 14(2),* 240-255.

Savaliya, R., & Abdul-Kader, W. (2020). Performance evaluation of the remanufacturing system prone to random failure and repair. *International Journal of Sustainable Engineering, 13(1),* 33-44.

Sturrock, D. T. (2019). Traditional Simulation Applications in Industry 4.0. In In: Gunal M. (eds) Simulation for Industry 4.0. Springer Series in Advanced Manufacturing. (pp.39-54). Springer, Cham

Sundin, E., (2019), The role of remanufacturing in a circular economy: Operations, Engineering and Logistics (pp. 31-60). John Wiley & Sons.

Swanberg, L. (2018), Engines Revived, [Online] https://www.volvotrucks.com/en-lb/news/magazine-online/2018/may/remanufacturing-engines.html# (May 5, 2020)

Tao, Z., Zhou, S. X., & Tang, C. S. (2012). Managing a Remanufacturing System with Random Yield: Properties, Observations, and Heuristics. *Production and Operations Management*, *21*, 797-813.

Teunter, R. H., & Flapper, S. D. P. (2011). Optimal core acquisition and remanufacturing policies under uncertain core quality fractions. *European Journal of Operational Research*, *210,* 241-248.

Yang, C. H., Wang, J., & Ji, P. (2015). Optimal acquisition policy in remanufacturing under general core quality distributions. *International Journal of Production Research, 53,* 1425-1438.

Yang, C. H., Bao, X. Y., Song, C., & Liu, H. B. (2016A). Optimal acquisition policy in remanufacturing systems with quantity discount and carbon tax scheme. *Tehnicki vjesnik, 23,* 1073-1081.

Yang, C. H., Liu, H. B., Ji, P., & Ma, X. (2016B). Optimal acquisition and remanufacturing policies for multi-product remanufacturing systems. *Journal of Cleaner Production, 135,* 1571-1579.

Yang, C. H., Ma, X., & Talluri, S. (2019). Optimal acquisition decision in a remanufacturing system with partial random yield information. *International Journal of Production Research, 57(6),* 1624-1644.

Yanıkoğlu, İ., & Denizel, M. (2020). The value of quality grading in remanufacturing under quality level uncertainty. *International Journal of Production Research*, 1-21.

Zhang, R., Ong, S. K., & Nee, A. Y. C. (2015). A simulation-based genetic algorithm approach for remanufacturing process planning and scheduling. *Applied Soft Computing, 37*, 521-532.

Zhou, J., Deng, Q., & Li, T. (2018). Optimal acquisition and remanufacturing policies considering the effect of quality uncertainty on carbon emissions. *Journal of Cleaner Production*, *186,* 180-190.

Zheng, Y., Zhang, C., & Su, C. (2019). Simulation on Remanufacturing Cost by Considering Quality Grade of Returns and Buffer Capacity. *Journal of Shanghai Jiaotong University (Science), 24(4),* 471-476.

Zikopoulos, C. (2012). Remanufacturing lot-sizing under alternative perceptions of returned units' quality. *International Journal of Business Science & Applied Management, 7*,12-22.

Zikopoulos, C. (2017) Remanufacturing lotsizing with stochastic lead-time resulting from stochastic quality of returns. *International Journal of Production Research, 55*, 1565-1587

This article can be cited: Andrew-Munot, M., & Jonathan Tanjong, S. (2022). Performance Analysis of Remanufacturing System Considering Inspection & Grading Policies, Sourcing Policies and Resource Policies Under Multiple Quality Scenarios: Towards Environmental Sustainability. *Journal of Optimization in Industrial Engineering*, *15*(2), 75-86.
Doi: 10.22094/joie.2022.1951658.193