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Determination of Criticality Indexes in the Remanufacturing Process: A GERT-Based Simulation Approach

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Abstract

The common end-of-life options are reuse, remanufacture, recycle, landfill, and incineration. In this paper one of the important “end of life options” (remanufacturing) has been analyzed. Among the related studies surveyed the various remanufacturing aspects, less attention has been paid to the stochastic process routing. In this regard, a remanufacturing process routing with stochastic activities is modelled as a GERT network. One of the efficient ways to analyze a remanufacturing process is the identification of the most effective activities on the cost and time of the process during the process implementation. Criticality indexes are suitable scales for this purpose. Therefore, to analyze the important aspects of the remanufacturing process, four criticality indexes are developed in this paper. These indexes measure the cost and time of the process and its activities to identify the activities with high importance in terms of cost and time. On the other hand, simulation is an efficient tool to cope with the uncertainties in the production problems. Hence a Monte Carlo approach (which is developed using Arena software) has been adopted to analyze the GERT based model and to calculate the criticality indexes. In addition, a mathematical approach using Moment Generation Functions has been adopted to calculate the expected value of the criticality indexes. A numerical example (a real case of lathe spindle remanufacturing) has been solved using both proposed approaches. The results show the acceptable performance of the proposed GERT based simulation approach.

Keywords:Monte-Carlo simulation; GERT problem; Remanufacturing processes; Criticality indexes

1. Introduction

Nowadays, in many industries, remanufacturing is one of the most important aspects of competition. Increasing products variety, short life of products, environmental regulations and sustainability issues propelled manufacturing industries to remanufacture the used products. Remanufacturing is “the process of bringing an assembly to like-new condition through replacing and rebuilding its components at least to current specification“(Ilgin & Gupta, 2012).In other words, remanufacturing is the way to exchange useless product to usable one along with decreasing adverse effects of discard disposal products. Remanufacturing preserves most of the materials in the original products, hence it needs fewer raw materials rather than manufacturing ofthenew products. Thus by reduction of raw material consumption, enormous savings can be achieved in energy consumption, and consequently reduction of$CO_2$and greenhouse gases emission.

Remanufacturing activities are applied to a large number of products. These include: automobiles, automotive parts, electric motors, tyres, compressors, telephones, televisions, electrical apparatus, vending machines.

Furthermore, remanufacturing reduces the flow of waste material by keeping them in use for longer time. Therefore,by the force of theenvironment organizations and governmental laws supporting, manufacturers have more motivated to remanufacturing issues especially in therecent years. Remanufacturing has also some benefits for both remanufacturers and customers, like higher profit margins than traditional manufacturing for remanufacturer, and lower prices for end users.Remanufacturing systems and their performance differ from common manufacturing systems, in terms of supply, production, distribution, inventory, and their intricacy. The yield of remanufacturing systems is more uncertain in terms of time, quantity, quality, and composition. The process routings are not necessarily fixed but they depend on the condition of returned products in remanufacturing systems. Therefore, the uncertainties of remanufacturing systems and returned products are significant issues in these systems. Practical remanufacturing process is not simply as its concept. It consists of disassembly return productsandbreak up them to do essential activities and then reassemble new yields.

Many firms around the world implement remanufacturing process for used products. Reports show that USA is the first priority in applying remanufacturing. A.C. electric company in the United State, have plants in some cities like Auburn and Bangor, remanufactures motors, generators, pumps and electrical switchgear, which turn out about £7 million of sales each year(Lund & Hauser, 2012). As another instance, almost 1billion $ saved in annual federal vehicle repair costs in theUnited States by remanufacturing auto part.

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1.1 . Comparison with other end-of-life options

Whenever a product reaches to the end of its useful life (End-of-Life) it may be conducted through different ways such as reuse, remanufacture, recycle, landfill, and incineration. Some differences between remanufacturing and other types of End-of-Life options are as follows:1)In aremanufacturing process, warranty is given to all parts of the products but in the other types, warranty is applied to only repair components and all major wearing parts in order. 2)Since remanufactured products involve greater work content than repaired or reconditioned products; they have higher levels of quality and performance.3)Products may lose their identity in remanufacturing process since any component that cannot be remanufactured after checking all parts, is replaced with a new component, while products preserve their identities in the otherprocesses.4) The number of upgrades in a remanufacturing process may be one or more, while the products in the other types have usually no upgrades(Ilgin & Gupta, 2012).

1.2 . Remanufacturing process

The used products, which are called cores, are classified to recycled materials and repairable cores by the inspection at the first step in remanufacturing process. After cleaning and disassembling repairable cores, the parts and subassemblies are inspected to determine whether they have severely damaged or not. If they haveseverely damaged, they would be sent to recycled materials, otherwise they would be sent to reusable or repairing parts. After performing all or some of the repairing activities on the repairable parts, they are used in reassembling new products accompanied with reusable and new parts. The last step in remanufacturing process is test-remanufactured products. If the test result is fail, remanufacturing process repeats again on the products.The Figure 1 shows the overall process.

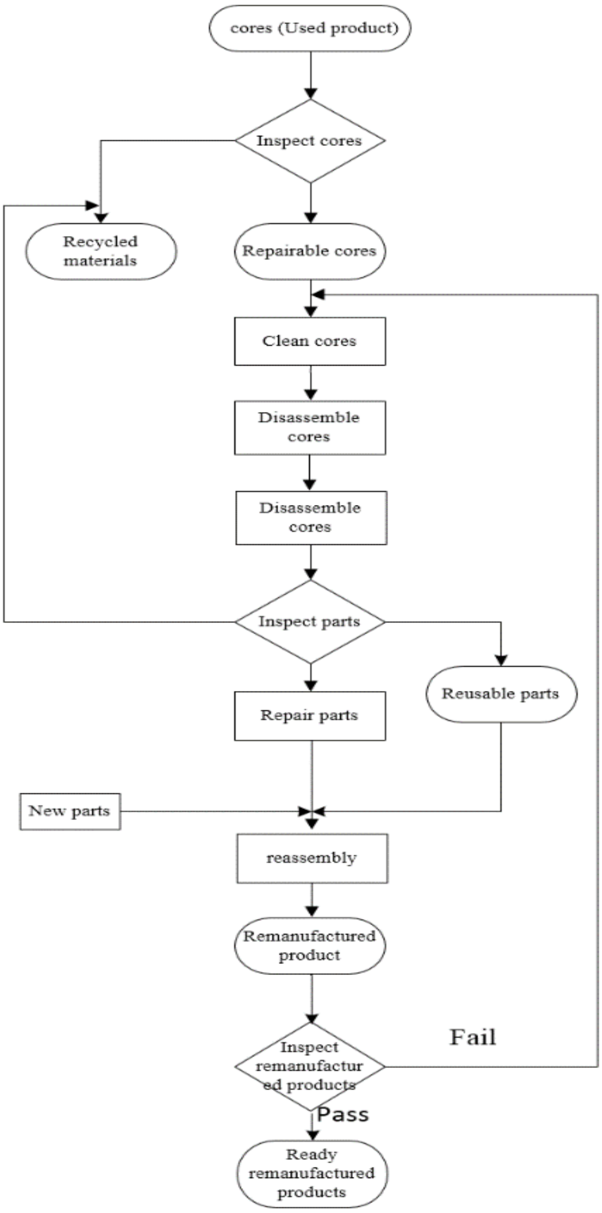


Fig. 1. A remanufacturing process

2. Literature Review

Many researchers have studied remanufacturing systems from varies point of views. Galbreth and Blackburn (2010)considered the uncertainty in product condition to optimal acquisition quantities in remanufacturing. Teunter and Flapper (2011)studied the influence of returned products quality into the product acquisition and remanufacturing policies.Johnson and McCarthy (2013) investigated the impact of remanufacturing on economic and environmental policies and explained the uncertainty of part failures in a new modelling approach.Huang et al. (2009)developed dynamic closed–loop supply chain models by considering stochastic parameters in remanufacturing systems. Corum et al. (2014)compared the total inventory cost, order variance in push and pull controlled hybrid systems and traditional systems using a simulation model by considering both manufacturing and remanufacturing options.M. E. Ketzenberg et al. (2006) surveyed the value of information in remanufacturing by recognizing the uncertainties of demands, returns and yields and M. Ketzenberg (2009) developed theprevious method by considering the uncertainty of product disposal.Mashhadi et al. (2015) developed a stochastic optimization model based on chance-constrained programming in terms of the uncertainties as quantity and quality of returns in remanufacturing process to obtain maximum profit of each used product.Ismail et al. (2014) investigated the environmental impacts assessment in a remanufacturing process using simulation methods. Zhou et al. (2010) surveyed a new approach for forecasting probability, quantity and expected time of return used products based on GERT networks.Robotis et al. (2012) studied the effects of uncertainty in remanufacturing cost on the used products remanufacturing and reusability level of main products enhancement in a firm that produce both new and remanufactured products.Zhang et al. (2016)propose a decision making approach for End-of-Life strategies selection based on the reliability of used parts at the end of their useful life and RUL (Remaining Useful Life) estimation. Analysing the cost indexes in remanufacturing processes studied by Sabharwal and Garg (2013) using the graph theoretic method.Clottey et al. (2012) is among the researchers which discussed uncertainty in the rate of return products and its subsequent challenges like production and inventory planning.Tao et al. (2012) surveyed the ordering of a serviceable product and the remanufacturing of multiple types of returned products (cores) into the serviceable product; furthermore they also consideredthe market demand, returned quantities of different type of cores and the remanufacturing yield of each type of core as uncertain options. Pandey and Thurston (2010) developed a method to determine component reuse decisions utilizing information set about product structure and remanufacturing systems.Ng et al. (2014) suggested a method to quantify product condition including wear-out life of the product, change of dimension and cleanliness level on product recovery decision making. Recently some uncertainty factors including recycling price, quality fluctuation coefficient, demand coefficient and the reusing ratio of products considered in a mathematical model on remanufacturing process of end-of-life construction machinery (Deng et al., 2017). Chakraborty et al. (2017) studied the characteristics of a remanufacturing process in opposition with barriers and critical success factors in an automotive engine case study and used TOPSIS approach to identify them.Zhou et al. (2016) translated remanufacturing process to a GERT network and based on that developed a forecasting model to predict the quality, time and probability of product return, recyclable parts and disposal.Li et al. (2011) investigated the uncertainty management of remanufacturing process utilizing GERT based analytical method;Li et al. (2013) extended the prior studied with representing an analytical method to analyse variability of remanufacturing process activities and compared the results of their method with the outputs of Arena simulation. It can be realized from cited studied review, that there is lack of research on a method to studying the most effective and important activities in the remanufacturing process based on the important parameters like cost and time. Many researches had focused on uncertainty of different characteristics of remanufacturing process, but the most impressive activities and deviation parameters of activities, like probability, time or cost of all process is not considered. Ren and Yuan (2012) described criticality indexes in GERT networks and calculated them using Monte Carlo simulation method. To the best of our knowledge, there is no research in the literature combining the concept of criticality indexes in the GERT based remanufacturing network. Remained parts of the paper are organized as follows: In the section 3, Remanufacturing process routing (RPR) is modelled using the simulation approach. In the section 4, a real case of lathe spindle machine is described and the related simulation model is presented. In section 5 the mathematical approach is presented to calculate the expected value of criticality indexes. Finally, some concluding remarks are presented in the section 6.

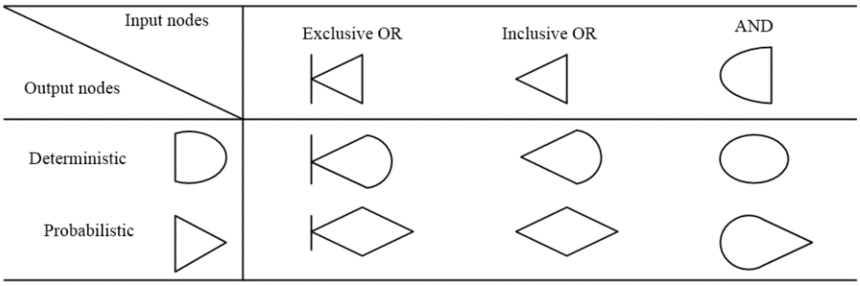
3. A RPR Simulation Model Based on GERT

After reviewing the literature, in this section we will discuss about the remanufacturing network and the approach to analyze it.

3.1 . Graphical Evaluation & Review Technique (GERT)

The deterministic network structure caused many restrictions in the network planning techniques, which means that:1)the activity cannot start before completion of all predecessors. 2)The network must be planned again if a repetition or rework is required during the process because no task can be repeated.3)The critical path is known as the longest path even though the other paths may be longer.4)The only way of completing the project is to do all tasks in order to reach the only ending event.In other words,GERT is a stochastic network analysis technique developed to planning the most complex projects. The complexity of project networks is due to nondeterministic activities and their sequence. AGERT network is composed of arcs, nodes, and flows. Arcsshow activities and nodes show events; every two nodes are connected by an arc. Flows represent parameters such as duration, cost, andprobability of arcs or nodes. Every task in a GERT network can take different path to completion by considering its condition; it means that the initial decision node can follow all further tasks, some or any of them.Also looping back to earlier events is acceptable in this type of network planning. The essential option in GERT networks calculation is deterministic activities attribute, any activity must has special attribute of its parameters e.g. time(Nicholas & Steyn, 2008). Six types of nodes in GERT networks represent different logical relations between inputs and outputs, which are shown in the Table1.

Table 1
Different types of GERT nodes



There are two approaches to solve GERT networks; analytical method and simulation. The analytical method needs much time to spend and involves some limitation to solving. However, in this paper, both approaches are used and compared with each other.

3.2 . Remanufacturing process routing (RPR) model

While manufacturing processes are almost linear and straight, Remanufacturing processes are highly stochastic and include reentrant, thus GERT networks approach is a propermethod for remanufacturing processes representation. Four remanufacturing routings based onGERT models (mentioned above) explained here.

1) Linear routing: as depicted in the Figure 2, there is no reentrant in operation processes and parts advance through a direct routing. The required time and probability of activity to be taken are shownwitht_{ij} and p_{ij}in this Figure (*i* and*j* are the number of nodes). *A*, *B* and *C* are the names of various activities corresponding their branches (branches indicate activities).

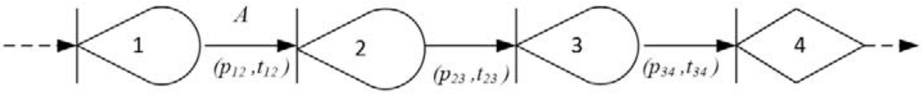


Fig. 2. Linear routing flow

2) Skipping routing: as shown in the Figure 3, cores proceed through some or all ofthe operations in this configuration. For example, some cores may need only *A* operation but others may need both operations *A* and *B* during their process in Figure 3.

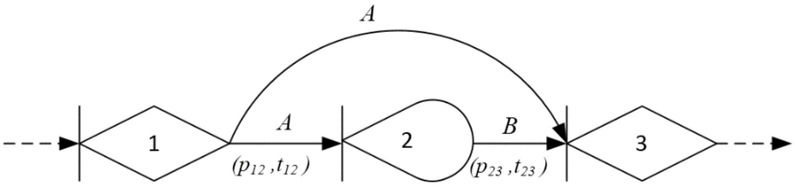


Fig. 3. Skipping routing flow

3) Feedback routing: depending on uncertainty of components, some operations require to repeat again, however the operation parameters may be quite different. As shown in the Figure 4, after completion ofprocesses *A* and *B*over a part, it returns to process *A* again.

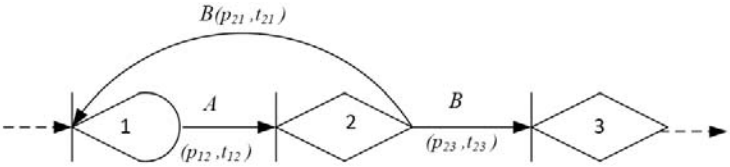


Fig. 4. Feedback routing

4) Branching routing: in some cases, maybe different ways exist with different probabilities and operating times versus exit node. Any part goes through one of these activities with special $p_{ij}$and t_{ij} and $\sum_{j=1}^{n} pij = 1$ in this type of routing. (Note that type of activities associated to branches could be diverse). The Figure5 shows the branchingrouting.

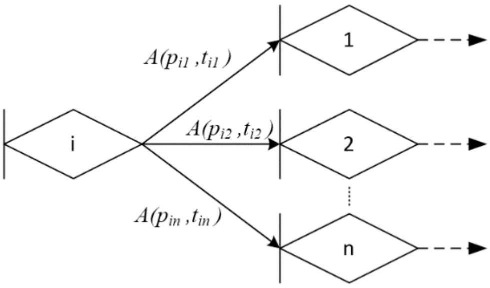


Fig. 5. Branching routing flow

4. Lathe Spindle Remanufacturing Example

In this section, a numerical example based on the remanufacturing process of a common machine tool (lathe spindle) is described. A spindle is an important part of the lathe machines. Used lathe spindles are approximately same in terms of functionality or shape but they may need different remanufacturing processes to be restored. Li et al. (2013) presented an example regarding the process of the remanufacturing of these parts and we adopted majority of our data from their work. Details of the process and its parameters are defined bellow.

As mentioned before, the time and realization of majority of activities in remanufacturing process are stochastic, therefore the utilization of GERT-based RPR model to representthe remanufacturing problem is possible. The reusable parts and recycled materials will be disassembled after the inspection of lathe spindles (cores) and the restof defectives enter the remanufacturing activities and go through path*2-13* or path*6-13* with a certain probability depending on their conditions as shown in the Figure6. Whereas remanufacturing is a high-stochastic process, some parts need reentrance to the past tasks like node 5 to node 2 or need to skip some tasks like node 11 to node 13 in the Figure6. Thus, each activity (arrow between i and j nodes) has definite probability $p_{ij}$and time distribution t_{ij}that shown as *(p_{ij}, t_{ij})* in the Figure 6. As shown in the Figure6, stochastic nodes have occurred following inspection tasks in this example, because the quality level of cores at the end of each inspection affect the next route. Lathe spindle remanufacturing consists of the following activities:Inspection, Grinding, Cleaning, Transportation, Brush plating, Digging groove, Coating. Details about these activities are shown in the Figure 6.

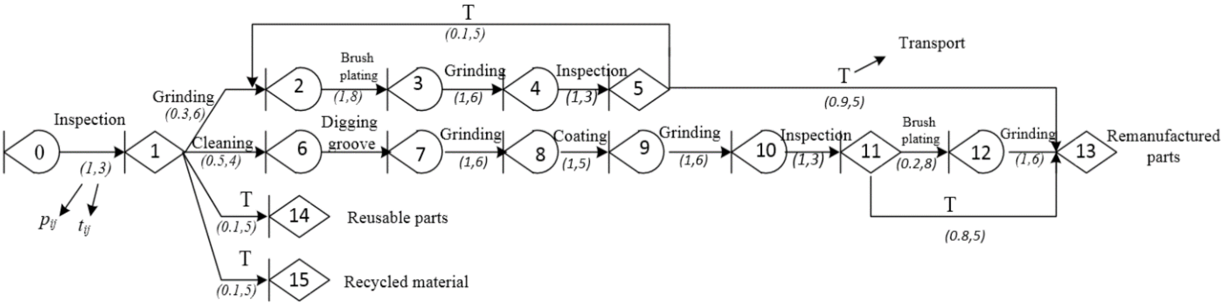


Fig. 6. GERT-based RPR model for lathe spindle remanufacturing example

We will analyze and discuss lathe spindle remanufacturing as an example based GERT networks, Monte-Carlo simulation methodand a mathematical model. The Table2 shows the activities parameters; probability, cost and time distribution and the Figure 7 shows its simulation model in Arena software.

Table 2
Probability and time distribution of lathe spindle remanufacturing activities

Activity	Conjoint Nodes	probability	Cost	Time Distribution (t_{ij}/minute)
Inspection	0 – 1 4 – 5 10 – 11	$P_{0,1} = 1$ $P_{4,5} = 1$ $P_{10,11} = 1$	$C_{0,1} = 15$ $C_{4,5} = 15$ $C_{10,11} = 15$	Normal distribution Mean = 3, σ = 0.2
Grinding	1 – 2 3 – 4 7 – 8 9 – 10 12 - 13	$P_{1,2} = 0.3$ $P_{3,4} = 1$ $P_{7,8} = 1$ $P_{9,10} = 1$ $P_{12,13} = 1$	$C_{1,2} = 20$ $C_{3,4} = 20$ $C_{7,8} = 20$ $C_{9,10} = 20$ $C_{12,13} = 20$	Normal distribution Mean= 6, σ = 0.1
Brush plating	2 – 3 11 – 12	$P_{2,3} = 1$ $P_{11,12} = 0.2$	$C_{2,3} = 50$ $C_{11,12} = 50$	Negative exponential distribution Mean = 8
Cleaning	1 – 6	$P_{1,6} = 0.5$	$C_{1,6} = 10$	Normal distribution Mean = 4, σ = 0.1
Coating	8 – 9	$P_{8,9} = 1$	$C_{8,9} = 15$	Negative exponential distribution Mean = 5
Transport	5 – 2 5 – 13 1 – 14 1 – 15 11 – 13	$P_{5,2} = 0.1$ $P_{5,13} = 0.9$ $P_{1,14} = 0.1$ $P_{1,15} = 0.1$ $P_{11,13} = 0.8$	$C_{5,2} = 10$ $C_{5,13} = 10$ $C_{1,14} = 10$ $C_{1,15} = 10$ $C_{11,13} = 10$	Constant t = 5
Digging groove	6 - 7	$P_{6,7} = 1$	$C_{6,7} = 38$	Negative exponential distribution Mean = 10

Because of the widespread usages of Arena software in simulation problems and its flexibility in the various types of problems, we engaged simulation approach via Arena software to solve and yield the outputs. Since remanufacturing operations are discrete (independent) sequence in time, so the simulation type is Discrete Event Simulation (DES) in which the occurrence of events is discrete. Arena simulation model of the lathe spindle example is as follow.

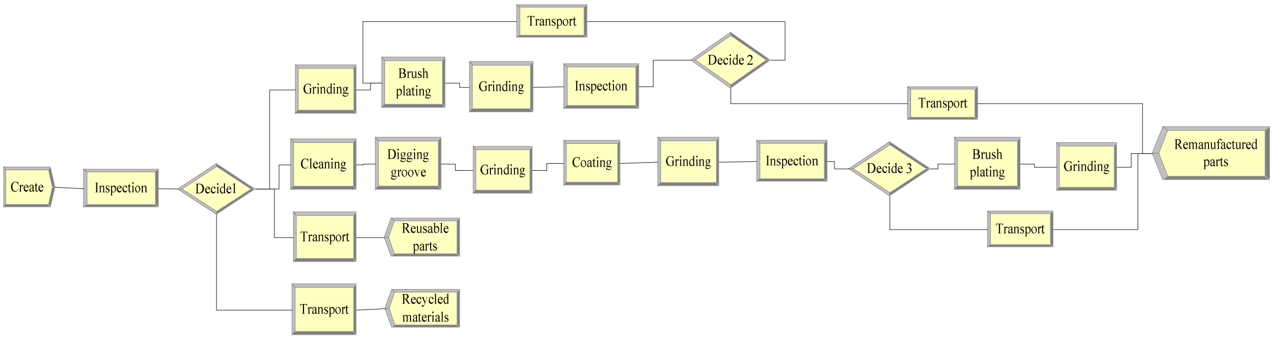


Fig. 7. Arena simulation model of lathe spindle remanufacturing

5. Calculation of Criticality Indexes in the GERT-Based RPR Model

One of the proper ways to improve the cost of a remanufacturing process is identification of the most effective activities on the cost and time of the process during remanufacturing process implementation, especially in complicate and long remanufacturing line. Herein we defined criticality indexes in GERT networks (which are more known in PERT networks). The criticality index indicates the relative variation degree of process parameter when a distinct variation degree of it or another parameter of an activity occurs in the network.

$$\mathrm{CI}_1 = \frac{\text{variation of process cost}}{\text{variation of activity cost}} \tag{1}$$

$$\mathrm{CI}_2 = \frac{\text{variation of process make−span}}{\text{variation of activity duration}} \tag{2}$$

$$\mathrm{CI}_3 = \frac{\text{variation of process cost}}{\text{variation of activity realization probability}} \tag{3}$$

$$\mathrm{CI}_4 = \frac{\text{variation of process make−span}}{\text{variation of activity realization probability}} \tag{4}$$

A mathematical method to calculating GERT networks characteristics like time of process, is applying the Moment Generation Function (MGF) of the random variable t_{ij}, associated with branch (i,j) , to convert additive t_{ij} to multiplicative t_{ij}. Theexpected time of lathe spindle remanufacturing process has calculated via this approach in equations 5 (Li et al., 2013) and with some modifications, can be used to calculatethe criticality indexes.

$$t_{0.13} = \frac{\left\{\begin{matrix} (t_{0.1} + t_{1.2} + t_{3.4} + t_{4.5} + t_{5.13})p_{1.2}p_{5.13}(1 - p_{5.2}) + \dfrac{[t_{2.3} + (t_{3.4} + t_{4.5} + t_{5.2})p_{5.2}]p_{1.2}p_{5.13}}{(1 - p_{5.2})^2} \\ +\{(t_{0.1} + t_{1.6} + t_{7.8} + t_{9.10} + t_{10.11} + t_{8.9} + t_{6.7}) \times (p_{11.13} + p_{11.12}) + (t_{11.13}p_{11.13}) \\ +(t_{12.13} + t_{11.12})p_{11.12}\}p_{1.6} \end{matrix}\right\}}{p_{0.13}} \tag{5}$$

Where:

$$p_{0.13} = \frac{p_{0.1}p_{1.2}p_{2.3}p_{3.4}p_{4.5}p_{5.13}}{1 - p_{2.3}p_{3.4}p_{4.5}p_{5.2}} + (p_{0.1}p_{1.6}p_{6.7}p_{7.8}p_{8.9}p_{9.10}p_{10.11}) \times (p_{11.13} + p_{11.12}p_{12.13}) \tag{6}$$

Proof: Appendix A.

To calculateCI_1 and CI_3, remanufacturing process cost is required. We assumed each arc i-j in GERT network has constant cost C_{ij}; then process cost can be obtained from the network structure and realization probability of it's activities. Equation 7 shows the Total Cost of remanufacturing process of lathe spindle example according to the Figure 6.

$$\begin{aligned} TC_{0.13} = {} & C_{01} + 0.3\left[C_{1.2} + (C_{2.3} + C_{3.4} + C_{4.5}) + \frac{1}{9}(C_{2.3} + C_{3.4} + C_{4.5} + C_{5.2}) + 0.9C_{5.13}\right] \\ & + 0.5[C_{1.6} + C_{67} + C_{7.8} + C_{8.9} + C_{9.10} + C_{10.11} + 0.2C_{11.12} + 0.8C_{11.13} + C_{12.13}] \end{aligned} \tag{7}$$

Proof: Appendix B.

We utilized just the remanufactured parts dispose outputs from Arena simulation model of lathe spindle system run results to calculate indexes and ignored Reusable parts and Recycled materials sections. Because they separate at the first inspection step while our purpose is, investigate the effect of cost and time derived from parts, which go through remanufacturing activities and transform to new products at the end of process. Variation extent of activity parameters (i.e. cost, time or realization probability denoted by "δ") is applied from *-50%* to *+50%* deviation from initial value (the steps long is *10%* in this extent) and each *CI*iscalculated per each deviation, then the mean of *CIs*iscalculated and represented as final activity *CI* as presented in the Table 3.Values obtained from simulation are the average of 100 replications of the Monte Carlo simulation while values of Expected value (calculated using equations (5)-(7)) are obtained by the expected values of the stochastic parameters. The gaps between the results of simulation and mathematical approaches is due to the randomness of the parameters in the simulation approach.

We can evaluate the activity parametersaffect on the remanufacturing process based on the numerical results presentedin the Table3. The calculation and simulation results arealmost the same, which confirms our proposed method.The criticality index CI_1, which shows the influence of activity cost on all process cost, is "*2.133*" for Grinding activity means that one unit increasing (reducing) in Grinding activity cost, cause 2.133 unites increasing (reducing) in remanufacturing process cost. In addition,Grinding activity$CI_1$is the biggest number between other CI_1s,which it means that Grinding activity cost has the most important rule on theremanufacturing cost.Regarding criticality index CI_2, if time of Inspection activities increase (decrease)one unit, *2.153* unit increasing (decreasing) in remanufacturing process time will be obtained. Evidently there are several Inspection activities in the process and their time distribution has straight effect on the overall process expected time. Negative *CIs* shows the contrary relation between activity and process parameters. In CI_3s, Transport activity equal to arc 5-13 has the biggest and negative amount; that one unit increasing (decreasing) in activity realization probability causes 0.909 unit decreasing (increasing) in remanufacturing process cost. From the Figure 6 we can see that increase arc 5-13 realization probability is equal to decrease arc 5-2 realization probability that is a reentrant activity and some activities must be done again following it; and more costs put to process.Transport activity (arc 5-2) has the biggest criticality index between CI_4s; so that one unit increasing (decreasing) in arc 5-2 realization probability, brings0.189 unit increasing (decreasing) in remanufacturing process make-span. As mentioned earlier arc 5-2 is a reentrant transport activity that three other activities depend on it to be done, so process time will be raised.

Table 3

Criticality indexes of lathe spindle remanufacturing activities

Activities	Conjoint nodes (for CIs related to realization probability)	Criticality Indexes							
		CI_1		CI_2		CI_3		CI_4	
		Simulation	Expected Value	Simulation	Expected Value	Simulation	Expected Value	Simulation	Expected Value
Inspection		1.320	1.333	2.428	2.153				
Grinding		2.133	2.133	1.922	2.024				
Cleaning		0.680	0.672	1.187	1.076				
Transport	5-2	0.866	0.803	1.024	0.961	0.649	0.622	0.189	0.166
	11-13					-0.362	-0.300	-0.086	-0.072
	5-13					-0.909	-0.861	-0.168	-0.144
Digging groove		0.680	0.672	0.794	0.815				
Coating		0.680	0.672	0.651	0.625				
Brush platting	11 - 12	0.453	0.433	0.486	0.508	0.184	0.204	0.0161	0.0169

After identifying the most impressive activities using criticality indexes (the ones have largest CI), we are going to understand how much deviation (increase or decrease) from parameters make maximum improvement in remanufacturing process. To this purpose, we can calculate specific criticality index of highlighted activity based on large scale of deviation of “δ” and find the best value of “δ” to optimize remanufacturing process. Drawing and analyzing the curve of calculated criticality indexes depending on “δ” for all activities help better realization of criticality of the distinguished indexes. The curvesare shown in the Figure8.

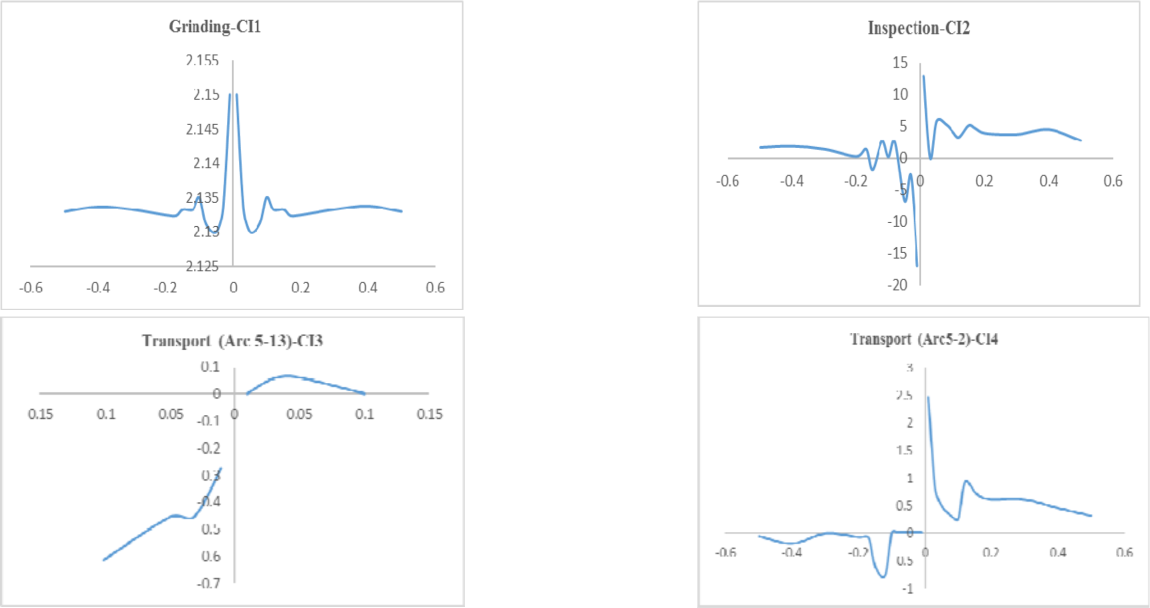


Fig. 8. The curves of criticality indexes

Based on the Figure 8, the followings can be concluded. 1) Decrease grinding activity cost about *-3%* and increase realization probability of arc *5-13*about *+5%*, cause optimized reduction in remanufacturing process cost. Moreover, decrease inspection activity duration about *-3%* and realization probability of arc *5-2* about *-12%* cause optimized reduction in remanufacturing process make-span. 2) Asmall changing in cost of Grinding activity (CI_1)

andduration of inspection activity*(CI₂),* remanufacturing process improvement can be occurred. Therefore, they are good alternatives for deviation. 3)Arc 5-2 and arc 5-13 are two ways of a decision module, which increase realization probability of one of them and cause decreasing in realization probability of the other one. In this example, +5% increase arc 5-13 and -12% decrease arc 5-12 realization probability are optimized deviationseparately; the management decisions and other various factors should be considered in this cases that which process parameter improvement is more notable, time orcost.4) There is no negative criticality index in Grinding CI_1.It means that relation between activity parameter deviation and process parameteris positivefor any value of δ.

6. Conclusions

Increasing the costs of raw materials forced the industries to use remanufacturing process. In this paper, we proposed a method for remanufacturing process cost and time improvement. The proposed method represents remanufacturing process based onGERT and analysing defined criticality indexes based on Monte-Carlo simulation and mathematical models.The similar results of simulation and mathematical models confirm our proposed method. We observed a significant improvement in cost and time of lathe spindle remanufacturing obtain by a little variation in some activities parameters. However, final decision depends on managers and different elements, but generally this method gives good directions about the process to managers and explicit the most effective operations. In the example surveyed in this paper, there are 7 types of activities: Inspection, Grinding, Cleaning, Transportation, Brush plating, Digging groove, Coating. Data about the times, costs and realization probabilities are presented in the Figure 6. Using Arena software, the GERT based remanufacturing network wasmodelled as a computer simulation model. After defining criticality indexes and running the simulationresults were obtained. We also derived the expected values of criticality indexes by using a mathematical approach. The comparison between the results of simulation and mathematical approaches justified the performance of the proposed simulation approach.Based on the results of criticality indexes, Grinding and Inspection activities were two important activities with high impact on the cost and duration of the process. Defining more criticality indexes (specially regarding important aspects of the remanufacturing processes) and evaluating and analyzing them in the remanufacturing process can be suggested as future works.In addition, analysing the different resources in the remanufacturing process (such as employees, inventories etc.) would be a future direction for interesting researchers.

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Appendixes

(A). Proof of equation (5)

The moment generation function (MGF) of the random variable t_{ij} is defined as $M_{ij}(s)$

$$M_{ij}(s) = E(e^{t_{ij}s}) = \int_{-\infty}^{+\infty} e^{t_{ij}s} f(t_{ij}) dt_{ij}$$

Where s is any real variable and $f(t_{ij})$ is the probability density function of t_{ij}.
The expected time that GERT network realized from node n to node m is:

$$t_{nm} = \frac{\partial}{\partial_s}[M_{nm}(s)]|_{s=0} =$$
$$\frac{\left\{\begin{matrix}(t_{01}+t_{12}+t_{34}+t_{45}+t_{5.13})p_{12}p_{5.13}(1-p_{52}) + \dfrac{[t_{23}+(t_{34}+t_{45}+t_{52})p_{52}]p_{12}p_{5.13}}{(1-p_{52})^2} \\ +\{(t_{01}+t_{16}+t_{78}+t_{9.10}+t_{10.11}+t_{89}+t_{67}) * (p_{11.13}+p_{11.12}) + (t_{11.13}p_{11.13}) \\ +(t_{12.13}+t11.12)p_{11.12}\}p_{16}\end{matrix}\right\}}{p_{0.13}}$$

where $p_{0.13}$ derived from MGF functions of $t_{ij}s$and Mason's rule(Agarwal et al., 2007):

$$p_{0.13} = \frac{p_{01}p_{12}p_{23}p_{34}p_{45}p_{5.13}}{1-p_{23}p_{34}p_{45}p_{52}} + (p_{01}p_{16}p_{67}p_{78}p_{89}p_{9.10}p_{10.11}) * (p_{11.13}+p_{11.12}p_{12.13})$$

(B). proof of equation (7)

Equation (7) is obtained from network paths and structure; the cores go through node 2 to node 13 path with 0.3 probability, or go through node 6 to node 13 path with 0.5 probabilityafter primary inspection, so 0.3 and 0.5 are the coefficients of 2-13 and 6-13 paths realization respectively. The 5-2 arc is reentrant with 0.1 realization probability and forms a convergent series as follow:

$$0.1(C_{2.3}+C_{3.4}+C_{4.5}+C_{5.2}) + 0.1^2(C_{2.3}+C_{3.4}+C_{4.5}+C_{5.2}) + 0.1^3(C_{2.3}+C_{3.4}+C_{4.5}+C_{5.2}) + \cdots$$
$$= \frac{0.1}{1-0.1}(C_{2.3}+C_{3.4}+C_{4.5}+C_{5.2}) = \frac{1}{9}(C_{2.3}+C_{3.4}+C_{4.5}+C_{5.2})$$

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