REAL-TIME PRODUCT RECOVERY DECISION MAKING ALGORITHM FOR SUSTAINABILITY

Kanchanasri, Passaporn (1); Moon, Seung Ki (1); Ng, Gary Ka Lai (2)
1: Nanyang Technological University, Singapore; 2: Advanced Remanufacturing and Technology Centre, Singapore

Abstract

Supporting long term benefits towards our society, a product recovery becomes a good alternative for handling End-of-Life (EOL) products. Instead of disposing all used products and producing waste, recovery options such as repair and reuse can be considered. They could be more cost-effective while saving our natural resources. A decision on product recovery option selection is necessary especially for an automated inspection. In this study, we propose a real time decision making algorithm for product recovery option selection. The proposed algorithm is focused on social and ecological impacts together with engineering and economic aspects. The objective is to develop a decision making algorithm to handle multiple conflicting criteria including natural resource consumptions, cost, and quality. The algorithm is designed to ensure that a product recovery decision is economy-effective and good for an environment and a human life in a long term. The modelling and simulation shows a potential to be implemented practically to support sustainability.

Keywords: Sustainability, Decision making, Product lifecycle management

Contact:
Passaporn Kanchanasri
Nanyang Technological University
Mechanical and Aerospace Engineering
Singapore
pass0001@e.ntu.edu.sg

1 INTRODUCTION

In a product life cycle, a product is used until its end of life. Normally, an End-of-Life (EOL) product is disposed. Once a remanufacturing, an industrial process in which a used product is restored to a like-new original product (Lund, 1984), was introduced, products have been considered to be repaired, bringing the used products to working order, instead of disposed. It gives a number of benefits to not only manufactures and customers but also our society. It could be more cost-effective (Mangun and Thurston, 2002), lower a product price, reduce waste, reduce natural resource consumptions, reduce pollutant emissions and so on.

An amount of used products is increasing while a landfill is limit. Lacking of a good management can lead to negative effects to our society. A product recovery is one way to contribute to sustainability to our society. There are various options to recover a used product, for example reuse, repair, refurbishing, remanufacturing, cannibalization, recycling with disassembly, recycling without disassembly, reconditioning, disposal, etc. A decision on a product recovery is very important. Making a proper decision can result in definite benefits to end users, an environment and also original equipment manufacturers (OEMs). OEMs have to take care of products when they are returned at the End-of-Life (Nagel et al., 1999). OEMs require a proper decision to manage their products effectively under economic constraints and uncertain product return volumes. It is a challenge to solve this problem. In order to select a proper solution for a used product, there are many decision making methods. In a case that it has a few choices, a decision tree can be used to find out a solution. A mathematical analysis can help determine a solution also. For a product recovery decision problem with complexities in an operational process, it is not easy for an inspector to handle while maintaining a standard decision. Differences of inspectors' skill and expertise could affect their decisions. It is possible that inspectors might select different recovery options based on their experiences. To make a standard, a logical and reliable decision making is essential.

An uncertainty of a product volume and a limitation of inspectors are concerning. An inspection is a labour-intensive and time-consuming task (Wassenhove, 2002). Automatic inspection becomes another solution to handle the issue. The inspection is expected to be done efficiently with a standardised quality. An automated approach for an inspection process utilizing a robot programming was introduced by Kuhlenkötter and Sdahl (2007). An automated system to inspect O-ring sealing surfaces by utilizing a laser digitizing system was presented by Keith (2001). Also there is an automated solder joint visual inspection method in the printed circuit board (PCB) assembly process (Oyeleye, 1999). Other is an automated inspection system for a manufactured part using a cloud of three-dimensional measured points and CAD models proposed by Prieto et al. (2002). Another is a method to detect form deviations of standard geometrical features (line, circle, plane, cylinder, cone, and sphere) of a manufactured part using a genetic algorithm (GA) proposed by Killmaier and Babu (2003). Benefits from an automated inspection could be perceived in previous studies especially improving a product quality and reducing a cost. Although there are many studies regarding an automated inspection, an approach for product recovery is not clearly identified.

In this regard, a real time inspection algorithm for product recovery option selection is proposed. It is developed to solve product recovery option selection problem for treating a used product at its End-of-Life. A product recovery option selection can be varied by types of users. Recycling companies, remanufacturers and OEMs have their own objectives and priorities (Kiritsis et al., 2003). The solution for each user could be different depending on the decision criteria. In this study, the algorithm considers three main criteria. One is a product quality. A product condition is assessed to ensure that the product quality is satisfying in an engineering aspect. Other is an economic aspect. The algorithm makes a decision under a cost constraint to ensure cost-effectiveness. Last but not least is an impact toward our society. Natural resource consumptions are taken into account for sustainability.

In chapter two, previous literature is reviewed. Then, in chapter three, the decision making algorithm is described in detail. An implementation is presented in chapter four. Conclusion and future work are summarized in chapter five.

2 LITERATURE REVIEW

Some research studies are related to a decision on product recovery or dispositioning, called in some literature (Fleischmann, 2001, Kulkarni et al., 2005). Thierry et al. (1995) presented an approach to recovery durable products called Product Recovery Management (PRM). Its objective was to

minimise the quantities of waste by recovering commercial and ecological values of products, components and materials. Krikke et al. (1998) introduced a two–phase algorithm using a stochastic dynamic programming for an optimal product recovery and a disposal strategy. It considered technical, economic, ecological criteria, also uncertainty aspects and quality classes including a functionality, a reliability, a remaining life time and a customer perception. Its objective was to maximise an estimated profit. Kiritsis et al. (2003) proposed a multi-criteria decision making handling several conflicting criteria which were not necessarily quantitatively defined. In addition, due to a success of evolutionary algorithm, an interest in how various constraints and objectives can be handled has rapidly increased (Fonseca and Fleming, 1998). A variety of multi-objectives evolutionary algorithms were presented. Jun et al. (2007) proposed a multi-objective evolutionary algorithm considering conflicting criteria which were cost and before/after recovery quality to solve a product recovery option selection problem. Recently, Ondemir and Gupta (2014) proposed an optimal recovery decisions approach using a linear physical programming. Table 1 shows reviewed approaches with their objectives, decision criteria, and an applied case.

Table 1. Product recovery decision making approaches, objectives, criteria and applied case

Method	Objective	Criteria	Applied case
A stochastic dynamic programming	• Maximise net profit	• Technical state • Processing properties of materials • The presence and removability of hazardous contents in assemblies • Technological status • Perception of consumers • Lost sales in primary markets • Quality requirements of secondary products and materials	TV
Multi-Criteria Decision Making	• Maximise number of employees to perform the scenario • Minimise CO_2 emissions • Minimise disassembly Cost	• Environmental indicator • Economic indicator • Social indicator • User preference	Electro-mechanical, electronic products, Telephone
Multi-objective evolutionary algorithm	• Maximise recovery value	• Cost • Quality- before and after recovery	Turbocharger
Linear physical programming	• Determine the optimum number of EOLPs to disassemble	• Demand for components and materials • Remaining useful life of the components • Recycled material demand	Sensor-embedded products (SEPs)

Each method has its advantage with specific constraints. A multi-criteria decision making can handle multiple conflicting and equally important criteria. A multi-objective evolutionary algorithm can generate all possible good alternative solutions in a single run.

Even though previous studies are related to product recovery option selection, they focus on a managerial strategy. In determining in advance what should be done with returned used products, little data is available for making a decision since the products have not yet been returned. Some factors or parameters require an estimation. This study focuses on making a decision based on the real input data and selecting a recovery option real-time to support an automated inspection. The proposed decision making algorithm for product recovery option selection is described in detail in the next section.

3 REAL-TIME DECISION MAKING ALGORITHM FOR PRODUCT RECOVERY OPTION SELECTION

This section presents the proposed decision making algorithm. First, product recovery options are specified in section 3.1. Then the algorithm is described through the designed (product) part inspection model in section 3.2. In section 3.3 decision making logic is explained in detail.

3.1 Product Recovery Options

There are various product End-of-Life options: reuse, repair, refurbishing, remanufacturing, cannibalization, recycling with disassembly, recycling without disassembly, reconditioning, disposal etc. (Thierry et al. 1995, Krikke et al.1998, Rose et al. 2002, Parlikad et al 2003, Jun et al 2007) In this study, three End-of-Life options at part level are considered as follows:

- Reuse: depending on decision criteria, a part is determined that it can be used further with no or minimal treatments such as cleaning.
- Repair: depending on decision criteria, a part is determined that it can be used after getting a treatment such as damage fixing.
- Disposal: depending on decision criteria, a part is determined that it cannot be used.

3.2 Product Part Inspection Model

Figure 1 shows the designed product part inspection model architecture. A product part is an input. A part recovery option which is reuse, repair or disposal is obtained as an output. The decision making logic is handled by four designed modules which are Part Inspection Module, Data Recorder Module, Data Analyser Module and Decision Maker Module.

Figure 1. Product Part Inspection Model Architecture

Table 2 shows a summary of decision making modules including theirs roles and data. An arriving product part is inspected at Part Inspection Module. This module checks a part condition. In this study, a crack length and a crack position are considered. Data from an inspection are then saved at Data Recorder Module for further analysing at Data Analyser Module. At Data analyser Module, data is analysed. Information and knowledge are retrieved and used to make a decision at Decision Maker Module. Decision rules are defined considering natural resource consumptions, quality and repair cost in qualitative manner.

Table 2. Summary of decision making modules

Module	Role	Data
Part Inspection Module	• Get part data • Check part damage	• Part Serial Number • Crack
Data Recorder Module	• Record part data	• Crack Length • Crack Position •
Data Analyser Module	• Adjust inspection instruction • Build part quality function • Evaluate part quality • Evaluate natural resource consumption • Evaluate repair cost	• Part section checked order • Part quality • Natural resource consumption • Repair cost
Decision Maker Module	• Define rules • Determine recovery options	• Part recovery option

3.3 Decision Making Logic

3.3.1 Assumptions

In this study, the following assumptions are considered.

- The decision is made by considering a part quality, natural resource consumptions and repair cost respectively.
- A good quality part has less damage than a bad quality part. A before-quality and after-quality of a part can be calculated by the part damage with a negative correlation relation.
- A repair cost of an End-of-Life part is not greater than a cost of an equivalent new manufactured product.
- If a part has a little damage, its repair cost is low. On the other hand if a part has a huge damage, its repair cost is high. Repair cost can be calculated by the part damage with a positive correlation relation.

3.3.2 Part recovery option selection definition

Part recovery option selection function is defined with constraints below.
Notations:

i Part index (1,2,..n)
j End-of-Life option index (1 for dispose, 2 for reuse, 3 for repair)
x_{ij} Boolean variable of part index i for the End-of-Life option j
q_{ij} Part quality of part index i for the End-of-Life option j
q^b_{ij} Part quality before recovery of part index i for the End-of-Life option j
q^{ll} Lower limit of part quality
q^{ll}_{ij} Lower limit quality of part index i for the End-of-Life option j
l_{ij} Natural resource consumption of part index i for the End-of-Life option j
l^{ul} Upper limit of natural resource consumption
c_{ij} Cost of part index I for the End-of-Life option j
c^{ul} Upper limit cost
$\bar{x}$ Decision variable
$Q(\bar{x})$ Part quality function
$L(\bar{x})$ Natural resource consumption function
$C(\bar{x})$ Cost function
$F(\bar{x})$ Decision function

$$F(\bar{x}) = [Q(\bar{x}), L(\bar{x}), C(\bar{x})] \ where \ \bar{x} = [x_{ij}] \tag{1}$$

$$Q(\bar{x}) = \sum_{i=1}^{i=n} \sum_{j=1}^{j=3} q_{ij} * x_{ij} \tag{2}$$

$$L(\bar{x}) = \sum_{i=1}^{i=n} \sum_{j=1}^{j=3} l_{ij} * x_{ij} \tag{3}$$

$$C(\bar{x}) = \sum_{i=1}^{i=n} \sum_{j=1}^{j=3} c_{ij} * x_{ij} \tag{4}$$

$$\sum_{j=1}^{j=3} x_{ij} = 1 \ for \ all \ i \tag{5}$$

$$q^b_{i1} * x_{i1} < q^{ll}_{i1} \ for \ all \ i \tag{6}$$

$$q^b_{i2} > q^{ll}_{i2} * x_{i2} \ for \ all \ i \tag{7}$$

$$l_{i3} * x_{i3} \le l^{ul} \tag{8}$$

$$c_{i3} * x_{i3} \le c^{ul} \tag{9}$$

$$x_{ij} \in \{0|1\} \ for \ all \ i, j$$

$$0 \le Q(\bar{x}), q^b_{ij}, q_{ij}, q^{ll}_{ij}, q^{ll} \le 1 \ for \ all \ i, j$$

$$C(\bar{x}), c^{ul} \ge 0$$

A decision function is formulated as Equation (1). A part recovery option is selected based on a quality (Equation (2)), natural resource consumptions (Equation (3)) and cost (Equation (4)). Constraints (5)-(9) determine a solution space. Constraint (5) indicates that for each part only one End-of-Life option can be selected. Constraint (6) indicates that any parts that have their qualities above the defined quality limit are not considered to be disposed. Constraint (7) indicates that any parts that have their qualities below the defined quality limit are not considered to be reused. Any parts which their qualities are worse than the configured lower limit quality are considered to be disposed. Any parts which their qualities are better than the configured upper limit quality are considered to be reused. Any parts which their qualities fall within the range programmed by configuration machine are considered to be repaired. It is not only a quality considered in the model, but also natural resource consumptions. The model checks an amount of natural resource consumptions of each part. If it is not over the defined acceptable threshold, the part is considered to be repaired. Constraint (8) indicates that a case that natural resource consumptions are greater than the limit is not rejected to be repaired. A cost is another criterion to be considered. The part recovery option will be recommended real-time with the defined cost constraint. Constraint (9) indicates that a repair cost is controlled not to be over the defined cost limit. Once the configured criteria are all checked, a part is recommended to be one of three recovery options which are reuse, repair or dispose.

4   IMPLEMENTATION AND RESULT

The proposed decision making algorithm is demonstrated through the modelling. Figure 2 shows the model diagram. It was verified and validated by five part inspection scenarios. Figures 3-7 show the experimental results. The simulation results demonstrate that the decision model is able to select a product recovery option for each part.

1. Case: all parts qualities are worse than the configured lower limit quality, an inter-arrival time is one minutes, one part per arrival
    o   Expected: parts are not recommenced to be repaired and reused
    o   Result: Dispose 91, Repair 0, Reuse 0
2. Case: all part qualities are better than the configured upper limit quality, an inter-arrival time is one minutes, one part per arrival
    o   Expected: parts are recommended to be disposed and repaired
    o   Result: Dispose 0, Repair 0, Reuse 91
3. Case: some parts qualities are worse than the configured lower limit quality, an inter-arrival time is two minutes, some part qualities are better than the configured upper limit quality, an inter-arrival time is one minutes and some part qualities are within the accepted repair range, an inter-arrival time is three minutes, one part per arrival
    o   Expected: a number of parts recommenced to be reused is higher than disposed and repaired respectively
    o   Result: Dispose 16, Repair 10, Reuse 30
4. Case: some parts qualities are worse than the configured lower limit quality, an inter-arrival time is three minutes, some part qualities are better than the configured upper limit quality, an inter-arrival time is two minutes and some part qualities are within the accepted repair range, an inter-arrival time is one minutes, one part per arrival
    o   Expected: a number of parts recommenced to be repaired is higher than reused and disposed respectively
    o   Result: Dispose 11, Repair 30, Reuse 15
5. Case: some parts qualities are worse than the configured lower limit quality, an inter-arrival time is one minutes, some part qualities are better than the configured upper limit quality, an inter-arrival time is three minutes and some part qualities are within the accepted repair range, an inter-arrival time is two minutes, one part per arrival
    o   Expected: a number of parts recommenced to be disposed is higher than repaired and reused respectively
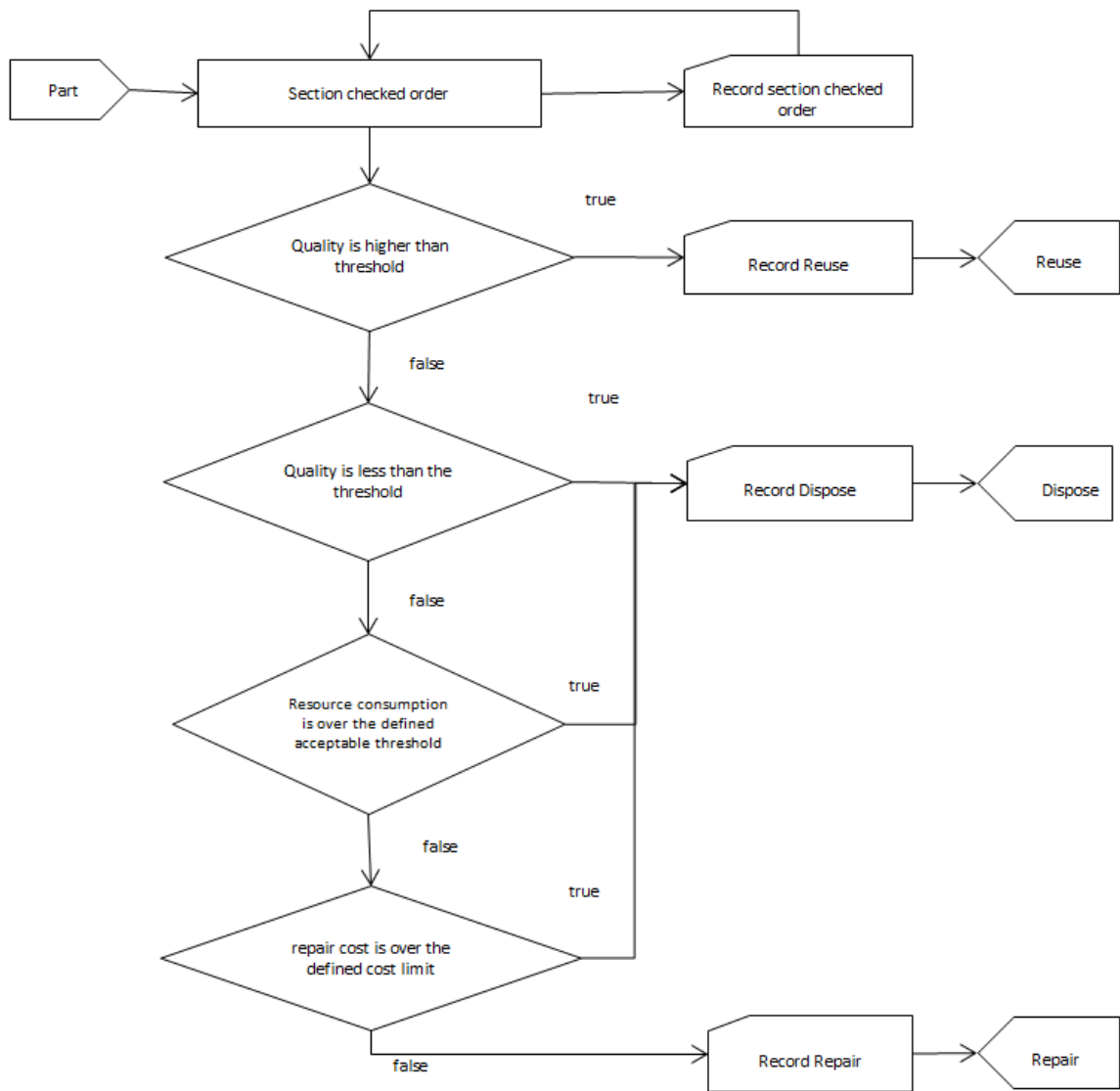   o   Result: Dispose 31, Repair 15, Reuse 10

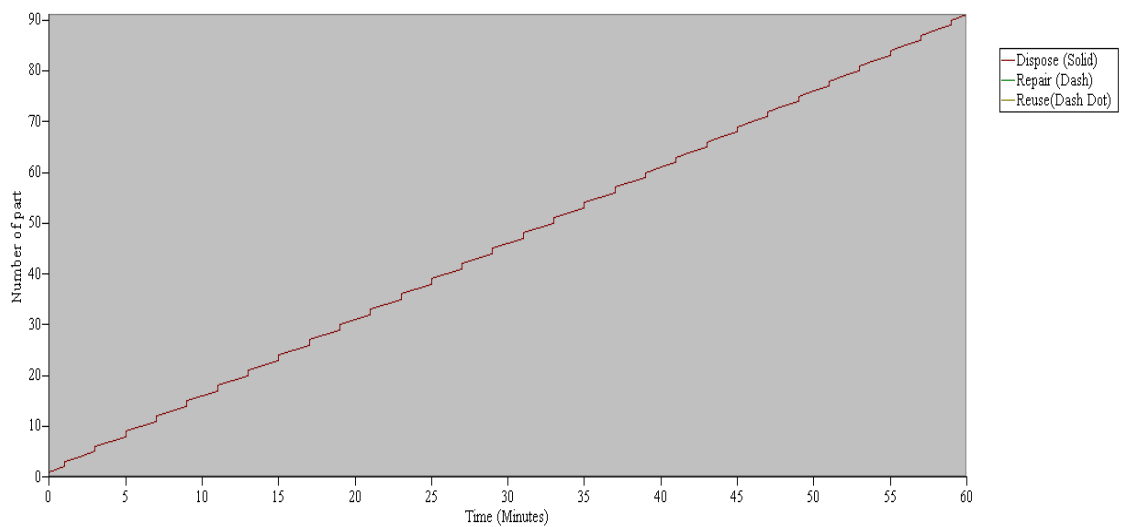*Figure 2. Decision Making algorithm modelling diagram*

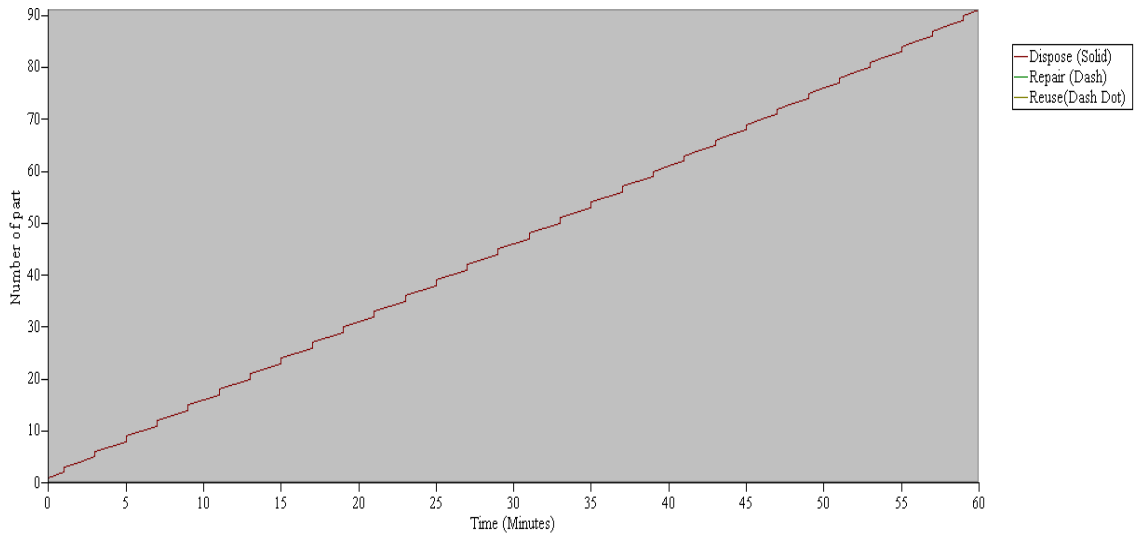*Figure 3. Simulated experimentation result for the Case 1*

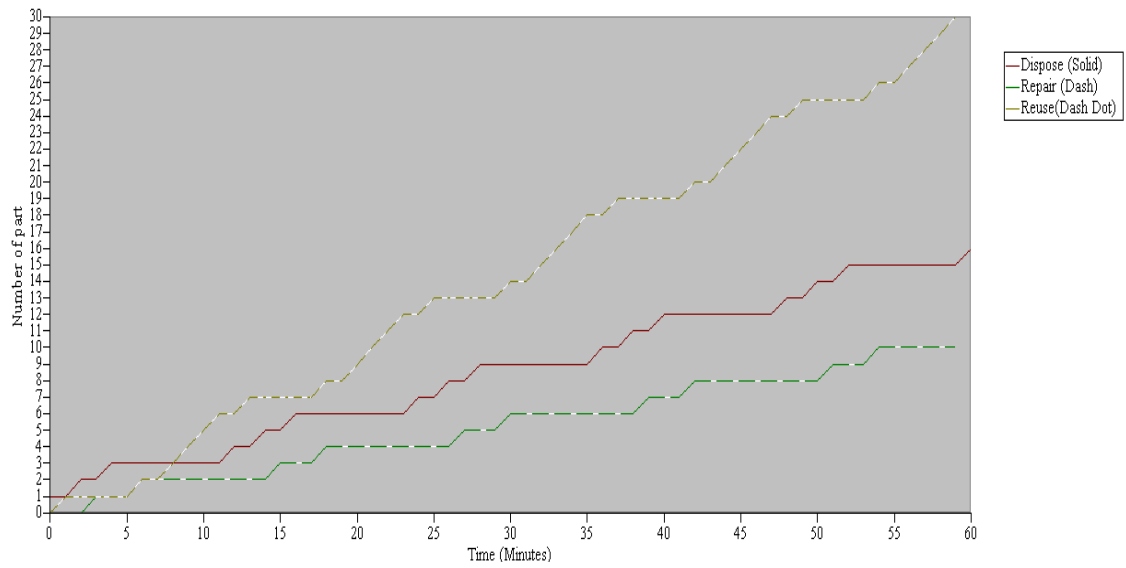*Figure 4. Simulated experimentation result for the Case 2*

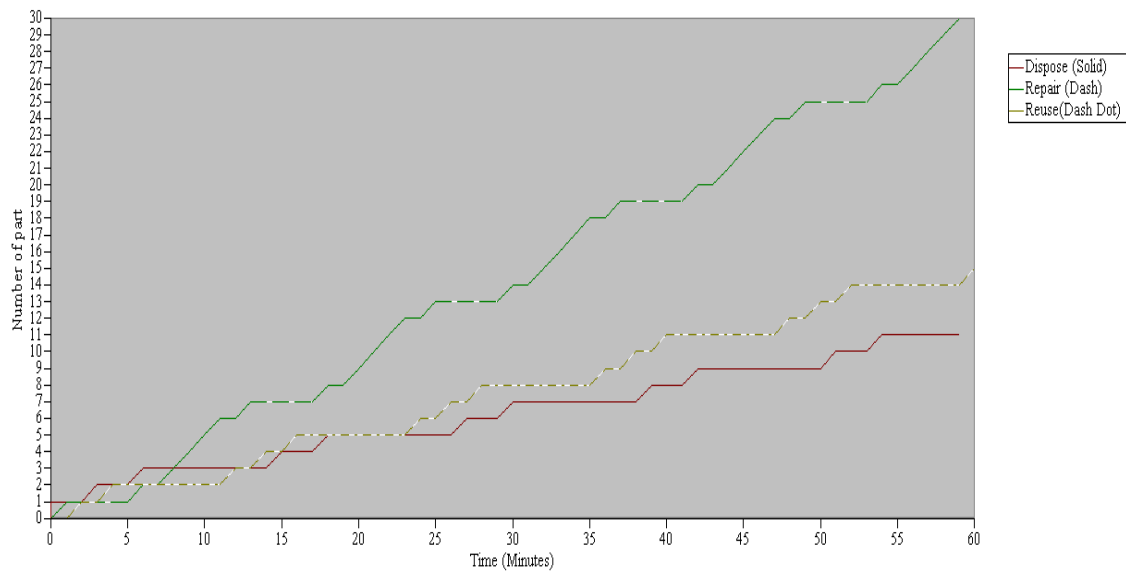*Figure 5. Simulated experimentation result for the Case 3*

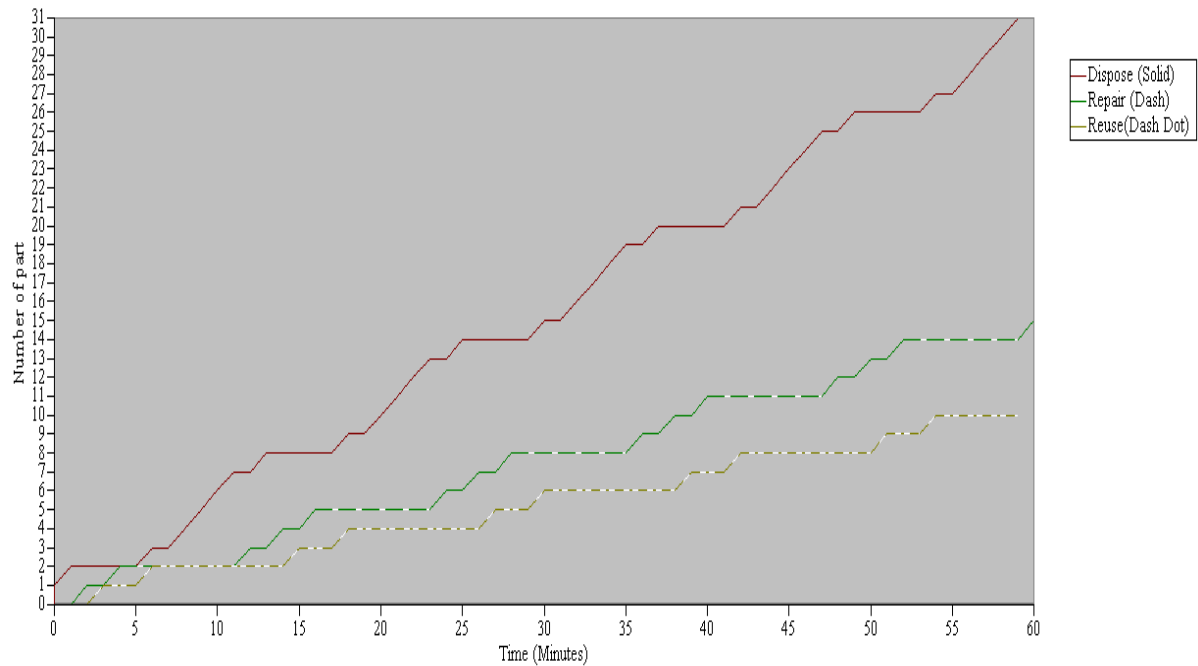*Figure 6. Simulated experimentation result for the Case 4*

Figure 7. Simulated experimentation result for the Case 5

5 CONCLUSION AND FUTURE WORK

The proposed decision making algorithm can handle part recovery option selection problems for a part inspection. It can handle multiple criteria i.e. cost, quality and natural resource consumptions. The proposed decision making algorithm is also able to adjust its logic based on the input data for further improvement in making a decision. A product recovery option selection is provided once the product is inspected. The model gives the same results as the expected inspection results. Since it is an automatic decision making, it provide the same standard decision without human bias. With the ability to learn an inspection pattern, the model can adjust its logic real-time in order to improve inspection performance. An inspection can be controllable and configurable. A multiple criteria decision problem could be solved by the model. The model results show a potential to support the automated inspection. The proposed decision making model was designed as a flow of an inspection process, not only decision making, an inspection time and a bottleneck were observed and analysed to be a guideline for automated inspection for remanufacturing. Currently the model can adjust its logic about finding a part damage occurrence pattern. Other techniques will be considered and more features will be added to enhance its capability. The data and information recorded during a process will be analysed to be made use of further. Lastly, an interface for a configuration setting will be designed and developed to provide a user friendly controlling.

ACKNOWLEDGEMENTS

REFERENCES

FLEISCHMANN, M. 2001. Reverse Logistics at IBM: An Illustrative Case. *Quantitative Models for Reverse Logistics.* Springer Berlin Heidelberg.

FONSECA, C. M. & FLEMING, P. J. 1998. Multiobjective optimization and multiple constraint handling with evolutionary algorithms. I. A unified formulation. *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on,* 28**,** 26-37.

JUN, H. B., CUSIN, M., KIRITSIS, D. & XIROUCHAKIS, P. 2007. A multi-objective evolutionary algorithm for EOL product recovery optimization: turbocharger case study. *International Journal of Production Research,* 45**,** 4573-4594.

KEITH, O. D. 2001. Automated inspection of the RSRM case O-ring seal surface. *37th Joint Propulsion Conference and Exhibit.* American Institute of Aeronautics and Astronautics.

KILLMAIER, T. & BABU, A. R. 2003. *Genetic approach for automatic detection of form deviations of geometrical features for effective measurement strategy.*

KIRITSIS, D., BUFARDI, A. & XIROUCHAKIS, P. Multi-criteria decision aid for product end of life options selection. Electronics and the Environment, 2003. IEEE International Symposium on, 19-22 May 2003 2003. 48-53.

KRIKKE, H. R., HARTEN, A. V. & SCHUUR, P. C. 1998. On a medium term product recovery and disposal strategy for durable assembly products. *International Journal of Production Research,* 36**,** 111-140.

KUHLENKÖTTER, B. & SDAHL, M. 2007. Automated inspection system for headlamp reflectors. *International Journal of Advanced Manufacturing Technology,* 32**,** 500-504.

KULKARNI, A. G., PARLIKAD, A. K. N., MCFARLANE, D. C. & HARRISON, M. Networked RFID systems in product recovery management. Electronics and the Environment, 2005. Proceedings of the 2005 IEEE International Symposium on, 16-19 May 2005 2005. 66-71.

LUND, R. T. 1984. Remanufacturing. *Technology review,* 87**,** 19-23, 28-29.

MANGUN, D. & THURSTON, D. J. 2002. Incorporating component reuse, remanufacture, and recycle into product portfolio design. *Engineering Management, IEEE Transactions on,* 49**,** 479-490.

NAGEL, C., #246, NILSSON, R. & BOKS, C. 1999. European end-of-life systems for electrical and electronic equipment. *Proceedings of the First international conference on Environmentally conscious design and inverse manufacturing.* Tokyo, Japan: IEEE Computer Society.

ONDEMIR, O. & GUPTA, S. M. 2014. A multi-criteria decision making model for advanced repair-to-order and disassembly-to-order system. *European Journal of Operational Research,* 233**,** 408-419.

OYELEYE, O. 1999. Automatic visual inspection of surface mount solder joint defects. *International Journal of Production Research,* 37**,** 1217-1242.

PRIETO, F., REDARCE, T., LEPAGE, R. & BOULANGER, P. 2002. An Automated Inspection System. *The International Journal of Advanced Manufacturing Technology,* 19**,** 917-925.

THIERRY, M., SALOMON, M., VAN NUNEN, J. & VAN WASSENHOVE, L. 1995. Strategic Issues in Product Recovery Management. *California Management Review,* 37**,** 114-135.

WASSENHOVE, V. D. R. G. J. A. L. N. V. 2002. The Reverse Supply Chain. *Harvard Business Review.*