A HYBRID META-HEURISTIC APPROACH FOR BUFFER ALLOCATION IN REMANUFACTURING ENVIRONMENT

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Dedicated to:

My great parents

for their incredible unconditional encouragement and support.

My beloved wife, Leyla

for her grace and her perfect provision

My Son, Ali

who is blessing from Almighty ALLAH

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ABSTRACT

Remanufacturing system is complicated due to its stochastic nature. Random customer demand, return product rate and system unreliability contribute to this complexity. Remanufacturing systems with unreliable machines usually contain intermediate buffers which are used to decouple the machines, thereby, reducing mutual interference due to machine breakdowns. Intermediate buffers should be optimized to eliminate waste of resources and avoid loss of throughput. The Buffer Allocation Problem (BAP) deals with allocating optimally fixed amount of available buffers to workstations located in manufacturing or remanufacturing systems to achieve specific objectives. Optimal buffer allocation in manufacturing and remanufacturing systems not only minimizes holding cost and stock space, but also makes facilities planning and remanufacturing decisions to be effectively coordinated. BAP in a non-deterministic environment is certainly one of the most difficult optimization problems. Therefore, a mathematical framework is provided to model the dependence of throughput on buffer capacities. Obviously, based on the survey undertaken, not only there exists no algebraic relation between the objective function and buffer size but the current literature does not offer analytical results for buffer capacity design in remanufacturing environment. Decomposition principle, expansion method for evaluating system performance and an efficient hybrid Meta-heuristic search algorithm are implemented to find an optimal buffer allocation for remanufacturing system. The proposed hybrid Simulated Annealing (SA) with Genetic Algorithm (GA) is compared to pure SA and GA. The computational experiments show better quality, more accurate, efficient and reliable solutions obtained by the proposed hybrid algorithm. The improvement obtained is more than 4.18 %. Finally, the proposed method is applied on toner cartridge remanufacturing company as a case study, and the numerical results from hybrid algorithm are presented and compared with results from SA and GA.

ABSTRAK

Sistem pembuatan semula adalah rumit kerana sifat stokastiknya. Permintaan pelanggan yang rawak, kadar pulangan produk dan sistem tidak boleh diharapkan menyumbang kepada kerumitan ini. Sistem pembuatan semula dengan mesin-mesin yang tidak boleh diharapkan biasanya mempunyai penimbal pengantaraan yang digunakan untuk memisahkan mesin, dengan itu, mengurangkan gangguan akibat dari kerosakan mesin. Penimbal pengantaraan harus dioptimumkan untuk menghapuskan pembaziran sumber dan mengelakkan kehilangan daya pemprosesan. Masalah pengagihan penimbal (*Buffer Allocation Problem* - BAP) melibatkan pengagihan secara optimal satu bilangan penimbal yang tetap yang sedia ada kepada stesen kerja yang terdapat dalam sistem pembuatan atau pembuatan semula untuk mencapai objektif yang khusus. Pengagihan penimbal yang optimal dalam sistem pembuatan dan pembuatan semula bukan sahaja dapat mengurangkan kos penyimpanan dan ruang stok, tetapi juga membolehkan keputusan perancangan kemudahan dan pembuatan semula diselaraskan dengan berkesan. BAP dalam persekitaran yang tidak berketentuan sudah tentu merupakan salah satu masalah pengoptimuman yang paling sukar. Oleh itu, satu rangka kerja matematik disediakan untuk memodel pergantungan daya pemprosesan pada kapasiti penimbal. Jelas sekali, berdasarkan kajian yang dijalankan, bukan sahaja hubungan algebra antara fungsi objektif dan saiz penimbal tiada tetapi literatur semasa tidak menawarkan keputusan analisis untuk reka bentuk muatan penimbal dalam persekitaran pembuatan semula. Prinsip penguraian, kaedah pengembangan untuk menilai prestasi sistem dan suatu algoritma carian Meta-heuristik hibrid yang cekap telah dilaksanakan untuk mencari pengagihan penimbal yang optimal bagi sistem pembuatan semula. Penyepuhlindapan simulasi (*Simulated Annealing* - SA) dengan algoritma genetik (*Genetic Algorithm* - GA) hibrid yang dicadangkan telah dibandingkan dengan SA dan GA tulen. Ujikaji pengiraan menunjukkan penyelesaian yang lebih berkualiti, lebih tepat, cekap dan dipercayai telah diperolehi menggunakan algoritma hibrid yang dicadangkan. Penambahbaikan yang diperolehi adalah melebihi 4.18 %. Akhir sekali, kaedah yang dicadangkan ini telah diaplikasikan pada syarikat pembuatan semula *toner cartridge* sebagai kajian kes, dan keputusan berangka dari algoritma hibrid telah diberi dan dibandingkan dengan keputusan daripada SA dan GA.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AI - Artificial intelligence
ANN - Artificial neural network
ACO - Ant colony optimization
ADDX - Accelerated Dallery-David-Xie algorithm
ATO - Assemble-to-Order
BAP - Buffer allocation problem
BAS - Blocking after service
BBS - Blocking before service
DDX - Dallery-David-Xie algorithm
DP - Dynamic programming
FMS - Flexible manufacturing system
GA - Genetic algorithm
GEM - Generalized expansion method
IDA - Immune decomposition algorithm
JIT - Just in time
LB - Level of buffering
MAP - Markovian arrival process
MOGA - Multi-objective genetic algorithm
MTO - Make-to-Order
MTS - Make-to-Stock
NT - Nested partitions
OEM - Original equipment manufacturer
OQN - Open queueing network
PC - Personal computers
SA - Simulated annealing
TH - Throughput
WIP - Work in process

WS - Workstation

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

Chapter one provides an explanation on the background of the current research with an emphasis on work-in-process (WIP) management, buffer designing for remanufacturing systems and its performance measurements. Thereafter, the problem statement is introduced to readers which is modelled and formulated as the basis of the current study. Then, research significance, scope, questions and objectives are presented. Finally, the thesis contributions and organization of thesis are presented.

1.2 Background of the Study

For over two centuries after the industrial revolution, living standards have improved by mass production, which reduces production cost significantly. However, mass production has used limited natural resources and also has been destructive to environment. These days, the environmental concern has been one of the major issues which has influenced the manufacturing industry as well. Currently, companies are increasingly implementing environmental practices not only for complying to governmental regulations, but also to obtain substantial economic benefits. One way to achieve these goals is to reuse the returned used products by remanufacturing which has been more considered by manufacturing companies, recently. Remanufacturing is a process of repairing end of life products and restoring them to a good conditions (Fleischmann, Bloemhof-Ruwaard *et al.* 1997, Bernard 2011). By means of remanufacturing, most of the used products can be return to a condition like new with warranty to match, which not only reduces environmental pollution but reduces energy consumption and professional labouring in production (Liu, Zhang *et al.* 2014). Using remanufacturing of an engine as an example, it saves 288.725kg of solid waste, 113kw of electric power, 8.3kg of aluminium, 55kg of steel, reduces of 565kg CO2, 3.985kg SOx, 1.01kg NOx, and 6.09kg CO (Li, Tang *et al.* 2013). Despite the fact that most remanufacturing activity can result in valuable and effective environmental influences, customers typically do not have any incentive and are not able to be engaged in the actual remanufacturing attempts by suppliers or even third parties.

The only reason for organizations to remanufacture returned products is not the economical push, but rather the enforcement of environmental regulations. Remanufacturing potential benefit is encouraging the research into how to design an effective remanufacturing system to maximize its performance. Also, in any manufacturing or remanufacturing industry, the aim is to satisfy customer demand on time while keeping production costs low. Therefore, manufacturers and remanufacturers take production planning, inventory control management and all other control policies into consideration more than before. Due to optimal control policy is not yet known for such a general situation, inventory management of such systems is much more of a concerned and difficult because besides the inventories for the end items, there are additional intermediate inventories for returned items (work in process) which have to be considered.

Inventory management in remanufacturing industry is also more challenging than in the manufacturing industry for two primary reasons. First, the levels of uncertainty faced by remanufacturing inventory planners are significantly higher. Specifically, supply and demand uncertainties are much more problematic in remanufacturing due to the uncertain nature of the product failures that drive core supply and end-item demand. The second major problem with regard to remanufacturing inventory planning is the structure of the inventory decision itself. If a company carries a large amount of buffers in between machines, then the cost of holding buffers (inventory holding cost) increases. But by having a large amount of buffers at certain locations in a remanufacturing system increases the throughput of the system. Instead, if a remanufacturing company has small buffers in a system it may reduce the throughput since machines are subjected to breakdowns and may lead to stock outs. Most companies are not willing to reduce their buffers at the cost of reducing their throughput. There is a need for striking a balance between the amount of inventory held between machines and the throughput of the remanufacturing line.

The allocating of buffers, which is the sizing of buffer stocks and identification of their location, is a very significant issue in manufacturing design and remanufacturing systems. Buffers between workstations in such system improve the system performance by reducing the effects of stochastic interference due to machine failures or variability in processing times (Harris and Powell 1999). In other words, adding buffers provide each part of a manufacturing or remanufacturing system with independent action when the workstations in the system are not synchronized, which increases long-run throughput.

The purpose of the current study is to develop an efficient algorithm that determines the appropriate buffer capacity configuration throughout the workstations within remanufacturing system in order to maximize its performance. Although extensive research has been performed on the buffer allocation problem, it is still an open research area because of several unique characteristics.

1.3 Statement of Problem

Nowadays, besides increased quality of production, companies gain competitive advantages having short cycle times in manufacturing and remanufacturing process. Due to the repetitive nature of production lines, a small increase in efficiency can result in substantial savings. This fact has made the improvement of production line efficiency the focal point of considerable research activities over the last few decades. Appropriate scheduling systems which cause short cycle times require minimal inventories. Many of scheduling strategies have been developed that seek to achieve minimal inventories. However, most of them could not achieve these objectives efficiently due to their inability to clearly realize how much buffer (inventory space) and where they should be allocated.

Obviously, not only zero inventories are inefficient but inventories also are needed in manufacturing or remanufacturing systems. However, the exact total inventory quantities, their sizes (WIP) inventories and locations are difficult to determine, since the effect of statistical fluctuations is impossible to be forecasted. Many real-world manufacturing and remanufacturing systems are facing high level inventory problems. However, there exist trade-off between setting inventory in high level, low level and zero inventories. On the one hand, low inventory levels reduce line performance due to starve workstations. On the other hand, in the manufacturing and remanufacturing systems, high work in process inventory levels cause long cycle time, which is a threat to the competitive advantage of a company.

Obviously, someone can increase the buffer capacities and thereby reduce interactions between the workstations. Because reducing interactions between the workstations makes the workstations more independent of each other to increase the throughput. Moreover, increasing the buffer capacities arbitrarily is not feasible in practice due to financial and spatial limitations. Therefore, finding buffer capacities that maximizes the performance of the system and at the same time it does not violate the financial/spatial constraints, in the study of manufacturing and specifically remanufacturing systems, is still an open question. The aim of current study is to provide a formulation (mathematical model) and also a methodology to maximize the performance of unreliable and non-balanced remanufacturing systems.

The buffer allocation problem can be characterized as a linearly constrained integer nonlinear programming problem. Its objective is to maximize system efficiency as measured by the throughput by optimally allocating a finite number of buffers between the stations. Formally the model can be expressed as follows:

$$\begin{aligned}&\textit{Maximize } TH(B)\\&\textit{Subject to}\\&\sum_{i=1}^{k} B_i = N\\&B = (B_1, B_2, \ldots, B_k)\\&B_i : \textit{non negative integers}, (i = 1,2,\ldots,k)\\&N : \textit{fixed nonnegative integer}\end{aligned}$$

Where the total available buffer *(N)* should be allocated among the *k*-buffer located between workstations so as to maximize the throughput rate of the system. In this formulation, *TH(B)* represents the system throughput rate which is a function of the buffers' size.

The possible number of configurations for allocating N available buffers between k-workstations can be demonstrated as follows.

$$\binom{N+i-1}{N} = \frac{(N+i-1)!}{N! * (i-1)!} \tag{1.1}$$

As an example, 20-machine line with 20 buffers and 200 total available buffers has over $1.2 * 10^{17}$states. This state space is too large to be considered, but the approximate decomposition technique and Meta-heuristic algorithm only require minutes of processing on a personal computer.

Most of the related previous works considered some assumptions which are not applicable to real cases. For instance, processing times and (or) time between failures (failure rates) have been considered deterministic in many researches (Sabuncuoglu, Erel *et al.* 2006, Manitz 2008, Alexandros and Chrissoleon 2009, Vergara and Kim 2009). However, this study is going to consider a remanufacturing system with unreliable workstations and non-balanced system in which the return products is following the Poisson distribution, and service, failure and repair rates are following the exponential distribution.

1.4 Objectives of the Research

Although optimal throughput of system can be achieved by placing large number of units of *WIP* inventory (buffers) in manufacturing or remanufacturing systems, large amount of buffers is undesirable. This is because, it will increase inventory investment, manufacturing or remanufacturing lead-times (customer waiting times) and therefore manufacturing and remanufacturing total cost. The main question in the current study is: how much buffer should be employed in a remanufacturing system? The main objective also is to develop a method (easily programmable) that can identify an optimal or near optimal buffer allocation that maximizes throughput very quickly and efficiently. Specifically, the objectives are the following:

1. To model an evaluative approach to measure performance of remanufacturing system efficiently.

2. To develop a hybrid Meta-heuristic algorithm for buffer capacity planning in remanufacturing facilities.

3. To evaluate the hybrid Meta-heuristic algorithm developed for remanufacturing system with unreliable and non-balanced workstations.

1.5 Research Scope

The scope of this research is limited to modelling a remanufacturing system and developing an evaluative and generative method to solve buffer allocation problem. The solution methodology includes decomposed expansion technique for calculating the system performance (as an evaluative method) and developed Meta-heuristic search algorithms (as generative methods) to optimize the buffer allocation in a serial-parallel remanufacturing system. According to Lee and Ho (2002), optimizing buffer allocation decouples the non-balance of processing time and breakdown time of machines and results in improved flow. This research considers unreliable and non-balanced workstation in remanufacturing system. To illustrate proof-of-concept, a testing methodology is also developed and the following are constrains of the current study:

i. Buffer capacity of each workstation is finite.

ii. Total available number of buffers is fixed.

iii. Each workstation is considered as queuing system.

iv. Processing time (service rate) for workstations is not equal.

v. Failure rate for each workstation is considered.

vi. The proposed solution methodology considers throughput of the remanufacturing system.

1.6 Significance of the Research

Remanufacturing offers organizations saving in costing by means of decreases in utilization of common assets. Decreasing so as to remanufacturing can be additionally useful to environment landfill wastes and reusing them as of now consumed in the first assembling of the items. Other than the natural advantages, remanufacturing likewise gives financial selling so as to motivate forces to firms the remanufactured items and augmenting the life cycles of utilized items. It also would permit producers to react to ecological and administrative weight by investing them to meet waste acting; having high efficiency, lower-cost items with less landfilling and utilization of crude materials.

The performance optimization in remanufacturing industry is the most significant issue due to uncertainties and complexities. According to the statement by Gupta (2005) there are two types of uncertainties in remanufacturing systems. Internal uncertainties include the yield rate of the process, the quality level of the product, the remanufacturing lead-time, and the possibility of station failure. The returned products' quality and quantity, the demand rate and the lead-times of new parts are as external uncertainties in remanufacturing industry.

These uncertainties cause remanufacturing planning to be faced by some problems such as undersupplying the finished good and work in process inventories and losing the competitive advantages of the market. Although there have been effective procedures to reduce the uncertainties' effects such as increasing the buffer size between the workstations, in reality, real life and physical constraints should be considered. As an example, work in process inventory and processing time are increased if the buffer size increases however, it will cause lead-time and costs of remanufacturing to be increased. Therefore, the most important issue in the current research is to consider above mentioned trade-off between buffer size and throughput of the remanufacturing system.

Making progress toward ideal performance of remanufacturing systems is of incredible importance because of the previously stated complexities and uncertainties. One can simply diminish the impact of complexities on the framework's execution by expanding the quantity of buffers at the workstations that shows these lacks. On the other hand physical requirements and numerous other genuine circumstances force a maximum level on the quantity of buffer sizes that can be suited in the remanufacturing systems. For instance, as the quantity of buffers is increased, the average time for processing and inventory level for work in process similarly should be increased which specifically influences the system performance and productivity.

Obviously, the average time for processing, work in process inventory level and mainly the throughput rate are common performance measures in manufacturing systems, for the remanufacturing systems, throughput rate is more significant here due to the false recognition that the remanufacturing is more hard to be financially justified. In this way, one of the basic issues is to distribute a given number of buffers remanufacturing workstations to maximize the system throughput rate. As above-mentioned, returned products’ uncertainties and complexities, in remanufacturing systems, lead to diverse routings. Therefore, the desired condition is to determine optimal buffer allocation that maximizes the throughput of the system with a constraint on the total available buffer sizes. Nowadays, companies faced difficulties for achieving the desired conditions:

- *Complicated combinatorial optimization problem*

  The buffer allocation problem is a difficult combinatorial optimization. Finding practicable solutions for this problem is huge and it is not mathematical to test all the practicable solutions considering the lead-time limitations. Thence efficacious search methods should be considered to solve the buffer allocation problems in manufacturing and remanufacturing systems.

- *Extremely difficult to identify optimal solution for large sized problems*

  According to Sabuncuoglu, Erel *et al.* (2006), the buffer allocation problem is far from to be accomplished. Most buffer allocation problems have been studied in small sized systems and as the problem size increases, it becomes more difficult to find the best allocation of buffer sizes.

- *Lack of unique solution*

According to Demir, Tunali *et al.* (2012), various assumptions were considered for buffer allocation problems and hence no unique solution was proposed. Considering the complexity of the problem, there is no known formula for buffer size and performance measures in the considered buffer allocation problems.

As a successful example, remanufacturing of capital goods has provided the greatest opportunities for businesses. The following comprehensive study shows the impact of remanufacturing industry on the economy. The study has been done by Lund (1996) which is summarised in Table 1.1.

Table 1.1: Remanufacturing activity in the US, Lund (1996)

Size and Scope	Annual industry sales	$53 billion	
	Number of firms	73,000	
	Direct employment	480,000	
	Average company employment	24	
	Average annual company sales	$2.9 million	
	Number of product	More than 46 categories	
Relative size	Industry sector	Employment	Shipment Value
	Remanufacturing	480,000	$53 billion
	Steel mill products	241,000	$56 billion
	Household consumer durables	495,000	$51 billion
	Pharmaceuticals	194,000	$68 billion
	Computers and peripherals	200,000	$56 billion

The following are the most often-cited reasons why companies consider remanufacturing (Teunter, van der Laan *et al.* 2000) from the sustainability point of view:

i. Economic reasons

To reduce consumption of raw materials and disposal costs by means of recovering the used products.

ii. Social reasons

Society demands companies to behave more respectfully and be aware of environmental threats, especially threats like emissions and the generation of waste.

iii. Legal reasons

In many countries such as members of the European Union, companies' responsibilities are held by legislation to recover or dispose the used products which they put on the market.

1.7 Research Contributions

This research opens a new perspective in intermediate inventory management for a remanufacturing system. It will also recommend companies considering buffer allocation problem to enhance their performance by maximizing the throughput. Based on the review of previous literature, researchers have rarely considered buffer allocation in remanufacturing systems (only one study). Beside this point, variability of all factors affecting remanufacturing system, unreliable operations of stations and the effect of finite buffer on system performance have not been investigated all together. The current research can be applied to any type of serial-parallel manufacturing and remanufacturing systems to maximize its performance. Also, the evaluative methods as well as the hybrid Meta-heuristic search algorithm developed in this research can be potentially implemented on balanced, unbalanced, reliable and unreliable systems with any type (serial, parallel, flexible manufacturing system, assembly) and size (small, medium and large lines).

This research offers three primary contributions that distinguish it from the existing remanufacturing inventory control literature. First, an evaluative method is developed to calculate throughput of the system and other performance measures accurately and efficiently. Second, a hybrid Meta-heuristic algorithm is implemented to optimize buffer allocation problem quickly in comparison with simple Meta-heuristic algorithms' performances. Finally, a numerical experiment, based on case study, is performed to offer managerial insight into the performance of the approaches under different levels of uncertainty.

1.8 Organization of Thesis

This research project is subdivided into several parts. Chapter 1 introduces the research focus on background of the study. It outlines the problem statements, objectives and purpose of the research, its significance and contributions of the current study.

Chapter 2 discusses the existing literature. In its first section publications on remanufacturing inventory management is presented, which is significant for this study. The second section reviews the publications related to evaluative methods for measuring system performance. The third section discusses about optimization algorithms applied for finding best buffer allocation.

Chapter 3 presents the overview of research methodology and stages of the methodology used in this research. The proposed evaluative method for calculating the performance measures of remanufacturing system and developed generative methods for searching the best of the feasible solutions and the validation of proposed methods by means of real case study are mentioned.

Chapter 4 deals with remanufacturing modelling process and implementation of combinatorial optimization methodology proposed in this study. It includes applying two evaluative methods on serial-parallel remanufacturing system with unreliable workstations and non-balanced line. Afterwards, development of two Meta-heuristics and one hybrid Meta-heuristic algorithm for obtaining best buffer configuration are presented in this chapter.

Chapter 5 represents the analysis phase of this research. Developed methods are employed on a system with single product, unreliable and non-balanced fourteen workstations and buffers at toner cartridge remanufacturing company. This example system is used to verify the aptness of the proposed model of this dissertation. The aptness of the proposed hybrid Meta-heuristic procedure is then verified against other two simple Meta-heuristic algorithms.

Conclusion and discussion about future directions of the research are presented in chapter 6 which should be considered for extending the work. The first option is to stay in the single-product environment, and thoroughly discuss more alternative scenarios. The second option is to switch into a multi-product environment with more complexity in the line (series-parallel line) and implement other kinds of evaluative and generative methods to find better solutions.

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