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Gen2 RFID 기반 폐쇄루프 공급망 관리 시스템에 관한 연구

Development of Gen2 RFID-based Closed-loop Supply Chain Management System

2018 년 2 월

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산업·조선공학부 산업공학전공

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이 논문을 공학박사 학위논문으로 제출함
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Abstract

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With the extended producer responsibility, which is a countermeasure for environmental problems such as resource depletion in manufacturing industries, responsibility of manufacturers who produce automotive, electrical and electronic equipment has been extended beyond production, retailing, to collection and recycling of the end-of-life products. Particularly in the case of recycling, a legal system has been introduced that enforces recycling at a certain rate or more on a mass basis. In this background, scope of the supply chain management also has been extended beyond forward process, which consists of sourcing, producing, and delivery, to reverse process. It is called closed-loop supply chain in terms of constantly using the resources that have been put into the manufacturing ecosystem. Proper operation of the closed-loop supply chain can maximize economic profit by value creation along with whole product lifecycle as well as complying with environmental legislation. However, chronic uncertainties of reverse process cause inefficiency in terms of overall performance of closed-loop supply chain. In terms of physical flow, the timing and quantity of end-of-life product return is difficult to predict. Moreover, recycling network is complex

because there are many participants in reverse process. In terms of product lifecycle, residual values of returned products are all different due to the factors like usage environments, user behaviors, and so forth. Moreover, this problem becomes even worse at component level. Many research efforts have been proved that real-information gathering can solve this problem. In this context, a system framework that minimizes uncertainties and facilitates various positive effects along with the product lifecycle by using the internet-of-things including radio frequency identification (RFID) and sensors, will be proposed in this dissertation. Unlike the existing approaches that only tag products, component-level individual tagging that tags not only products but also components will be proposed for more detailed lifecycle information management. Especially, encoding the family relationships among the components, by using user memory that is provided by Gen2 RFID protocol, will be proposed to extract new contribution. Information system including RFID tag encoding scheme, will be designed to strictly comply with the established standards to ensure compatibility within the industries in the future. Additionally, potential effects will be examined. Real-time monitoring and maintenance (RMM) and counterfeit prevention scheme, which are intangible effects in terms of product service in the middle-of-life phase, will be introduced. Especially, sweeping scan approach to prevent structural counterfeits of products by using the family relations in the user memory, will be introduced. Also it will be shown that the proposed system is valuable for remanufacturing process streamlining and hybrid remanufacturing/manufacturing production planning with numerical studies.

Keywords: Product Recycling, Closed-loop Supply Chain, Product Lifecycle Management, Production Planning, RFID, Industrial Sustainability.

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Notice: This dissertation contains the following published articles and book chapters that are written by Young-woo Kim as the first author. References excluding those are following the dissertation guideline.

[1] Kim, Y.-w., Chang, T.-W., and Park, J., Gen2 RFID-Based System Framework for Resource Circulation in Closed-Loop Supply Chains, *Sustainability,* vol. 9, p. 1995, 2017.

[2] Kim, Y.-w. and Park, J., Designing a Lifecycle Integrated Data Network for Remanufacturing Using RFID Technology, in *Advances in Production Management Systems. Competitive Manufacturing for Innovative Products and Services: IFIP WG 5.7 International Conference, APMS 2012, Rhodes, Greece, September 24-26, 2012, Revised Selected Papers, Part II*, C. Emmanouilidis, M. Taisch, and D. Kiritsis, Eds., ed Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 160-167, 2013.

[3] Kim, Y.-w. and Park, J., A Lifecycle Data Management System Based on RFID Technology of EPC Class1 Gen2 v2, in *Advances in Production Management Systems. Innovative and Knowledge-Based Production Management in a Global-Local World: IFIP WG 5.7 International Conference, APMS 2014, Ajaccio, France, September 20-24, 2014, Proceedings, Part II*, B. Grabot, B. Vallespir, S. Gomes, A. Bouras, and D. Kiritsis, Eds., ed Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 294-301, 2014.

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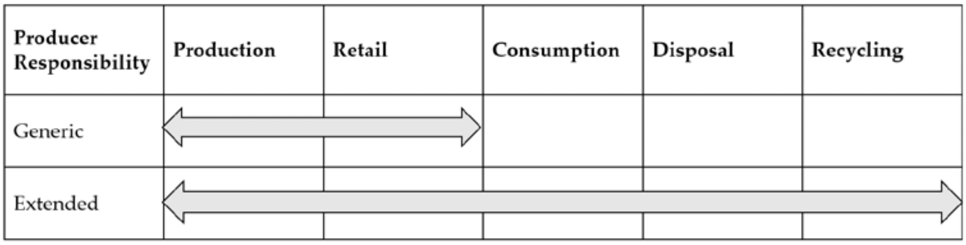
1. Introduction

1.1. Product Recycling

Modern industrialization started from the industrial revolution provides various conveniences as well as environmental destructions, i.e., greenhouse gas emission, destruction of ozone layer, natural resource depletion. As the number of products is increasing, major elements such as lead, copper, and iron will be depleted in at least 100 years [4]. For example, copper, that has about 720 million tons of reserve, will be depleted in 2044 is production continues to grow at current rates [5, 6]. Product recycling is the one of representative eco-friendly movements in the manufacturing sector [7]. Extended producer responsibility (EPR) that was claimed by the Swedish government in the early of 1990s is the primary concept that builds the eco-friendly trends. [8].



<Figure 1.1> Extension of the producer responsibility

Original equipment manufacturers (OEM) are responsible for the collection, recycling, and disposal of the end-of-life (EOL) products produced by themselves with the establishment of the EPR as depicted in <Figure 1.1> [9]. Accordingly, EPR-based environmental regulations that impose a recycling duty in a particular quota are raised worldwide.

EU ELV (European Union End-of-Life Vehicle) directive and WEEE (Waste of Electrical and Electronic Equipment) are known as representative EPR-based environmental regulations. The ELV directive aims not only to promote recyclability of vehicles by pushing OEMs to manufacture without hazardous materials, but also to achieve sustainability by setting quantified recycling target — 85% of reuse and recycle, and 95% of reuse and recovery [10]. The WEEE directive sets the goal of recycling for all types of electrical and electronic equipment at least 4kg on average per inhabitant per year [11].

Product recycling is valuable not only for environmental conservation via regulation compliance, but also for achieving economic benefits. Cost for virgin sourcing can be reduced by using recovered resources or components for manufacturing or by selling remanufactured parts in a spare-part market. Especially, it is expected that rare earth materials (REM)—that have been widely used to produce electronics parts due to excellent material properties, i.e., Neodymium Iron Boron for magnets, Lanthanum for EV (Electric Vehicle) batteries—can become more valuable as a result of their rarity and regional imbalance of reserves as listed in <Table 1.1>. The recovery of these materials has become increasingly important as an enabler of a competitive advantage under an era of the resource war.

<Table 1.1> Top-3 countries of REM reserves

Type of REM	Top-3 Countries	Portion of reserves (%)
Lithium	Bolivia, Chile, China	86.4
Manganese	South Africa, Ukraine, USA	90.0
Nickel	USA, Cuba, Canada	44.7
Cobalt	Congo, Australia, Canada	63.8
Tungsten	China, Canada, Russia	81.1
Titanium	China, South Africa, India	55.7
Rare Earth Elements	China, CIS (The Commonwealth of Independent States), USA	82.7

Moreover, the breadth of the market for remanufactured goods continues to grow and diversify. Hence, economic value of product recycling is still growing [12].

Returned items can be recycled with various recycling options which can be categorized as listed in <Table 1.2> according to aesthetic, functional condition, and residual value of them.

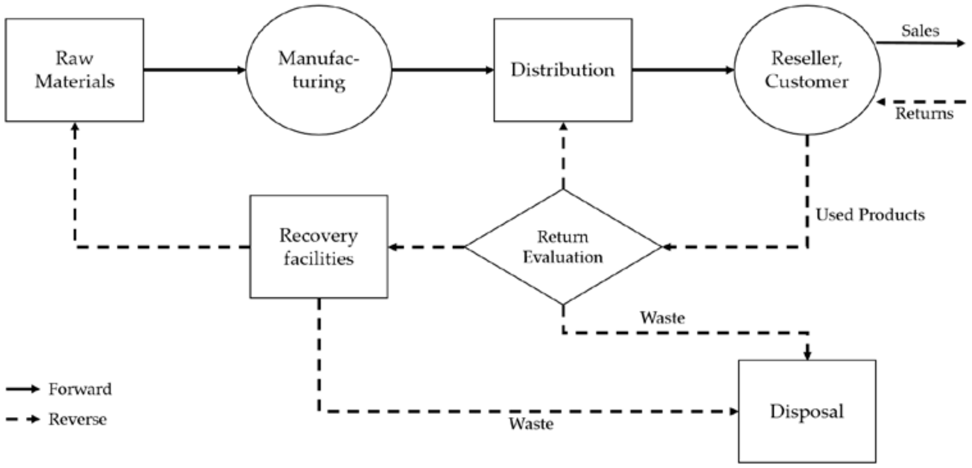
<Table 1.2> Hierarchy of recycling options

Recycling Options	Descriptions [13]	Cost/Resource Circulation Efficiency
Reuse	An item is used for its original purpose without repair	Better
Remanufacturing	An item maintains its identity and structure and is restored as a like-new product	↑
Material Recovery	An item is disassembled, shredded and/or separated to recover raw materials	↓
Disposal	An item is sent to disposal sites either for landfill or incineration	Worse

The recycling options in order of resource efficiency, and in opposite order of processing cost, are reuse, refurbish, material recovery, and disposal.

1.2. Closed-loop Supply Chain

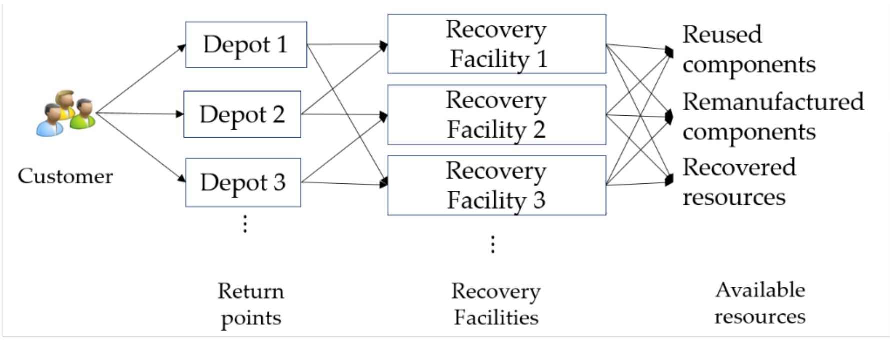
Traditionally supply chain management aims to operate the forward process—sourcing, production, and delivery—by seamless integration. A closed-loop supply chain (CLSC) integrates the reverse process —including the collection, inspection, recycling and re-distribution—with the conventional forward process as depicted in <Figure 1.2> [14, 15].



<Figure 1.2> Schematic diagram of the closed-loop supply chain [16]

The importance of a CLSC has arisen to meet the environmental demand. This requires OEMs to design, control, and operate the CLSC in order to maximize value creation over the entire lifecycle of a product [17]. Economically and environmentally efficient management can be realized by well-managed CLSC.

However, CLSC have trouble in execution even though it seems to be beneficial theoretically. Because the reverse process has an inefficiency problem caused by the lack of real-time information likewise the bullwhip effect in the conventional forward process [18].



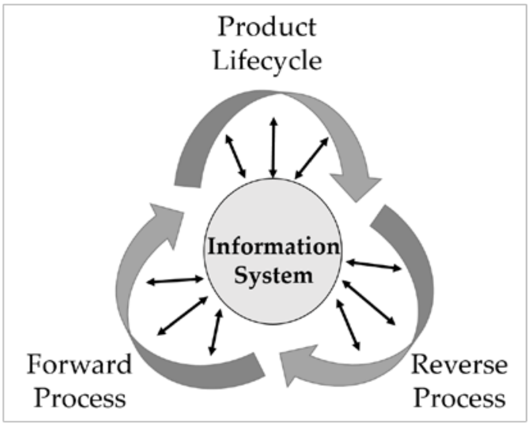
<Figure 1.3> Physical flow in the reverse process

The underlying cause of the inefficient CLSC is the uncertainty which can be categorized to: (1) physical flow, (2) quality of returned items. First, uncertainty related to the physical flow results because the exact timing and quantity of product return are unknown. Moreover, manufacturers do not have visibility of the recovered resource—which is considered as the resource available for production—because of a complex return network (diagrammatically presented in <Figure 1.3>) consisting of a number of return points and recovery facilities. Many remanufacturers are disadvantaged by high inventory levels and inefficient remanufacturing planning due to the covert distribution network. For this reason, more than a half manufacturers conduct a hybrid manufacturing/remanufacturing plan based on experience only [19].

The uncertainty related to the quality of returned items is also due to absence of a product lifecycle history. The quality of returned products varies with usage environment, user behavior, and the events that occurred during product lifecycle. Moreover, components that consist of a product have different qualities due to the substitution or repair in the MOL phase.

Hence, it is essential to make an appropriate recycling option decision based on accurate estimation of residual value and inspection in order to operate a recycling system efficiently in terms of cost and resource circulation. However, it is difficult to evaluate the returned items without any lifecycle information until the returned item has been disassembled into its low-level components and tested. To avoid the risk of quality, remanufacturers prefer material recovery to reuse or remanufacturing. In this case, we lose an opportunity to extend lifecycle of returned items which could be restored to good-as-new condition without losing identity. This incurs additional costs from treatment processes. Also, alloy material cannot be recovered in its original form, but as elements. Furthermore, recovery of rare earth materials cannot be guaranteed to be perfect, even though recovery techniques are improving.

As many research efforts claimed that achieving visibility in the supply chain can solve the inefficiency problems stated above which caused by lack of real-time information via information gathering and sharing [20, 21]. Visibility of physical flow enables to prevent inventory related problems and unnecessary sourcing. Efficient manufacturing/remanufacturing planning can be facilitated by using statistical and optimization models with real-time information. Furthermore, visibility of product lifecycle provides meaningful clues to estimate residual value accurately. Product lifecycle information facilitates efficient recycling activities that maximizes resource circulation efficiency and minimizes processing costs.



<Figure 1.4> Integrated chain

Then it is important to gather real-time information and to interact continuously within the big chain in <Figure 1.4> which consists of forward and reverse process in the CLSC as well as product lifecycle in order to maximize profit and resource circulation efficiency.

1.3. Internet-of-Things

As the Internet-of-Things (IoT) era entered, countless objects, interconnected by RFID (Radio Frequency Identification) and wireless sensor networks (WSN), generate, store, and process a large amount of real-time data [22]. The term 'Internet-of-Things' was proposed firstly to indicate uniquely identifiable and interoperable connected objects with RFID in the context of supply chain management in Proctor & Gamble [23]. There are numbers of definitions for the IoT as presented below.

- The worldwide network of interconnected objects uniquely addressable based on standard communication protocols (RFID Group)
- 'Things' are active participants in business, information, and social processes where they are enabled to interact and communicate among themselves and with the environment by exchanging data and information sensed about the environment, while reacting autonomously to the real world events and influencing it by running processes that trigger actions and create services with or without direct human intervention (Cluster of European research projects on the Internet-of-Things)

By applying analytics techniques to gathered real-time information including sensor data, IoT helps to extract useful insights to enhance everything in the world. In this way, there are several applications in various fields: ubiquitous healthcare [24], smart grid and metering [25], smart home [26], smart retail [27], smart city [28, 29], smart water [30], and smart transportation/logistics [31]. IoT improves overall performance including faster response time for manufacturing sector also [32].

RFID is the one of enabling technologies, which provides a unique identifier to any particular physical object by attaching an RFID tag to itself. It is an automatic identification and data capturing technology using radio frequency transmission [33]. Also, it enables real-time tracking to tagged objects. Hence, RFID has been used for improved supply chain management by gathering real-time information with its traceability [34]. WSN, another pillar of IoT, enables real-time monitoring of information with sensors. Visibility of product lifecycle can be achieved by using the IoT. Gathered information can be utilized to various CLSC operations. For instance, RFID-based sensor integration, which means that RFID tags are added to the sensor, satisfies need of real-time monitoring. Unique identification of any object as well as access to every associated information with it throughout lifecycle can be provided by using the RFID-sensor integration [35].

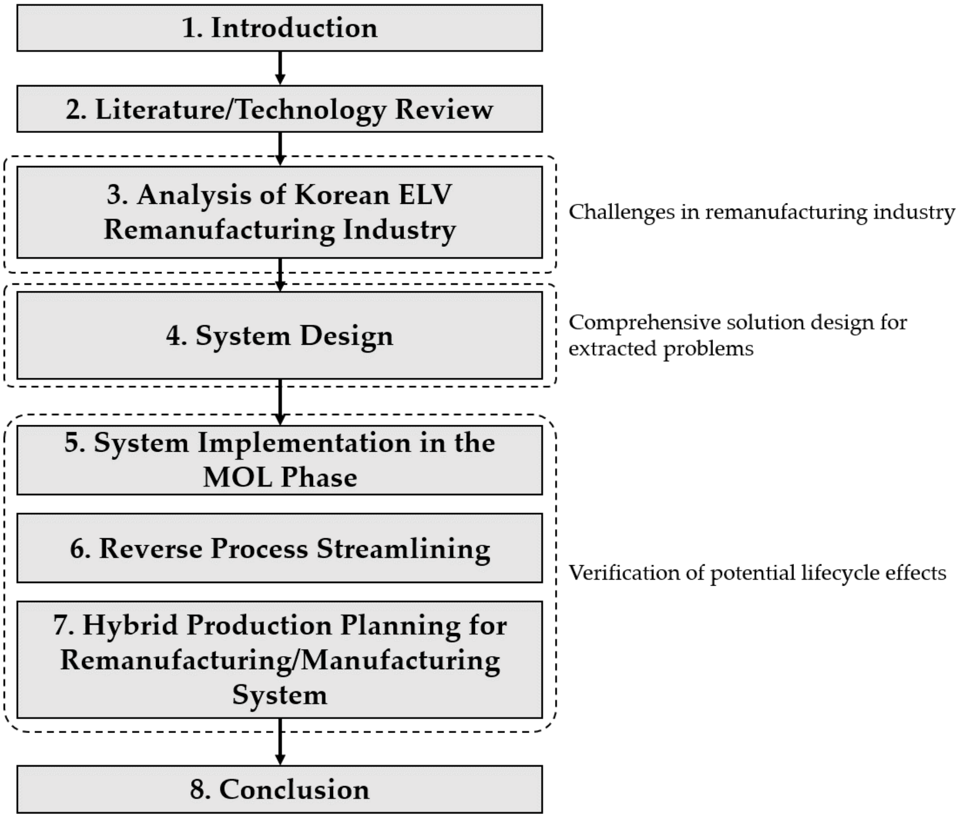
1.4. Goal and Scope

The principal goal of this dissertation is the development of a system framework for the closed-loop supply chain management using Gen2 RFID technology. By taking advantage of the IoT, a system that gathers real-time information within the product lifecycle and supply chain will be proposed. Ultimately, this dissertation aims to maximize economic and environmental value creation, which was defined by Tonelli *et al.* [36] as the objective to achieving the industrial sustainability.

One key contribution of this dissertation is that it examines possibility of using new features provided by Gen2 protocol such as user memory, to facilitate more detailed lifecycle information management with component-level tagging. Unlike existing approaches that only tag at a product level, the proposed system tags products as well as individual components for modular products such as automotive. RFID mainly plays a role as an enabler for achieving visibility within CLSC and the product lifecycle as it has been done in several literatures or industries. However, it is shown how new features can be applied to enhance conventional CLSC management systems.

Another contribution is that it builds a data architecture based on current standards. Information sharing among stakeholders – OEMs, suppliers, recovery facilities, customers, governmental authorities – is the key enabler to achieve the sustainable supply chain. It helps to guarantee interoperability, which enables seamless information sharing scheme.

Finally, a comprehensive approach that covers product lifecycle integrated CLSC will be proposed. Although many studies to this subject has been done, they limit the scope narrowly – to building a data architecture, to proving the efficiency of single CLSC operation. This dissertation illustrates potential positive effects throughout whole product lifecycle, from the perspectives of OEMs, product service, and governments.



<Figure 1.5> Pictorial overview of this dissertation

This dissertation consists of three main parts as depicted in <Figure 1.5>.

The first part (Ch.3) investigates the problem relating to the CLSC from industrial point of view. The proposed system aims to cover modular products that satisfy following conditions: (1) products with various types of components; (2) components have relatively high remanufacturing value; (3) components/products have their own second-hand, remanufacturing market; (4) CLSC operations – repair, substitution, maintenance service – are frequently happen in the middle-of-life (MOL) at a component level. Automotive is a representative modular product which satisfies the conditions listed above. Hence, this part borrows the example of automotive to figure out the characteristics of CLSC for modular products. Problems will be extracted by analyzing the current situation of Korean ELV remanufacturing industry. Also classification by underlying cause of each problem will be done. Finally, problems that can be solved by using RFID, will be drawn. The first part addresses the following research questions:

- What is the problem within the real world situation of remanufacturing industry?
- How the problems can be classified?
- Which problems can be solved by adoption of RFID?

The second part (Ch.4) is about system design to provide comprehensive solution approach for the CLSC. Firstly, physical elements which consist of the proposed system, will be introduced in order to facilitate lifecycle information gathering. And component-level individual tagging scheme towards more detailed lifecycle information management follows. Secondly, potential effects will be illustrated by using lifecycle information gathering. Especially, it will be explained that how the new features provided by Gen2 RFID can create additional value. It will also be important to store a lot of information generated in the IoT environment. This part discuss which information should be needed and how to store it efficiently, in order to operate the proposed system. The following research questions addressed:

- How RFID can be applied to the system?
- How the new features provided by Gen2 RFID can be contributed?
- Which positive effects can be derived by the proposed system?
- Which information will be useful?
- How the information can be stored efficiently?

The third part (Ch.5 through Ch.7) focuses on verification of potential effects derived by the proposed system. Chapter 5 presents real-time monitoring and maintenance (RMM) and counterfeit prevention schemes, which are intangible effects in terms of product service. In the remainder of this part, the value of the information visibility provided by the proposed system in terms of remanufacturing process and production planning respectively. In Chapter 6, remanufacturing process will be streamlined by analyzing generic process and applying the proposed system. Then, it will be shown that remanufacturing process is improved than generic process with numerical examples. Hybrid production planning model for remanufacturing/manufacturing system (RMS) with the proposed system will be explained in Chapter 7. This chapter proposes an integer linear programming (ILP) based mathematical model for multi-period hybrid production planning in consideration of multiple products with different components. Numerical experiment will be presented to prove that the proposed system is more efficient with two mathematical models, one for the proposed system, and the other for the generic system. Also, the sensitivity analysis for this model will be executed by changing various parameters in order to extract the characteristics of remanufacturing model.

2. Literature/Technology Review

2.1. Literature Review

2.1.1. Product Lifecycle Management and Closed-loop Supply Chain Management

Product lifecycle management (PLM) is closely related to the objective of this dissertation that gathers lifecycle related information. PLM which aims to seamlessly integrate information generated throughout the product lifecycle and ensure its availability to every entity in the industry [37], provides the necessary information to make the product recycling process efficient, as argued by Parlikad and McFarlane [38]. The amount of quality-related product information decreases as time passes [39]; consequently, this lack of information creates difficulties in recycling activities [40]. However, traditional PLM systems lack visibility in the MOL and EOL phases [41]. In addition, they could not provide useful functions such as counterfeit prevention and recycling decision support.

Several researchers addressed these problems by claiming that information technology helps to preserve lifecycle information and reduce transactional costs [39, 42]. Subsequently, the concept of closed-loop PLM (CL2M) emerged [43-45]. These systems extract new product knowledge and expand the coverage of the PLM to the entire product lifecycle using IoT technologies to identify the product and gather information feedback. Framling *et al.* conduct a comparative study on PLM application approaches based on an RFID-based EPC network, a uniform resource identifier and worldwide article information [46]. With the advancement in the information communication technologies, several researchers built a framework for PLM with a product embedded information device (PEID) using RFID and a framework for data integration and synchronization [47-49]. PEID, also called "intelligent product", "smart product", and "communicating material", consists of identification devices in addition to communication capabilities.

There are studies which find a framework for CLSC including reverse logistics, both practically and theoretically. From practical point of view, characteristics of CLSC is all different according to the characteristics of target industries. Chan *et al.* proposed a framework for automotive which defines key components to be recycled according to recycling value [50]. Shi *et al.* defined information flow in the battery CLSC, and built an information platform [51]. Millet presented a practical framework for designing the reverse logistics channel based on 18 reverse logistics channeling policies [52]. However, there also exists research efforts to build generalized comprehensive framework. From process point of view, an ERE-GIO methodology was proposed to define and integrate forward process and reverse process [53]. Barker and Zabinsky internalized product recovery activities into forward logistics [54]. They discussed potential trade-offs within the CLSC network with case studies. This strategic perspective on the

CLSC can be found also in Defee *et al.* [55]. Lambert *et al.* proposed a framework considers seven important elements of the reverse logistics system (coordinating system, gatekeeping, collection, sorting, treatment, information system, and disposal system) and divided it into three hierarchical levels, namely, strategic, tactical, and operational [56]. Morana and Seuring proposed integrated flow of CLSC with three-level framework which consists of society, chain, and actor [57]. However, lifecycle information gathering concepts and quantitative effects are hard to find in these kind of studies.

2.1.2. Linkage between PLM and CLSCM

The concept of CL2M is helpful, not only for product development but also for product recycling. Daaboul *et al*. attempted to integrate CL2M with reverse logistics design by using integrated product data in order to calculate environmental impacts and select the most efficient reverse logistics network [58]. Um *et al*. proposed a comprehensive architecture for u-PRMS (ubiquitous product recovery management system) which collects the product information related to product recovery [59]. Likewise, closed-loop product information with wireless technologies was proposed to utilize for recycling activities [60].

The use of a unique identification system to gather lifecycle information was claimed to facilitate recycling as well as closed-loop supply chain operations [61-64]. Information about the product usage condition indicates how to process the returned product [65]. Klausner *et al.* propose an

Information System for Product Recovery (ISPR) and the so-called EDL (Electronic Data Log)—similar to the PEID— be integrated with a product to record lifecycle data [66]. Li *et al.* examine the role of big data generated in the IoT paradigm throughout the entire product lifecycle including product recycling [67]. Simon *et al.* propose the LifeCycle Data Acquisition (LCDA) system to improve reuse rate, which stores and manages static and dynamic data generated throughout the product lifecycle and showed benefits in terms of cost [68]. Ilgin and Gupta used a simulation study to prove that sensor-embedded products reduce holding, backorder, disassembly, disposal, testing, and transportation costs [69].

2.1.3. Studies on Applications of Unique Identification and Lifecycle Information Gathering

Unique identification also supports the recycling process by improving its efficiency. Lu *et al.* propose an RFID-based information management framework with a feasible solution to offer complete information on plastic recyclables [70]. Saar *et al.* propose a system that sends disassembly and work instructions to mobile phones by scanning the barcode to distinguish the product family [71]. Luttropp and Johansson propose the recycling information matrix and attempt to store it in GID-96 RFID tags to enhance recycling efficiency [72]. Item-level identification with lifecycle information can be optimized in terms of waste reduction as well as remanufacturing quality [73]. Cao *et al.* showed how the lifecycle gathering system supports shop floor planning and control in a plastics recycling plant [74].

Several researchers propose estimation schemes for residual values using data driven methods such as linear multiple regression, kriging techniques, artificial neural networks, and fuzzy logic based on lifecycle information [75-79]. Ondemir *et al.* conduct a study on optimal EOL management in closed-loop supply chains using RFID and sensors to reduce labor-intensive and expensive disassembly jobs by capturing lifecycle information [80]. Fang *et al.* proposed a general procedure for residual life estimation of sensor-embedded products. [81] In other way, there exists an effort for automatic classification of returned products by using computer vision [82]. Although these studies investigate the use of lifecycle information to estimate the residual value of returned products and to reduce various costs, they did not consider recycling and disassembly process of the returned products.

There are many studies that have examined various effects by gathering lifecycle information using RFID or other information technologies described above. However, most studies provide identity only at the product level. For modular products, which have frequent operations at the component level, it is necessary to provide a unique identity at the individual component level for more detailed management. Also, any study cannot be found so far that considers Gen2 RFID standard including user memory application and encoding schemes.

2.1.4. Production Planning for Remanufacturing

Production planning and control for remanufacturing is more complicated than traditional manufacturing environment due to the following characteristics [83]:

- Uncertain timing and quantity of returns
- Need to balance returns with demands
- Disassembly of returned products
- Uncertainty in materials recovered from returned items
- Requirement for a reverse logistics network
- Complication of material matching restrictions
- Highly variable processing times
- Stochastic routings for materials for remanufacturing operations

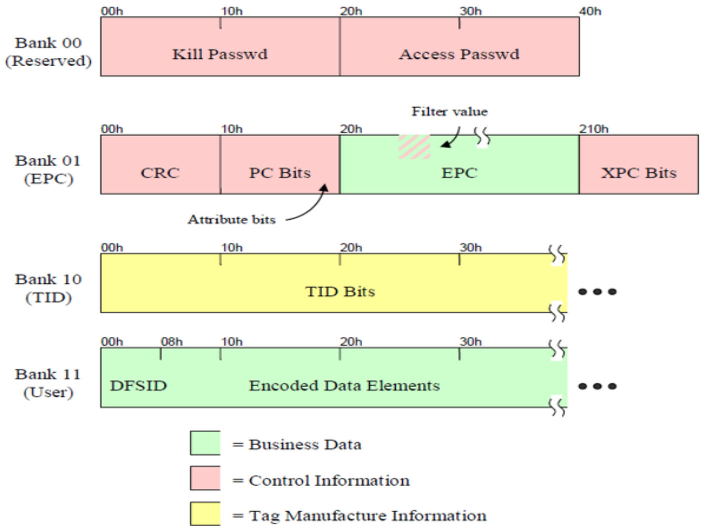
Production planning and control-related studies belongs to one or more category(s) among following categories: aggregate planning; forecasting; capacity planning; master production scheduling; scheduling; ordering system; logistics; inventory management and control [84]. In this dissertation, researches which focused on inventory management and control and master production scheduling will be introduced.

Depuy *et al.* [85] presented a production planning with component recovery under uncertain supply and demand with component purchasing schedule based on material requirements planning, which is similar to Ferrer and Whybark [86]. These two approaches deal with component as well as product. Similarly, researches that deal with remanufacturing production planning including component level recovery has been done: fuzzy multi-objective linear programming model (FMOLP) to solve remanufacturing planning decisions with multiple components and multiple machines for a single product remanufacturing system [87]; FMOLP to solve lot-sizing problems with multiple products, multiple components, and joint components in uncertain environments [88]; mixed integer linear programming-based multi-period production planning with deterministic returns and demands considering market segmentation [89]. Remanufacturing planning studies with similar approaches considering only at a product level also exist: multi-stage, multi-period, multi-product capacitated production planning [90]; dynamic programming approach to make a recycling decision whether to manufacture, remanufacture, or dispose [91]; uncapacitated multi-product production planning with no backlog and no disposal [92]. And there were studies that proved the value of grading and sorting in terms of production planning and control activities [93-96].

2.2. Technology Review: RFID and Gen2 Standard

RFID can identify and track any tagged objects by using radio frequency in real time through EPCIS (Electronic Product Code Information Service). RFID has been used in retail, logistics, and healthcare as a substitute for barcoding. Although barcoding and RFID both have labels, readers, and backend system, there are advantages of RFID over barcoding: no line of sight required; multiple parallel reads possible; individual items instead of an item class can be identified; read/write capability [97, 98].

The RFID standards provided by GS1 are categorized into two categories: Technology standards, which define a protocol of communication between RFID tags and readers, and data standards, which specify the format of RFID tags. Among various technology standards, UHF (Ultra High Frequency) RFID has been used for supply chain management. The most recent UHF RFID standard, EPC Class1 Gen2 is a truly unique international and interoperable protocol which is faster and more secure than the former UHF RFID standards [99]. Further Gen2 tags are logically separated into four banks of passwords (bank 00), EPC (bank 01), tag identification bits (bank 10), and user memory (bank 11) as depicted in <Figure 2.1>.



<Figure 2.1> Logical memory map of Gen2 RFID tags (source: GS1)

There are several data standards for encoding the EPC according to the purpose of use [100].

<Table 2.1> EPC encoding schemes (source: [100])

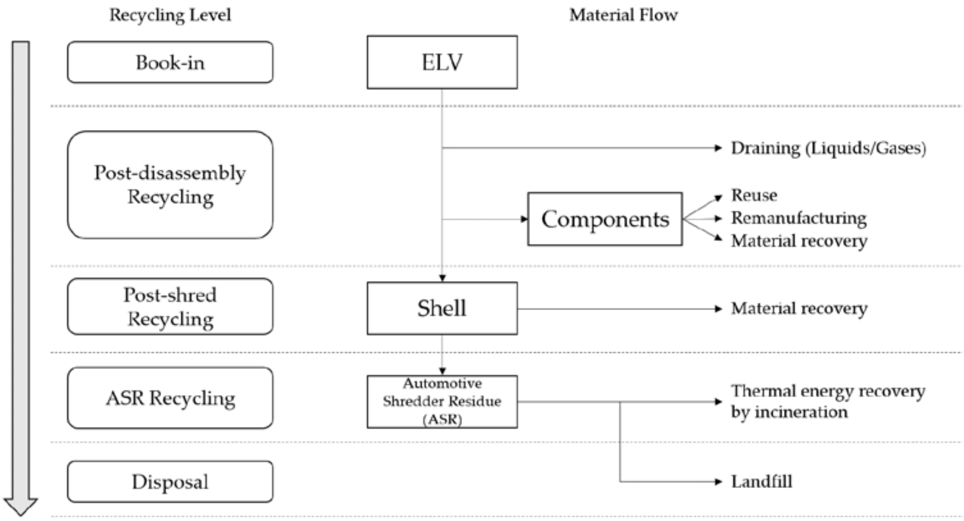
EPC scheme (acronym)	**EPC scheme (full name)**	**Tag encodings**	**Typical use**
SGTIN	Serialized Global Trade Item Number	sgtin-96 sgtin-198	trade item
SSCC	Serial Shipping Container Code	sscc-96	pallet load or other logistics unit load
GRAI	Global Returnable Asset Identifier	grai-96 grai-170	returnable/reusable asset
CPI	Component/Part Identifier	cpi-96 cpi-var	technical industries (e.g. automotive) – components and parts
GID	General Identifier	gid-96	unspecified
USDOD	US Department of Defense Identifier	usdod-96	US dept. of defense supply chain
…	…	…	…

User memory in bank 11 provides supplementary encoding for user convenience such as electronic surveillance and maintenance logging [101].

3. Analysis of Korean ELV Remanufacturing Industry

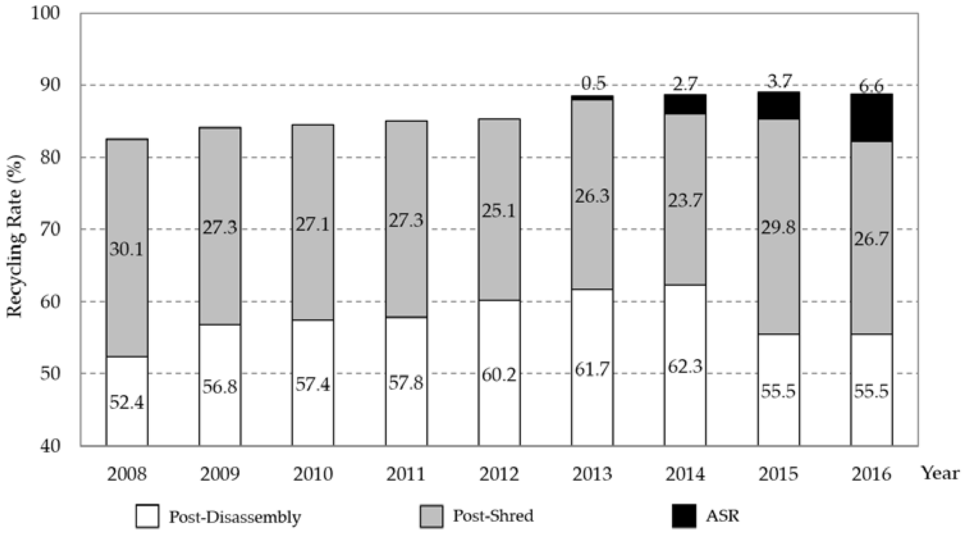
3.1. Overview

Domestic ELV remanufacturing is based on 'Act on Resource Circulation of Electrical, Electronic Equipment and Vehicles' that is similar to ELV directive and WEEE directive. This also sets quantified recycling target for ELVs as same as ELV directive.



<Figure 3.1> Recycling levels and corresponding material flow

After acquiring ELV, recycling levels can be divided into three stages, namely, post-disassembly recycling, post-shred recycling, and ASR (Automotive Shredder Residue) recycling, in sequential order, according to the reverse process as depicted in <Figure 3.1>. At the first step, draining and recycling of liquids and gases are executed after the ELV returns. Consequently, the ELV is dismantled to components; recycling decision for each component will be made according to the condition and residual value. If a component is good to reuse or to remanufacture, it can be recycled with its own identity; and it enters forward process or spare-part market. Otherwise, it might be shredded to scrap metal and natural resources will be recovered from it. Also, material recovery is executed for the shell. ASR can be recovered as thermal energy by incineration.



<Figure 3.2> Annual recycling rate by recycling levels

Although total recycling rate is increasing, some limitations are derived according to the annual recycling rate presented in <Figure 3.2>: (1) recycling rate for post-disassembly was decreased after 2015; and (2) ASR recycling is the main driver to increasing total recycling rate. According to the recovery hierarchy presented in <Table 1.2>, it can be concluded that resource circulation efficiency is not enough. Hence, recycling rate of post-disassembly, which can be reused or remanufactured, should be increased to operate efficient recycling system.

3.2. Problem Extraction and Classification

Problems for the domestic ELV remanufacturing industry, which are presented in literatures [102, 103], can be categorized as listed in <Table 3.1>.

<Table 3.1> Problems on domestic ELV remanufacturing industry

Category	Problem details
Poor return network	• Domestic junkyards usually treat core components as scrap metal • Overseas remanufacturers obtain core components cheaply; they re-export the components after remanufacturing more expensively
Quality-related issues	• Adoption of the quality certification system is being delayed due to the conflict among government ministries • Poor quality of remanufactured parts due to poor test techniques • The absence of historical repair logs harm reliability of remanufactured parts in the customer market • It is not profitable due to low price of remanufactured parts
Poor network of remanufactured parts	• Production planning and inventory management is unsystematic due to covert distribution network
Premature remanufacturing techniques/infrastructure	• (See <Table 3.2>)

For general manufacturing systems, adequate sourcing is considered important. In a similar vein, smooth collection of returned EOL products, which are the primary sources for remanufacturing, is essential for remanufacturing industry. However, it has failed to supply EOL products to the remanufacturing system due to the absence of a return network. Also, domestic junkyards usually treat the EOL products as scrap metal rather than source for remanufacturing, because of the absence of priority for use of circulated resources. Given this situation, overseas remanufacturers obtain the core components cheaply; and they re-export the components after remanufacturing more expensively.

Secondly, there are issues relating to the quality of remanufactured components. It can be linked to the premature remanufacturing techniques/infrastructure. Poor quality of remanufactured parts due to poor test techniques, and the absence of historical repair logs harm reliability of remanufactured parts in the customer market. Accordingly, a price for remanufactured parts is 20-30% of the price of newly manufactured parts. Hence, incentive for investment to the remanufactured market seems to be not enough because probability of gaining economic benefits from remanufactured market is relatively low. Moreover, customers can have a negative outlook on using remanufactured parts, because it may be a direct link between life and death, even though they are inexpensive. One of the ways to solve this problem is to introduce a quality certification system. Currently, target products for remanufacturing is collaboratively decided by ministry of environments and ministry of trade, industry and energy. Due to the disharmony between ministries, notice of the target products is delayed, and it is becoming a limiting factor for quality certification.

The third problem is come from poor network of remanufactured parts. Except for some companies, most companies have a covert distribution network. And they do remanufacturing in MTO (Make-to-Order) or RTO (Remanufacture-to-Order) process. It causes a high level inventory problem as well as inefficient production planning.

Finally, problems from premature remanufacturing techniques and infrastructure are listed in <Table 3.2> by process flow.

<Table 3.2> Problems on domestic ELV remanufacturing process

Remfg. Process	**Problems**
Disassembly	• Unsorted inventory of dismantled parts • Damages of parts • Maintaining cleanliness of components • Unsystematic process
Cleaning	• Maintaining cleanliness of components • Difficulty on cleaning process • Insufficient facilities for worker safety
Testing	• Insufficient number of test equipment • Insufficient failure cause analysis techniques • Accidental risk due to poor test techniques
Repair	• Difficulties of implementing repair process due to insufficient failure cause analysis • Problems on clearance due to lack of equipment and work ethic
Re-assembly	• Insufficient number of fixtures • Time delay due to the absence of standardized process • Quality problem due to the absence of standardized process

Current problems of domestic ELV remanufacturing industry can be categorized as follows: (1) social problems (SOC) related to a social atmosphere or structure (such as governmental issues), (2) environmental problems (ENV) related to work ethics and work environments, and (3) technical problems (TEC) which come from unstandardized process or premature techniques. Also the technical problems can be classified according to what is the enabler to solve underlying causes as follows: visibility of supply chain (SC), visibility of product lifecycle (PL), and enhanced remanufacturing process (RP). Then, the problems listed in <Table 3.1> and <Table 3.2> are categorized as presented in <Table 3.3>. RFID applicability for each problem is also presented.

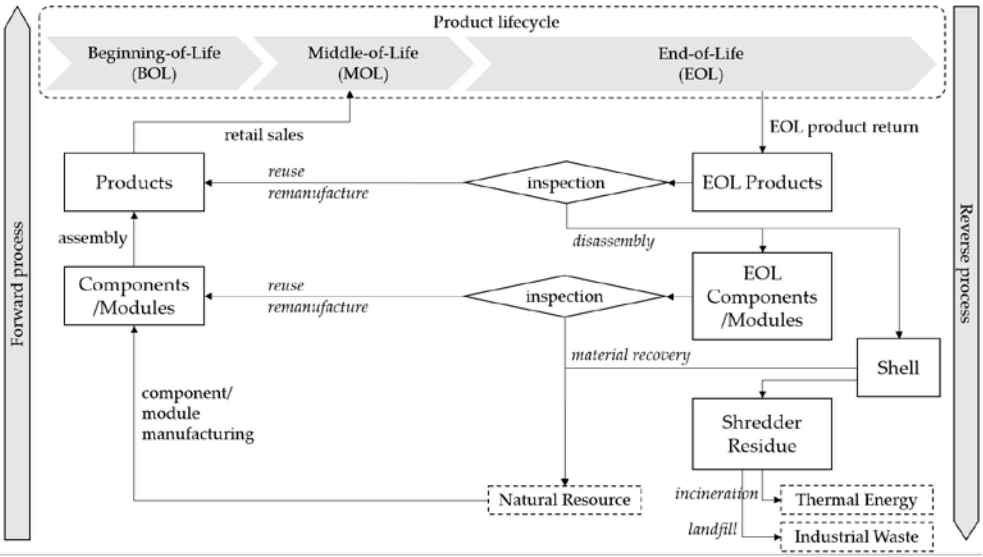
<Table 3.3> Classified problems on ELV remanufacturing and its RFID applicability

Category	Problem details		Characteristics	RFID applicability
Core return	Poor return of core components		ENV, TEC(SC)	○
	Relatively high portion of material recovery		TEC(PL)	○
Quality-related issues	Delay of quality certification system adoption due to the governmental conflicts		SOC	×
	Poor test techniques for remanufactured parts		TEC(RP)	×
	Absence of repair history log for remanufactured parts		TEC(SC, PL)	○
Network of remanufactured parts	Covert distribution network		SOC, TEC(SC)	△
	Problems related to high inventory level		TEC(SC)	○
	Inefficient hybrid production planning		TEC(SC)	○
Remanufacturing Techniques/ Infrastructure	disassembly	Unsorted inventory of dismantled parts	TEC(RP)	○
		Damages due to bad load state	ENV	△
		Cleanliness of core components	ENV	×
		Absence of systematic disassembly process	TEC(RP)	○
	cleaning	Cleanliness of core components	ENV	×
		Difficulties of perfect cleaning	TEC(RP)	×
		Insufficient facilities for worker safety	ENV	×
	testing	Insufficient number of test equipment	SOC, ENV	×
		Insufficient failure cause analysis techniques	TEC(PL)	○
		Poor test techniques	TEC(RP)	×
	repair	Difficulties of implementing repair process due to insufficient failure cause	TEC(PL)	○
		Problems on clearance due to lack of equipment and work ethic	ENV	○
	re-assembly	Insufficient number of fixtures	ENV	×
		Time delay due to the absence of standardized process	TEC(RP)	○
		Quality problem due to the absence of standardized process	TEC(RP)	○

4. Design of the Proposed System

4.1. Lifecycle Information Gathering and Component-level Tagging

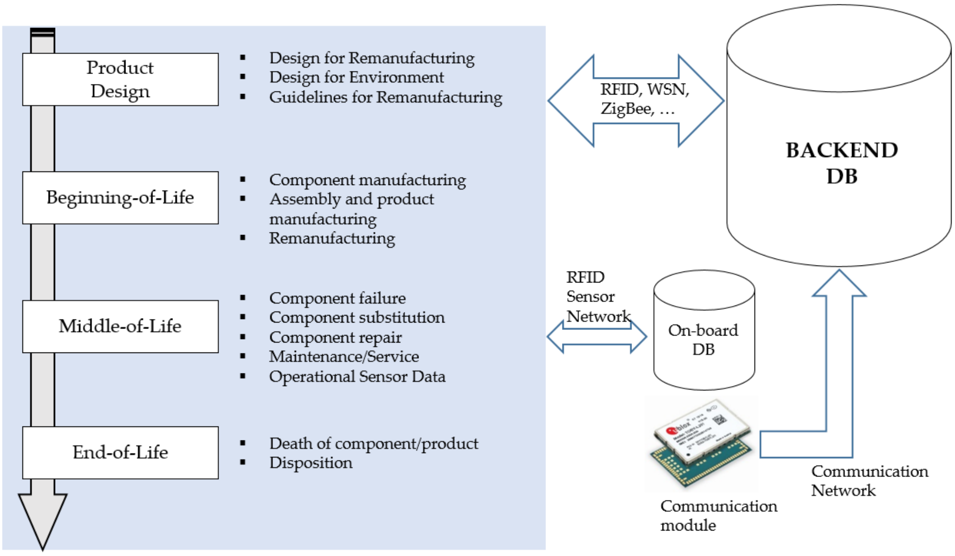
As stated earlier, uncertainties about physical flow within the CLSC and quality within the product lifecycle negatively affect CLSCs. The proposed system aims to solve these problems, and ultimately to operate the CLSC efficiently in terms of costs and resource circulation, by gathering real-time information generated among the product lifecycle integrated CLSC which is presented in <Figure 4.1>.



<Figure 4.1> Product lifecycle integrated CLSC

For the reverse process, a returned product can be reused or remanufactured, but it rarely happens in a real-world situation. Most of the returned products are disassembled into lower level components and a shell. Components are reused or remanufactured if their condition turns out to be well enough for reuse or remanufacturing by inspection. Otherwise, it is recovered as raw material after shredding with shell. Finally, shredder residue can be recovered as thermal energy by incineration. The current inspection system manually grades returned items based on expert opinions, without any lifecycle information. However, difficulty exists with accurate estimation of residual value. For this reason, components that can be remanufactured are shredded imprudently for material recovery. It causes inefficiency in terms of processing cost and resource circulation.

To solve this kind of problem, accurate estimation of residual value by using lifecycle information, which is related to not only MRO (Maintenance, Repair, and Overhaul) but also usage environments, is essential. The proposed system aims to make the most appropriate recycling decisions by using lifecycle information—such as MRO logs and sensor data about usage environments— gathered by RFID and RFID-based sensor integration as depicted in <Figure 4.2>.

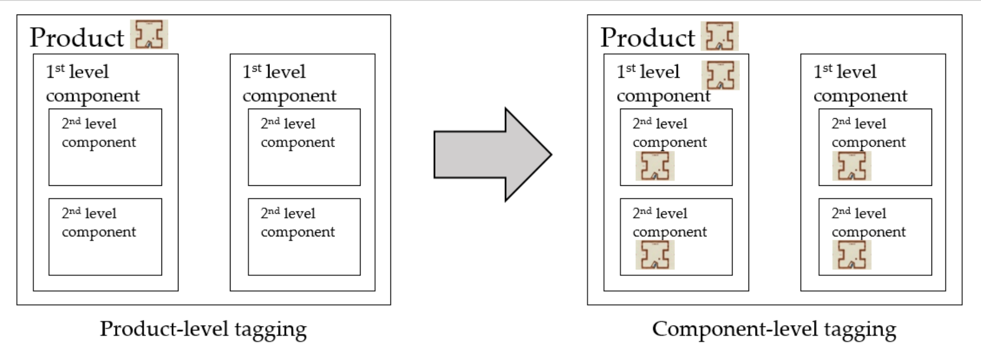


<Figure 4.2> Lifecycle information gathering

Lifecycle events and CLSC operations—production, component substitution, MROs, disassembly, and recycling activities— occur on a modular basis. For example of the automotive sector, components are traded in a component level for substitution. Moreover, value of remanufactured components is relatively high. For this reason, individual identification which facilitates component-level traceability will be helpful for various fields.

In addition, gathering lifecycle information for each component facilitates more efficient recycling, in terms of process efficiency and recycling performance, via detailed lifecycle management. For example, let there be a module that is in a bad condition. However, some component in that module can be reused or remanufactured according to its lifecycle. For this case, if grading is executed based on condition of a module only, without any concerns about respective condition of lower level components, it is necessary to risk losing the remaining life expectancies for good-to-reuse or good-to-remanufacture components. On the other hand, even if the condition of a module looks good to reuse, one of the key components of the inner core may pose a risk of catastrophic failure. To hedge this kind of risk, inspection should be made for component by component after full level of disassembly. However, there is a possibility that there will be unnecessary disassembly jobs.

In this context, component-level tagging is proposed that tags products as well as lower level components unlike conventional product-level tagging that only tags the product. (Diagrammatically represented in <Figure 4.3>)



<Figure 4.3> Product-level tagging and component-level tagging

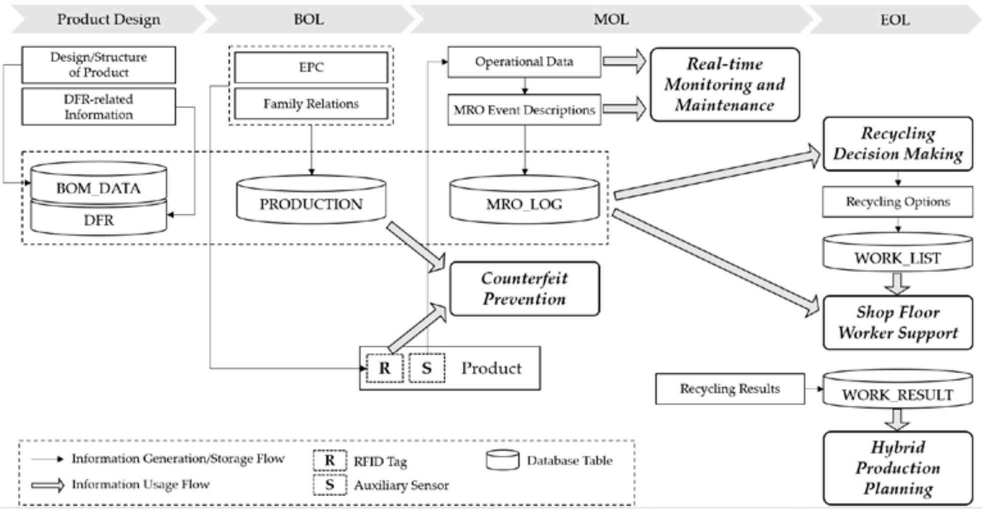
Component-level tagging, which is more detailed tagging scheme compared to the item-level tagging, facilitates accurate estimation of residual value for each component based on lifecycle information. This avoids unnecessary disassembly jobs as well as degradation of resource circulation efficiency. Although the number of RFID tags used by the proposed system is greater than conventional product-level tagging approaches, the price of the Gen2 RFID tag is currently about $ 0.1 per unit, which will be cheaper as time passes. Hence, RFID tag costs are not expected to be a significant problem versus the value generated by component-level tagging.

However, it is unrealistic to tag every component in the product like the automotive which consists of more than 20,000 components. Hence, component-level individual tagging scheme should consider the level of tagging, which determines that what component should be tagged, from the product design phase. Level of tagging, which is closely related to selection of remanufacturing target components as described in Chapter 3, can be differentiated according to design consideration, material used, economic aspect, and directive requirements. Product modularization traditionally has been determined by the factors of standardization, functional independence, cost, ease of manufacturing, and ease of maintenance. These factors are expanding to gain lifecycle benefits including the EOL phase. Especially in terms of recycling, material compatibility is considered to facilitate proper recycling or disposal processes for different materials. In terms of remanufacturing, remanufacturing target components are grouped into easily detachable modules [104]. Also technological stability, functional up-gradability, long life, ease of quality assurance, and ease of repair are factors that gaining attention to increase reuse potential [105]. In this context, component-level tagging should consider following factors:

- Tagged object is independent functional unit;
- Tagged object is distributed in its current form;
- Remanufacturing should be feasible;
- Remanufacturing potential should be over certain level;
- Estimation of degradation through using real-time sensing is enabled (not mandatory);
- Easily detachable.

Various types of UHF RFID tags can be used depending on the characteristics of the components to be attached. For instance, a circuit integrated RFID tag can be attached to electronic parts such as engine control units; for components which have metal surface, metal tags can be used to prevent interference due to the signal reflection.

4.2. Information System Framework and Lifecycle Implications



<Figure 4.4> Information system framework

<Figure 4.4> shows information generation and information flow, as well as expected effects by lifecycle phase.

In the Product Design phase, information about product design—such as specifications of components and assembly structures among the components— is generated. This information related to the bill-of-materials (BOM) is stored in BOM_DATA table. Instructions about disassembly and recovery works are stored in DFR (Design for Remanufacturing) table.

The BOL (Beginning-of-Life) phase starts with the production of components and products. Each item receives an EPC as a unique identity, with individual RFID tagging directly following its production. EPCIS (Electronic Product Code Information Service) facilitates real-time tracking of tagged objects to monitor status of them throughout whole product lifecycle. Likewise, upper-level components, modules, and products are also tagged with their EPCs. In addition, family relations, such as parent, child, and sibling, are created during assembly. For example, let module A be produced by the assembly of components B and C. In this case, B and C are the children of module A. Inversely, module A is a parent of B and C. Finally, B and C are siblings. The PRODUCTION table contains information related to production such as EPC, production date, the worker who manufactures the item, family relations of manufactured items.

The proposed system gathers real-time information about maintenance, repair and overhaul (MRO) events. Moreover, RFID-based sensor integration scenario which sends information gathered by auxiliary sensors through RF communication facilitates real-time monitoring of product usage environment [35]. Product lifecycle visibility can be achieved by storing data that affects performance and residual value as well as MRO events in the MRO_LOG table.

The proposed system facilitates various positive effects by using the stored data described above as a backend database. Counterfeit prevention and Real-time Monitoring and Maintenance (RMM) are provided for product service in the MOL phase. For products that have vitalized second-hand market, frauds may exist— such as covering up accident history or using non-genuine components instead of genuine ones. The proposed system prevents these kinds of frauds by reference to MRO_LOG and by comparing family relations between RFID tags and the backend database.

In addition, RMM can be facilitated by real-time data capturing and analysis with auxiliary sensors. Sensors can be used to observe real-time data of key factors and send them to the analytics module by RF communication. This would enable us to detect an anomaly as an indication of potential failure in observations by the data driven method in the analytics module. When the system detects the anomaly, a notification message is sent to the user in order to prevent critical damage. These kinds of sensing and control solutions have recently been diffusing into factories, to manage equipment and production processes by obtaining various measurements. Aim of this dissertation is to apply this solution to the product service area.

The EOL phase starts when a product is disposed of by a customer. After collection, the manufacturer decides how to recycle the returned product based on its condition. The proposed system enables data-driven recycling decision based on gathered lifecycle information. Recycling decisions for each component are made individually and simultaneously, because the proposed system collects lifecycle information for each component by component-level tagging. Thereafter, recycling decisions indicate which component should be reused, remanufactured, disassembled, or shredded.

Decision of recycling option is closely related to remaining useful life (RUL) estimation. Prognostics, which predicts system lifetime, is to predict RUL such as time to failure or risk of failure based on current condition and past operation profile [106, 107]. Prognostics can be categorized into physical, experimental, data-driven, and hybrid. Especially, data-driven methods are useful when large quantity of noisy data should be transformed logically to estimate RUL [108]. RUL estimation also can be categorized into empirical and non-empirical techniques. Empirical techniques consist of destructive testing that estimates RUL by analyzing operational data obtained during reliability testing process, and non-destructive testing that aims to assess technical performance and to sort out potentially unreliable item [109]. For instance of non-destructive testing, Reyes et al. (1995) attempted to assess reuse potential of AC induction motors by analyzing noise, and Potter et al. (1999) proposed an optical inspection for electronic component reuse [110, 111].

However, those kind of methods are limited to the fact that long time to reliability test, and disassembly should precede test in some cases, as Klausner et al. [66] pointed out. Non-empirical techniques which use maintenance database have been presented to compliment the limitations. Keller and Maudie (2001) used a failure tracking database to identify failure rate and to predict lifetime for the case of silicon micro-machined accelerometer in the automotive airbag deployment system [112]. Wang et al. (1999) also presented an estimation scheme for reliability, failure rate, and mean time between failures based on field failure database of CNC lathes [113]. Non-empirical methods are also challenging against the fact that the information does not reflects clearly operational condition. Hence, operational data and MRO history should be combined in order to make an accurate RUL estimation.

As Ondemir and Gupta (2014) also claimed, recycling decision is made after an EOL product arrives based on lifecycle information which is retrieved along with unique identification serial [114]. The difference of this dissertation is that recycling decision for each component is made. Studies about methodologies for estimation of RUL based on lifecycle information have been carried out as Si et al. (2011) [115] reviewed comprehensively. Also this kind of effort is closely related to the CBM methods described in Section 5.1. However, there have been less of efforts to link RUL estimation and recycling option decision. Mazhar et al. (2007) [77] attempted to estimate RUL of the washing machine by subtracting estimated actual life from estimated mean life that derived from Weibull distribution. Actual life is estimated by using regression analysis and neural network with test data such as motor rotation speed, winding temperature, power, current, and voltage. Hu et al. (2014) [116] proposed a threshold-based remanufacturing strategy for the double row cylindrical ball bearing. Reliability is predicted by using support vector machine with vibration data as an online monitoring degradation signal.

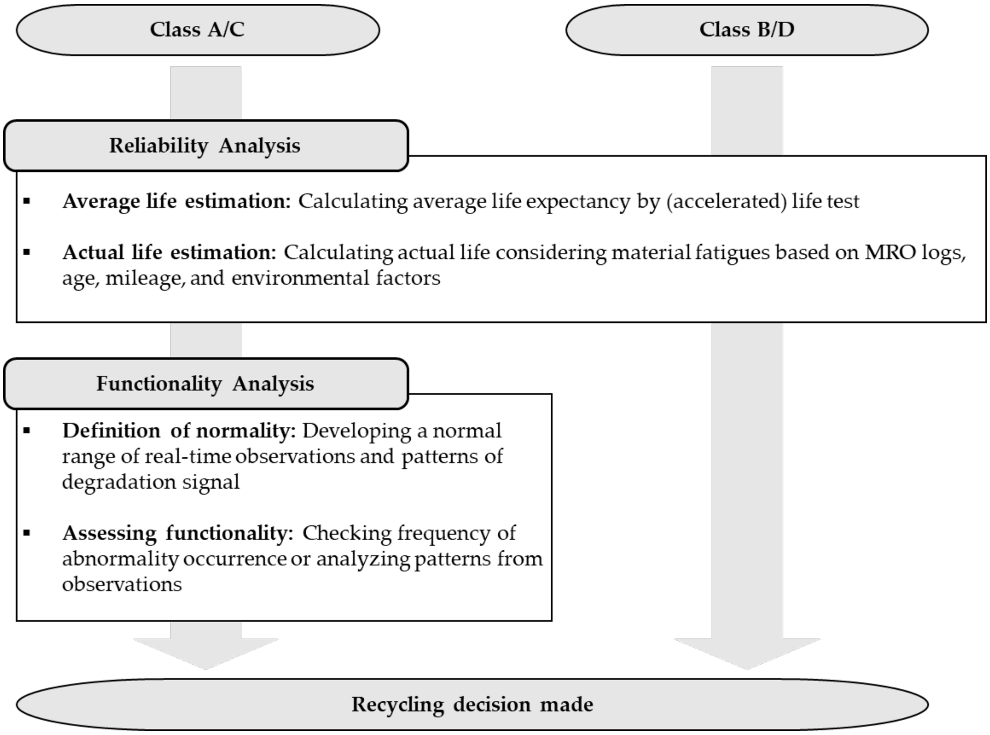
RUL estimation through an identical methodology does not make sense because characteristic and role of each component is all different.

Components or modules can be divided into four classes according to characteristics as listed in <Table 4.1>. One of classification criteria is whether the sensing data directly or indirectly describes current performance of components. The other criteria is functional type of components. A component may plays a role of independent function, or it may executes sub-functions for the independent function.

<Table 4.1> Components classification

Component Class	**Explanation ability of sensed data**	**Functional type**	**Component instances**
Class A	Direct	Independent	Engine, Starter motor, Alternator, Batteries
Class B	Direct	Sub-function	Cylinder head
Class C	Indirect	Independent	ECU, ABS, Other electronic modules, Sensors
Class D	Indirect	Sub-function	Axles, Other inner mechanical parts, Wire harness, Shell parts

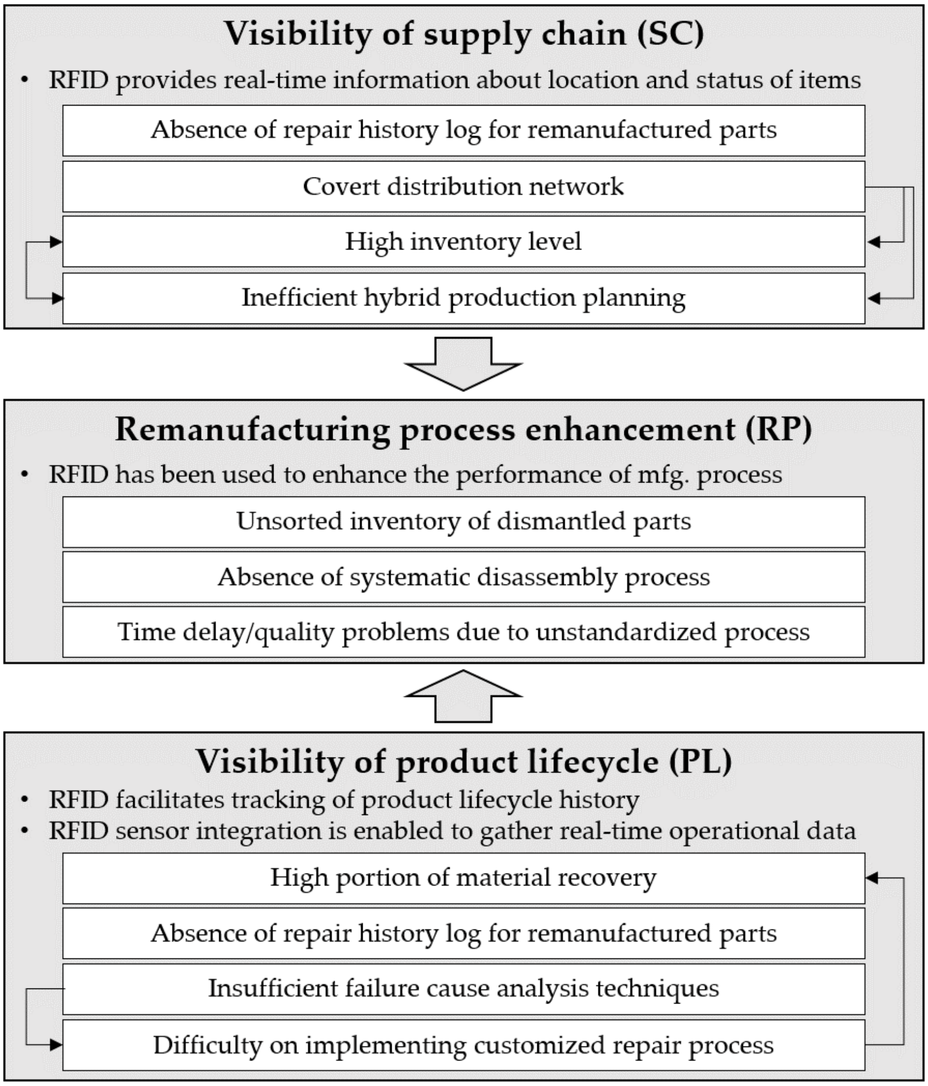
Components which belong to Class B or D need assessment in terms of material fatigue because they generally execute mechanical sub-function. In addition to the fatigue assessment, components which belong to Class A or C need to be assessed in terms of functionality. Hence, recycling decision making process based on RUL estimation is depicted in <Figure 4.5>.



<Figure 4.5> Recycling decision making process based on RUL estimation

Workers on the remanufacturing shop floor receive a job with predefined work instructions in the DFR table, according to the recycling decision made and stored in WORK_LIST table; this supports and enables workers to perform jobs accurately.

Results of recycling activities are clearly recorded in the WORK_RESULT table. This not only facilitates obvious evidence for regulatory compliance, but also enables efficient planning of manufacturing or remanufacturing by promoting resource awareness.



<Figure 4.6> Problem solving framework

Problems, which are categorized in <Table 3.3>, are interconnected within each category as depicted in <Figure 4.6> that presents how the problems can be solved by RFID implementation. Firstly for the problems which can be solved by achieving visibility of supply chain, covert distribution network causes high inventory level as well as inefficient hybrid production planning. Inversely, the reason of high inventory level would be inefficient hybrid production planning. These problems can be solved with real-time information about location and status which is provided by RFID traceability.

Likewise, interconnectivity also exists for the problems caused by lack of product lifecycle information. Analysis for failure causes is difficult due to lack of product lifecycle information. It makes the obstacle to implement customized repair process to each returned item. This is the reason why remanufacturers prefer shredding and material recovery to remanufacturing in order to avoid potential risk of failure. Successively, resource circulation efficiency is decreased. However, the proposed system facilitates accurate analysis for failure causes by gathering real-time operational data with RFID sensor integration. Accordingly, appropriate customized repair processes for each component can be facilitated. Also, it leads to increase resource circulation efficiency. Also non-volatile records for repair history log raise the reliability of remanufactured parts in the market.

By using these characteristics of RFID, it has been used to enhance the performance of manufacturing process. Likewise, remanufacturing process could be improved by using RFID. Remanufacturing industry has dynamic and complex environment consists of many stakeholders. Especially, for third party remanufacturers should handle different types of products and components made by different companies. Hence, difficulties to manage inventory with this environment lead to the inventory problem. Session and using part reference would be helpful to solve the problem. Gen2 RFID protocol provides four sessions, which allow readers to conduct independent inventories, with any tag only able to participate in one session. Each session has two inventory flags to represent its current status, and a state transition occurs when a tag is powered during a predefined persistence time. This enables us to read tags only in the particular state or session. Finally, the tags in the four types of sessions can be read without missing or without redundancy in high populations and dynamic environments. An RFID reader gate that consists of multiple readers for each session is able to read the returned product, as well as every component in the product, simultaneously. This is expected to be helpful for inventory management problems of various types of components.

The proposed system facilitates systematic disassembly process by deciding disassembly level with decision support system at the outset of book-in stage. Positive effects on remanufacturing shop floor in detail, including systematic disassembly, will be illustrated in Section 6.

4.3. Design of Data Architecture

A data architecture is designed for RFID tags, and the backend database that supports the operation of the proposed system. Even though the capacity of RFID tags is increasing, there is obviously a limit. Therefore, it is important to discuss which data should be stored and how data should be stored efficiently. The proposed system stores the required minimum information in RFID tags in a unified format and the remainder in the backend database in a relational form.

First, RFID encoding scheme is proposed. In this dissertation, the focus is on bank01 (EPC) — which provides a unique identity for each individual item — and bank11 (user memory), among four banks logically separated.

The Component/Part Identifier (CPI) encoding scheme is considered, which was originally designed for the unique identification of parts or components in technical industries (such as the automotive industry), to represent an EPC [100]. Its structure is similar to that of other standards with a header, filter value, partition value, GS1 company prefix, component/part reference, and serial number. The CPI standard is divided into CPI-96, which has a fixed space of 96 bits, and CPI-var, which has a variable space ranging from 86 to 224 bits, as listed in <Table 4.2>.

<Table 4.2> Comparison of CPI-96 and CPI-var encoding schemes

Scheme	CPI-96	CPI-var
Total bits	96	86~224
Header	8	8
Header value (binary/hexadecimal)	00111100/3C	00111101/3D
Filter	3	3
Partition	3	3
GS1 company prefix	20-40	20-40
Component/Part reference	31-11	12-150
Serial	31	40

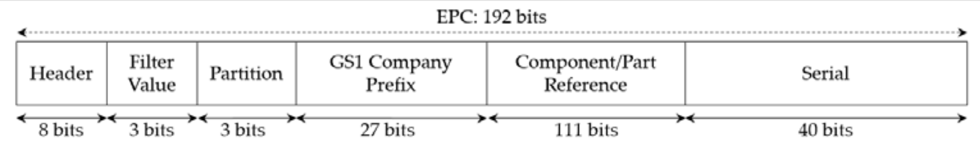
The CPI standard has variable space for GS1 company prefix and component/part reference, which is controlled by partition value as presented in <Table 4.3>.

<Table 4.3> CPI-var partition table

Partition Value	**GS1 company prefix**		**Component/Part reference**	
	Bits	**Digits**	**Maximum bits**	**Maximum characters**
0	40	12	114	18
1	37	11	120	19
2	34	10	126	20
3	30	9	132	21
4	27	8	138	22
5	24	7	144	23
6	20	6	150	24

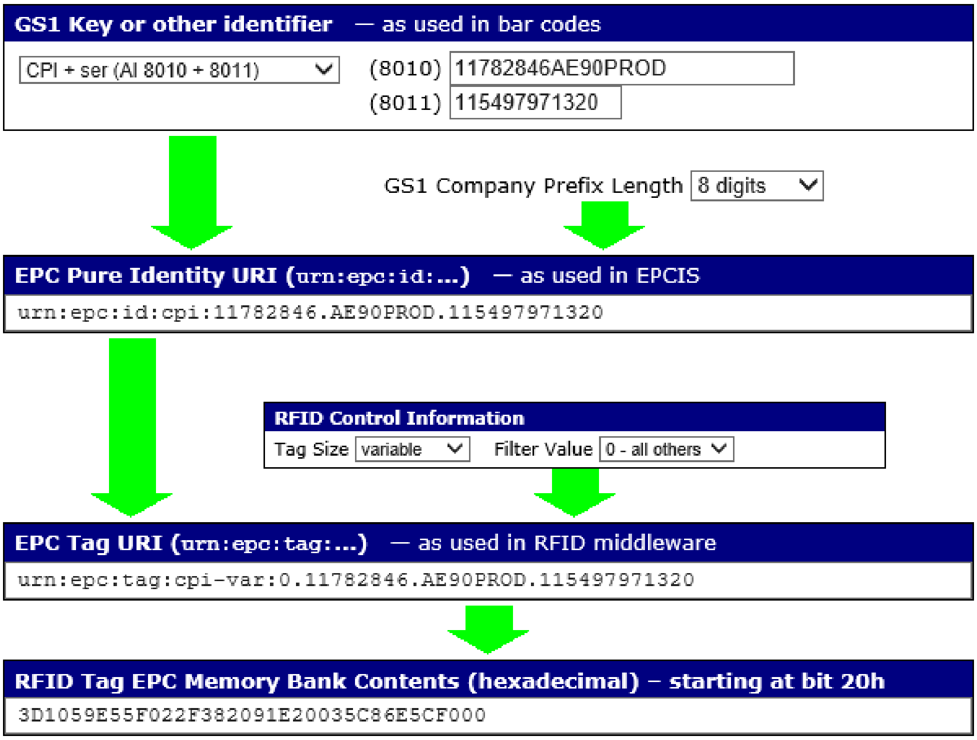
The CPI-192 encoding scheme (diagrammatically presented in <Figure 4.7>) is proposed with partition value of 4, which identifies more than 3.5 X

10^{53} respective items, by assigning 27 bits to represent the GS1 company prefix, 111 bits to represent the component/part reference, and 40 bits to represent the serial number. The proposed encoding scheme can minimize the waste of register capacity as one of the computational resources because the processor runs in 32 or 64 bits and 192 bits is the largest common multiple of 32 and 64 among the available space provided by CPI-var.



<Figure 4.7> Proposed CPI-192 EPC encoding scheme

GS1 company prefix that identifies companies, has usually 8-digit integers. Component/part reference has 8-digit characters. Finally, serial has 12-digit integers as an identifier. For convenience, an encoding scheme for part reference is proposed as follows: first 3 digits indicate product family; fourth digit indicates BOM level; last 4 digits indicate part name. Example of CPI-192 encoding scheme is presented in <Figure 4.8>. In this example, an object tagged belongs to product family 'AE9' in BOM level 0.



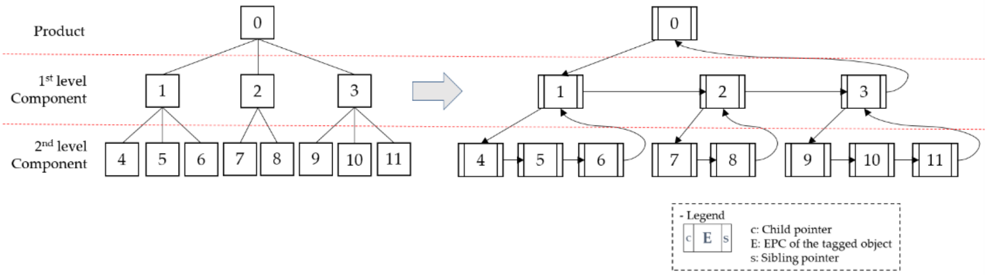
<Figure 4.8> Example of the proposed CPI-192 encoding scheme
(source: GS1 EPC encoder/decoder)

The user memory architecture should be designed more cautiously than the design of EPC, which simply follows predefined standards. Because the available space is definitely limited even though it has been on the rise. Then it is important to determine which data should be stored and how to store it efficiently to ensure that the user memory encoding is stable to achieve interoperability. RFID tags have been used to represent a unique identity for the tagged object. In this context, the proposed system uses the user memory space to represent family relations about the tagged item as a part of the identity, by using a partial ring structure with child and sibling pointers. A physical representation by using child and sibling pointers to represent a tree structure, as is the case for family relations, is used in the IBM Information

Management System (IMS) hierarchical database management system [117]. A file of which the attribute has multiple values, such as a parent with multiple children, is known as a not-quite-flat file. The use of a variable-length record to store this kind of file would not be problematic. However, using a variable-length record is not unrealistic because many software products only permit the use of fixed-length records and the additional establishment of an encoding standard would not be beneficial. Well-known ways in which to store a not-quite-flat file with fixed-length records are as follows:

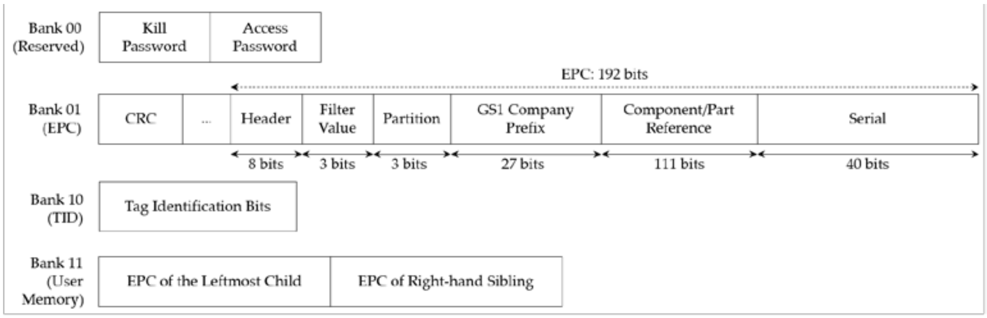
- Include space in the memory for the maximum possible number of records;
- Store in separate records and indicate the location by pointer;
- Include space for partial storage in the memory, store overflowed records separately and indicate them by pointer.

The first option is wasteful in terms of memory space and it is also unstable because the maximum possible number of records varies with circumstances. The other options are a burden on separate space. At this point, a partial ring structure in which every node has uniform record length is proposed, with child and sibling pointers that represent family relations among components and indicate only the leftmost child and right-hand sibling. In the proposed structure nodes, the lowest level has a null value as a child pointer. However, a sibling pointer of the rightmost node among the nodes with the same parent, indicates its parent in order to form a chain, as shown in <Figure 4.9>.



<Figure 4.9> Proposed partial ring structure

The overall memory map of the Gen2 tag that contains CPI-192 standard in EPC bank and family relationship in user memory bank is shown in <Figure 4.10>.



<Figure 4.10> Overall Gen2 RFID tag memory map

As stated above, a backend database contains information in a relational form to support CLSC operations. Relational database is consist of multiple tables [118]. <Table 4.4> explains, which entity types (it also called ‘table’) consist of the backend database, which attributes consist of each entity type, the role of each entity type, and data types for each attribute.

<Table 4.4> Entity type descriptions

Name of entity type (table)	**Contained information**	**Attribute**	**Data type of attribute**
PRODUCTION	Production-related	EPC	Composite attribute: • CompanyPrefix: INT(8) • PartReference: VARCHAR(8) • Serial: INT(12)
		ParentEPC	(Same as EPC)
		BirthDate	DATE
		DeathDate	DATE
		RemfgDate	DATE
BOM_ DATA	Product structure, component specifications	PartReference	VARCHAR(8)
		ChildPart Reference	VARCHAR(8)
		SiblingPart Reference	VARCHAR(8)
		Mass	(DOUBLE) [1]
DFR	Job instructions about product recycling by part references and recycling options	PartReference	VARCHAR(8)
		EOLOption	INT
		JobDescription	VARCHAR
MRO_ LOG	Maintenance/service log in the MOL phase	MRO ID	INT
		EPC	(Same as EPC)
		MRO DATE	DATE
		MRODescription	VARCHAR
WORK_ LIST	Generated list of recycling jobs for each component	WorkNo	INT
		EPC	(Same as EPC)
		EOLOption	INT
		PrecedentWorkNo	INT
WORK_ RESULT	List of results for recycling jobs done	WorkNo	INT
		WorkDate	DATE
		EPC	(Same as EPC)
		EOLOption	INT
		EOLResult	(DOUBLE) [1]

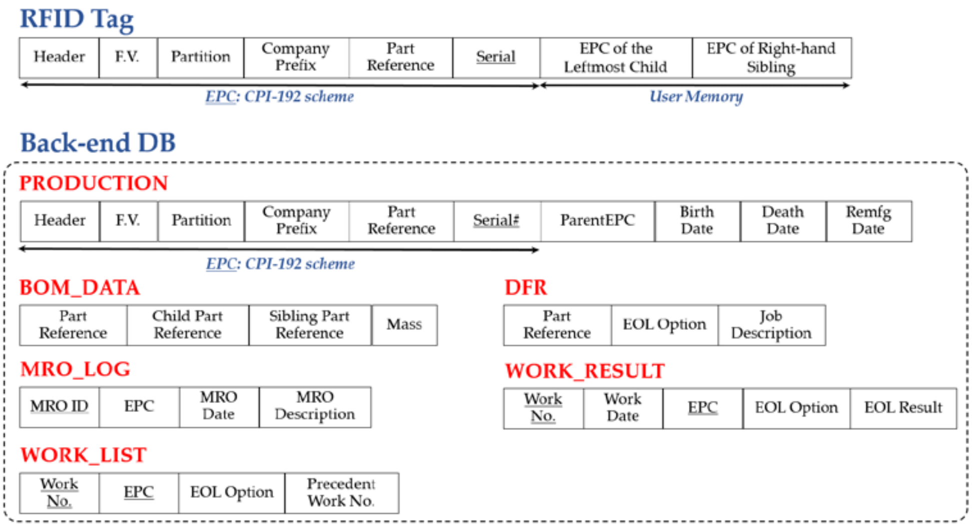
[1] Attributes that are not considered detailedly in this dissertation

EPC is a composite attribute that can be divided to multiple simple attributes; every attribute is simple attribute except the EPC. Composite attribute is used to refer to the value itself, or to a specific simple attribute. EPC, itself, is a unique identifier of an object. However, the proposed system only refers to the contents contained in the EPC including part references. This is the reason why EPC is designed as a composite attribute. <Table 4.5> shows the description of which value of EOLOption indicates.

<Table 4.5> Descriptions by values of EOLOption

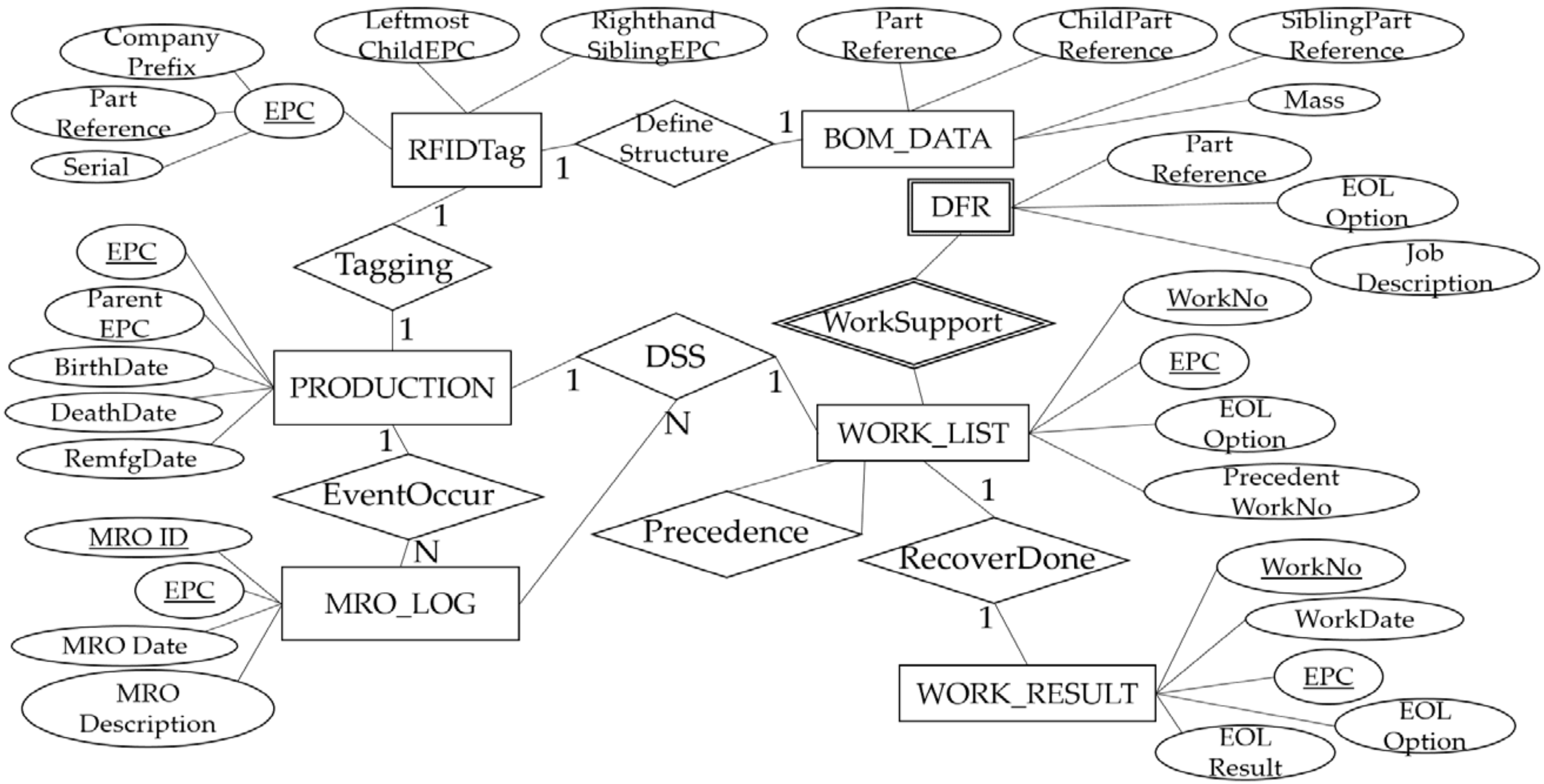
EOLOption	Description (for the components that cannot be disassembled)	Description (for the components that can be disassembled)
1	Reuse	Reuse
2	Remanufacture	Remanufacture
3	Material recovery	Disassembly

Conceptual design and corresponding conceptual schema are carried out in this dissertation in order to apply without regard to the type of DBMS (database management system). <Figure 4.11> presents overall conceptual database schema including backend database and RFID tags, which satisfies entity and referential integrity constraints.



<Figure 4.11> Conceptual database schema for the proposed system

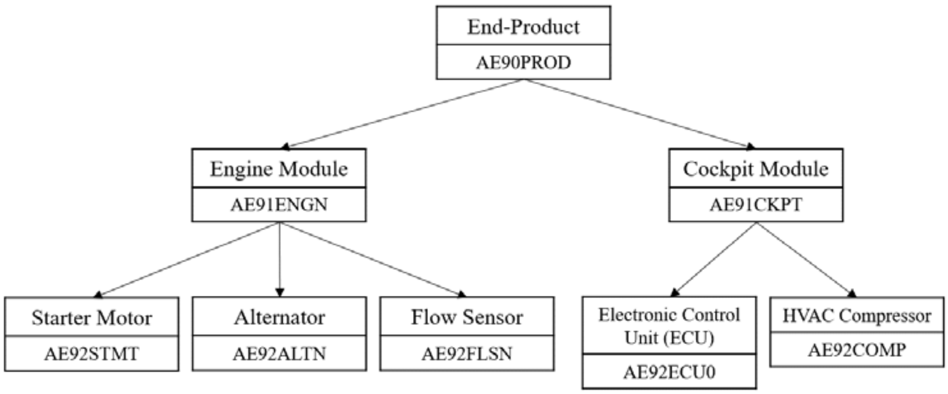
Accordingly, an entity-relationship diagram (E-R diagram) is presented which defines relationships among entity types as shown in <Figure 4.12>. Interactions between entity types will be illustrated in the next subsection.



<Figure 4.12> E-R diagram for the proposed system

4.4. Database Transactions for Potential Effects

In this subsection, database transactions are illustrated with the example of automotive products as presented in <Figure 4.13>.



<Figure 4.13> Example: BOM structure of the automotive product

The BOL phase of an item (components, modules, and products) starts from manufacturing of itself. For example of manufacturing of an engine module by assembly of a starter motor, an alternator, and a flow sensor. Firstly, components in the lowest level are tagged individually right after their production as shown in the upper side of <Figure 4.14>. Also, production-related information such as EPC, BirthDate is stored in PRODUCTION table. Likewise, when an engine module is produced, a tag is attached to it. Family relations among the components of the engine module occur. According to the predefined BOM structure (diagrammatically presented in <Figure 4.13>), an engine module is a parent of starter motor, alternator, and flow sensor; alternator is a sibling of starter motor; flow sensor is sibling of alternator; finally, engine module is a sibling of flow sensor.

RFTAG

EPC	CHILDEPC	SIBLINGEPC
11782486.AE92STMT.184354879655	(null)	(null)
11782486.AE92ALTN.204857450979	(null)	(null)
11782486.AE92FLSN.551388754465	(null)	(null)

PRODUCTION

EPC	PARENTEPC	BIRTHDATE	DEATHDATE	REMFGDATE
11782486.AE92ALTN.204857450979	(null)	17/10/30	(null)	(null)
11782486.AE92FLSN.551388754465	(null)	17/10/30	(null)	(null)
11782486.AE92STMT.184354879655	(null)	17/10/30	(null)	(null)

assembly

RFTAG

EPC	CHILDEPC	SIBLINGEPC
11782486.AE91ENGN.554899350016	11782486.AE92STMT.184354879655 (1)	(null) (2)
11782486.AE92ALTN.204857450979	(null)	11782486.AE92FLSN.551388754465
11782486.AE92FLSN.551388754465	(null)	11782486.AE91ENGN.554899350016
11782486.AE92STMT.184354879655	(null)	11782486.AE92ALTN.204857450979

PRODUCTION

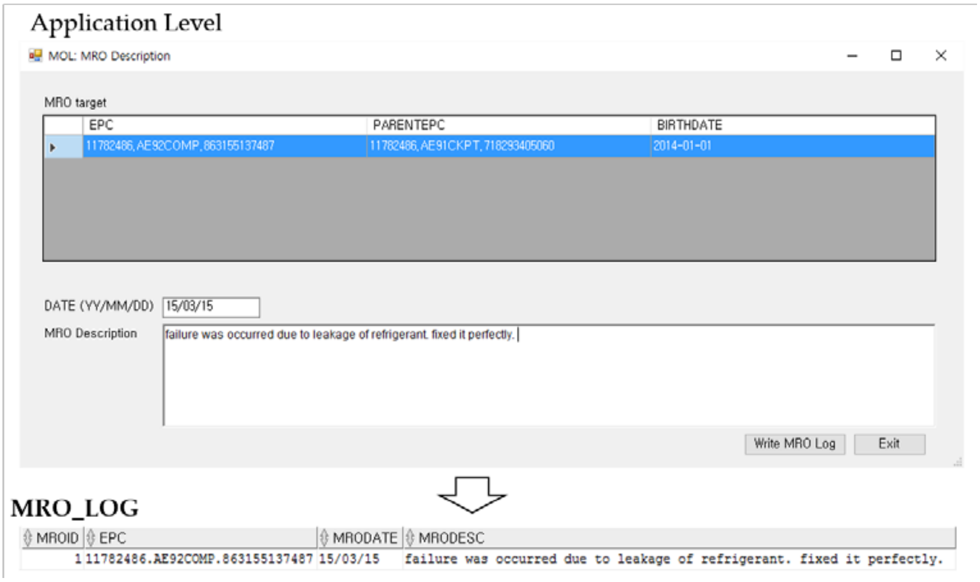
EPC	PARENTEPC	BIRTHDATE	DEATHDATE	REMFGDATE
11782486.AE91ENGN.554899350016	(null) (3)	17/10/31	(null)	(null)
11782486.AE92ALTN.204857450979	11782486.AE91ENGN.554899350016	17/10/30	(null)	(null)
11782486.AE92FLSN.551388754465	11782486.AE91ENGN.554899350016	17/10/30	(null)	(null)
11782486.AE92STMT.184354879655	11782486.AE91ENGN.554899350016	17/10/30	(null)	(null)

<Figure 4.14> Database changes with module manufacturing

For RFID tags, family relations stored in their user memory are presented in the lower side of <Figure 4.14>, and also as follows: (1) Engine module has the EPC of the leftmost child, starter motor, in ChildEPC attribute; (2) For the lowest level components, they have EPC of right-hand sibling in SiblingEPC attribute. In the PRODUCTION table, family relations are stored in a bottom-up direction: (3) The lowest level components have EPC of the engine module as a ParentEPC. Also, encoded family relations in the BOL phas7e, should be updated for RFID tags and PRODUCTION table both, when substitution is made in the MOL phase.

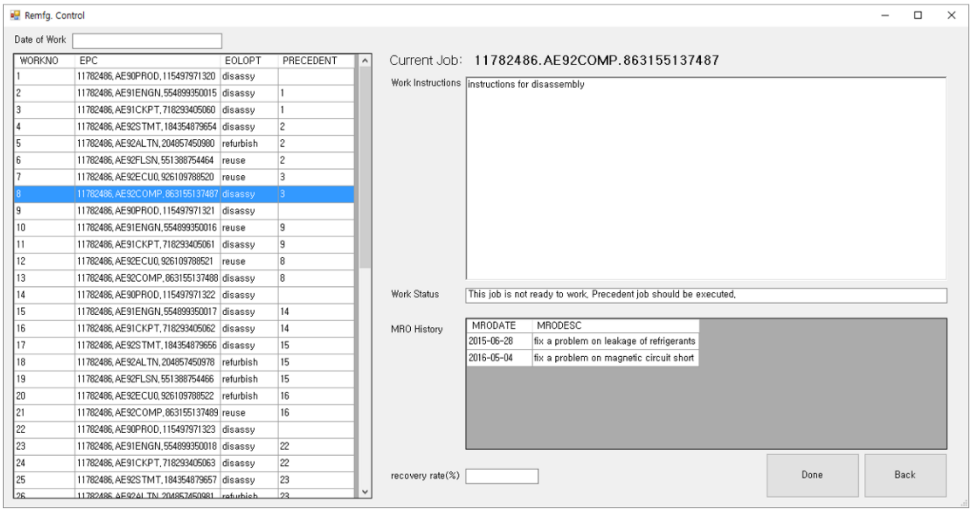
Stored family relations facilitate counterfeit prevention on product structure. In this dissertation, cross-checking – which compares

PRODUCTION table in the backend database and user memory, and sweeping scan – which compares family relations in user memory in a tag-by-tag manner – are proposed to avoid structural counterfeits. Detailed explanation of counterfeit prevention approaches will be explained in subsection 5.2.



<Figure 4.15> Storing MRO operations in the MOL phase

Another transaction in the MOL phase is about MROs. For example as depicted in <Figure 4.15>, a compressor was failed due to leakage of refrigerant, however it was fixed perfectly. MRO_LOG table contains a log for this MRO event to provide this information when it is needed. This kind of information can be a clue to estimate residual value when automated grading with decision support system is executed. For example, even though a component has been used in a short period of time, if a component has a critical failure, it cannot be remanufactured. Else if the component goes to shop floor to be remanufactured, a worker will be able to concentrate on the work by referring to the MRO logs. Workers on the shop floor also could be supported as depicted in <Figure 4.16>.



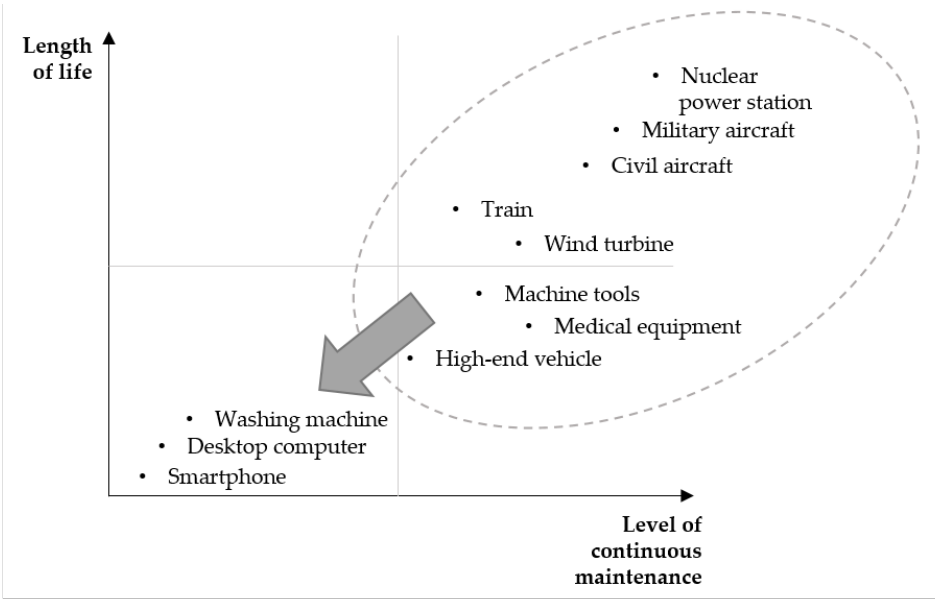
<Figure 4.16> Shop floor worker support application

When a target item is identified by RFID, after arrival in shop floor, workers may have explicit instruction – part reference, defined recycling option for the job, what should be recovered from this component, and so forth. It helps workers to do their job accurately by minimizing human errors.

5. System Implementation in the MOL Phase

5.1. Real-time Monitoring and Maintenance

Prior to entry this subsection, although real-time monitoring maintenance (RMM) is one of potential benefits could be derived from the proposed system, detailed technical approaches are not covered by this dissertation. Related concepts will be introduced instead of detailed approaches in this subsection.



<Figure 5.1> Scope of continuous maintenance and its diffusion direction. Reproduced from reference [119].

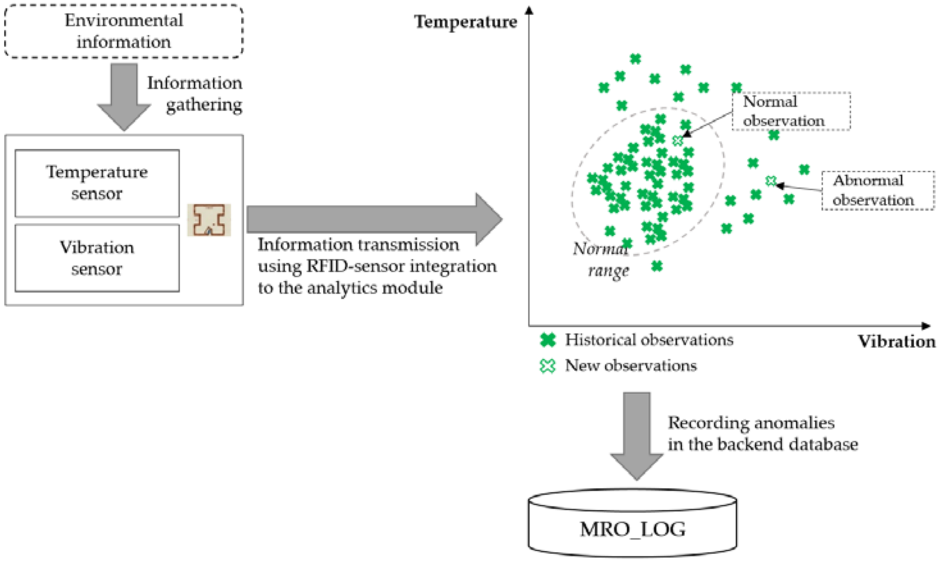
Research efforts and implementations of continuous maintenance has been done for high valued products, which has following perspectives:

- Technology intensive;
- Expensive;
- Reliability should be guaranteed critically.

However, the scope of continuous maintenance will be expanded in a left-bottom direction, as depicted in <Figure 5.1>, with product servitization in addition to the proliferation of IoT. Hence, it will be expanded for the consumer products such as automotive.

Real-time monitoring can be facilitated either by auxiliary sensor network [120], or by analyzing machine signals [121]. Based on differences in how information is acquired and draws conclusions, diagnostic and prognostic tools can be divided into data-driven or model-based since Vachtsevanos *et al.* (2007) claimed [122]. Diagnostics is to determine which component or module is causing a failure on the system; and prognostics is to estimate the residual value.

Considering cost and applicability, data-driven monitoring and diagnostics would be suitable for consumer products with auxiliary sensors.



<Figure 5.2> Framework for RMM

Let there be a component that significantly affected by temperature and vibration. It means that there is a normal range of observations which indicates that a component is in normal condition. By using RFID-sensor integration scenario, a component that has sensors to gather information about temperature and vibration transmits the information to the analytics module as depicted in <Figure 5.2>. If the analytics module detects an anomaly among the observations, it informs the customer to prevent a serious failure before it occurs.

There are various types of RFID-based sensor integration as listed in <Table 5.1>. It can be divided into hardware integration and virtual integration depending on how the sensor data is transmitted. Also, virtual integration can be divided into adjacent and ambient depending on where the sensor is located.

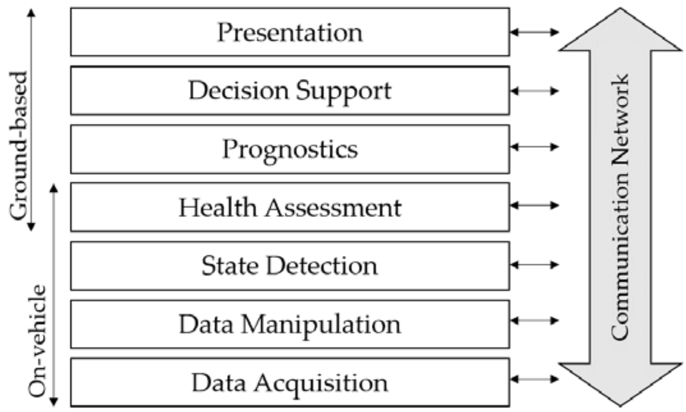
<Table 5.1> Category of RFID-based sensor integration

<table>
<tr><td>Hardware Integration</td><td colspan="2">Sensor data is read through the radio frequency interface</td></tr>
<tr><td rowspan="3">Virtual Integration</td><td colspan="2">Sensor data is logically associated with the identity of the objects</td></tr>
<tr><td>Adjacent</td><td>Sensor is on the tagged object</td></tr>
<tr><td>Ambient</td><td>Sensor is in the environment of the tagged object</td></tr>
</table>

Virtual integration would be better to implement RMM. Hardware integrated sensors seems to be impractical, because it need especially long-life batteries. Also, if sensor data is rarely synchronized with external database, data loss due to battery loss or failure has to be considered. On the other side, end users are free in terms of system integration with virtual integration. This is not limited by tag manufacturers and developer tools because integration relies on software.

The analytics module facilitates finding hidden patterns among the observations by using data-driven methods. Especially, artificial neural network (ANN), Bayesian networks (BN), evolutionary algorithms, and stochastic petri nets (SPN) have been used for monitoring and diagnostics with numerous examples of successful applications. Data-driven methods can be categorized to classification, regression, clustering, summarization, dependency modeling or association rule learning, and change and deviation detection according to objectives [123]. Among these categories, RMM uses classification or clustering methods in order to detect anomalies which are far from the normal range. K-means algorithm, Gaussian mixture model, regression tree, ensemble method, naïve Bayes classifier, k-NN (Nearest Neighbor), and support vector machine are the representative methods to be used to this kind of system.

Standardization is important to implement the system, then it has been addressed to interface various types of sensors and protocols. To achieve interoperability, the OSA-CBM (Open System Architecture for Condition-Based Maintenance), which defines a seven-layered approach as depicted in <Figure 5.3> using the unified modeling language (UML), was proposed with participants from a wide range of industrial, commercial, and military sector. This architecture consists of following layers: Data Acquisition (DA), Data Manipulation (DM), State Detection (SD), Health Assessment (HA), Prognostics Assessment (PA), Decision Support (DS), and Presentation (PR).



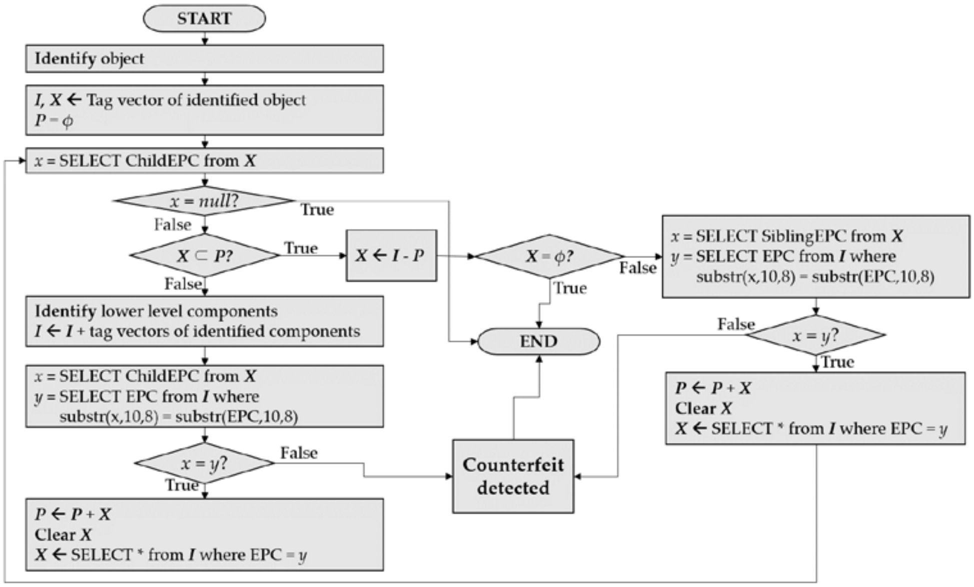
<Figure 5.3> OSA-CBM layers [124]

Many companies in the aerospace sector has pursued the development of the standard and implementation for vehicle health management [125, 126]. Based on this efforts, the scope is not limited to aerospace sector, it is expanding to ground vehicles [127-130].

5.2. Counterfeit Prevention

Several kinds of problems are associated with counterfeit products. For example, if a customer who has a counterfeited product wants to repair or exchange it according to the warranty, the warranty service could be denied as a result of the indication of the product being counterfeit. Furthermore, the proposed system prevents forgery of the product history in a way similar to the deletion of accident logs. It is important to address these kinds of security problems for the sake of public order in the second-hand market, which is growing. In Section 5.2, two approaches—sweeping scan and cross-checking— to detect falsification of product structure are proposed.

Sweeping scan detects counterfeits by comparing family relations in RFID user memory within a product and components. Flowchart of the approach is presented in <Figure 5.4>.



<Figure 5.4> Flowchart of sweeping scan approach

Nomenclature for <Figure 5.4> is listed in <Table 5.2>.

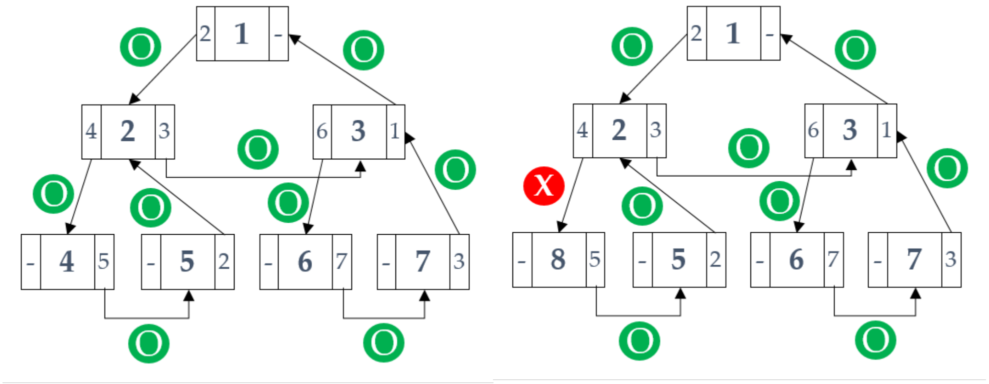
<Table 5.2> Nomenclature for the flowchart of sweeping scan

Variable	Type	Description
$\boldsymbol{X}$	set	Set of tag vector of examination target
$\boldsymbol{I}$	set	Set of tag vectors of identified components
$\boldsymbol{P}$	set	Set of tag vectors which are examined previously
x	element	ChildEPC or SiblingEPC of target component
y	element	Actual EPC of comparison target

Tag vectors consist of information which is stored in RFID tags. It have three elements as follows:

$$\text{Tag vector } \vec{v} = (ChildEPC, EPC, SiblingEPC)$$

The sweeping scan is employed in the top-down direction. At first, a product and an EPC of its leftmost child are identified in the first level. Then, an actual EPC of the leftmost child in the first level is compared with a previously identified EPC in the user memory of the product. If these values are different, falsification on product structure could be detected. For the first level component, falsification is also detected by comparing actual EPCs and identified EPCs of its leftmost child and its right-hand sibling in its user memory. Thereafter, every linkage between components, as well as the product can be compared by sweeping in a counterclockwise direction as defined in the proposed partial ring structure. <Figure 5.5> is presented to explain how sweeping scan works with simplified example for better understanding.



(a) **(b)**

<Figure 5.5> Simplified examples: (**a**) No counterfeit; (**b**) Counterfeited

For example in <Figure 5.5(a)>, a procedure of sweeping scan is described in <Table 5.2>. The sweeping scan procedure terminates without breaks because there is no counterfeit. However, the procedure will be terminated in the fourth step while the example in <Figure 5.5(b)> processed. Because set X and set I have no common node.

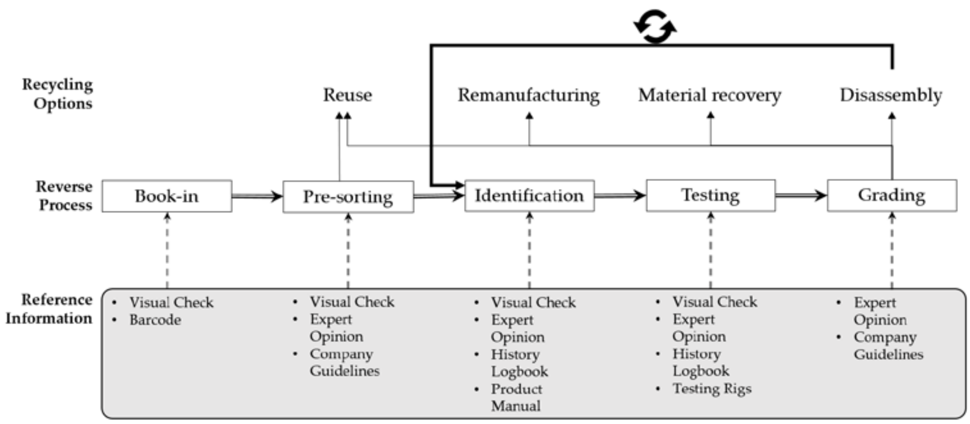
<Table 5.3> Procedure for sweeping scan

(Seq.no.)Type	*set X*	*set I*	*set P*	x	y	Description
(1) Initial	(2,1,-)	(2,1,-)	ϕ	2		There is a child.
(2) Child	(2,1,-)	(2,1,-), **(4,2,3)**, (6,3,1)	ϕ	2	2	Matched.
(3) Changing target	(4,2,3)	(2,1,-), (4,2,3), (6,3,1)	(2,1,-)	4		There is a child, and set ***(I-P)*** is not null.
(4) Child	(4,2,3)	(2,1,-), (4,2,3), (6,3,1), **(-,4,5),** (-,5,2)	(2,1,-)	4	4	Matched.
(5) Changing target	(-,4,5)	(2,1,-), (4,2,3), (6,3,1),(-,4,5), (-,5,2)	(2,1,-), (4,2,3)	-		There is no child. Then, go to sibling.
(6) Sibling	(-,4,5)	(2,1,-), (4,2,3), (6,3,1), (-,4,5), **(-,5,2)**	(2,1,-), (4,2,3)	5	5	Matched.
(7) Changing target	(-,5,2)	(2,1,-), (4,2,3), (6,3,1), (-,4,5), (-,5,2)	(2,1,-), (4,2,3), (-,4,5)			There is no child. Then, go to sibling.
(8) Sibling	(-,5,2)	(2,1,-), **(4,2,3),** (6,3,1), (-,4,5), (-,5,2)	(2,1,-), (4,2,3), (-,4,5)	2	2	Matched.
(9) Changing target	(4,2,3)	(2,1,-), (4,2,3), **(6,3,1),** (-,4,5), (-,5,2)	(2,1,-), (4,2,3), (-,4,5), (-,5,2)			There is a child but it was treated already. Then, go to ***(I-P)***, (6,3,1).
(10) Changing target	(6,3,1)	(2,1,-), (4,2,3), (6,3,1), (-,4,5), (-,5,2)	(2,1,-), (4,2,3), (-,4,5), (-,5,2)			There is a child, and set ***(I-P)*** is not null.
(11) Child	(6,3,1)	all nodes including **(-,6,7)**	(2,1,-), (4,2,3), (-,4,5), (-,5,2)	6	6	Matched.
(12) Changing target	(-,6,7)	all nodes	(2,1,-), (4,2,3), (-,4,5), (-,5,2), (6,3,1)			There is no child. Then, go to sibling.
(13) Sibling	(-,6,7)	all nodes including **(-,7,3)**	(2,1,-), (4,2,3), (-,4,5), (-,5,2), (6,3,1)	7	7	Matched.
(14) Changing target	(-,7,3)	all nodes	(2,1,-), (4,2,3), (-,4,5), (-,5,2), (6,3,1), (-,6,7)			There is no child. Then, go to sibling.
(15) Sibling	(-,7,3)	all nodes including **(6,3,1)**	(2,1,-), (4,2,3), (-,4,5), (-,5,2), (6,3,1), (-,6,7)	3	3	Matched.
(16) Changing target	(6,3,1)	all nodes	all nodes			There is a child but it was treated already; And ***I-P* = ϕ**.

6. Remanufacturing Process Streamlining

6.1. Elimination of the Unnecessary Loop

As presented in Parlikad and McFarlane [38], conventional recycling process goes through the sequence book-in, pre-sorting, identification, testing, and grading.

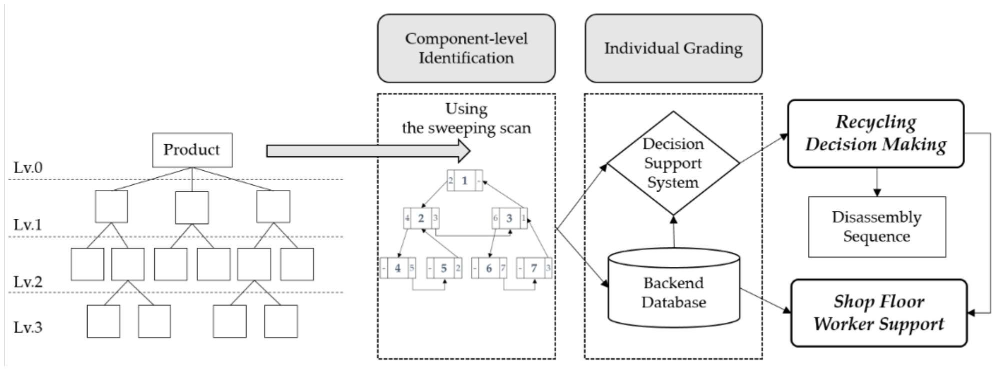


<Figure 6.1> Unnecessary loop in the conventional recycling process

In the pre-sorting stage, items that could be reused with minimal repair are sorted out based on company guidelines, expert opinion, and aesthetic conditions. Otherwise, recycling options are decided for each item to determine how to recycle through identification, testing, and grading process. This recycling process seems to be feasible for the single-product which does not have any functional subcomponent. However, the products that could be handled by the proposed system, consist of many functional units with numerous components. To recycle this kind of products, there exists an unnecessary loop that consists of identification, testing, and grading as shown in <Figure 6.1>. At first, a product is disassembled to first level components usually, because reuse of an EOL product without any disassembly is rarely happens. For the disassembled first level components, the history log and expert opinion after identification will be used for grading, on which a decision for the appropriate recycling option is based. If the component is graded as good-to-reuse or good-to-remanufacture, it goes to the shop floor. Otherwise it should be disassembled to lower level components, and the same loop of identification, grading, and testing for the lower level components should be performed iteratively until the lowest level is reached. Let this situation be *Recycling Policy 1*.

For another recycling policy *Recycling Policy 2*, it is assumed that the system dismantles the product to the lowest level components unconditionally without any grading, and that a recycling decision is made only for them, to avoid the unnecessary loop as well as hidden potential failure causes.

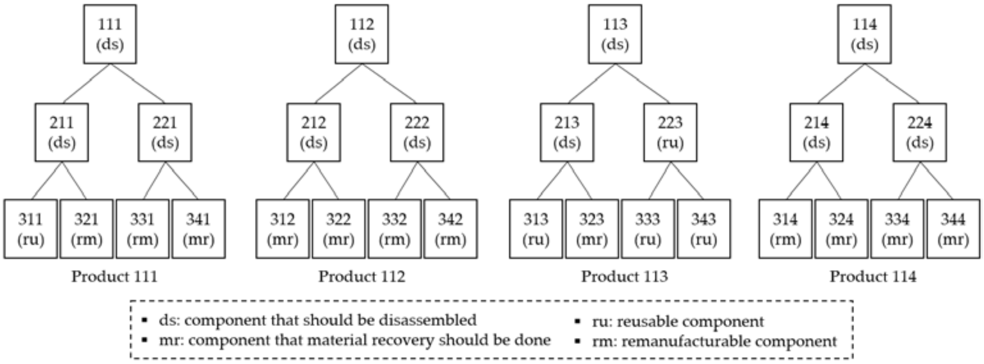
In this subsection, enhanced recycling process is derived by using the proposed system as depicted in <Figure 6.2>. The proposed system facilitates component-level individual identification by using the sweeping scan approach. When an EOL product arrives in the book-in stage, the system identifies the product as well as every component in the product. After the identification step, the decision support system selects a recycling option for each component based on lifecycle information gathered during the whole product lifecycle. Subsequently, the corresponding job sequence for recycling is derived. Thereafter, the remanufacturing work is carried out according to the job sequence on the remanufacturing shop floor. When the worker receives the job, the MRO logs and the job instruction are displayed on the monitor for worker support.



<Figure 6.2> Enhanced recycling process

In the *PPS*, a recycling policy for the proposed system, a component that is worth reuse or remanufacturing goes to the shop floor after testing; other components will be disassembled or recovered as raw materials.

An illustrative example is presented to show how the proposed system differs from the conventional remanufacturing systems. Let there be four returned products, all with different qualities as shown in <Figure 6.3>. Each box indicates a component and a number in the box indicates an EPC of each item. Each digit in the 3-digit EPC in the example indicates as follows; first digit indicates the BOM level, second digit indicates part types, and the last digit indicates the serial number. An appropriate recycling option of whether to reuse, remanufacture, disassemble, or recover in raw materials — as derived from the decision support system for each item— is given in parentheses.



<Figure 6.3> Example: returned products and qualities of items

To do recycling activities for product 113 in the example, the product is dismantled first because reuse or remanufacturing at the product level is rarely happened in the general situation. For *Recycling Policy 1*, components 213 and 223 are identified and graded. Then, component 223 goes to the shop floor for reuse, and 213 is disassembled. Components 313 and 323, derived from 213, are also treated according to their recycling options after identification and grading. For *Recycling Policy 2*, a product and every component at the first level are disassembled. Then second level components are recycled after identification and grading. *PPS* is different to other scenarios because identification and grading for every component in a product is executed at the first scan. Then, disassembly of 113 and 213, and material recovery of 323, are executed consecutively; material recovery of component 323 is executed without any test. The other components, 223 and 313, are reused after testing, according to the recycling decision made during the first scan. <Table 6.1> presents job sequences to recycle four products in the example for each recycling policy.

<Table 6.1> Job sequences for each recycling policy

Recycling policy	Job sequence
Recycling Policy 1	ds111 > ig211 > ds211 > ig311 > t311 > ru311 > ig321 > t321 > rm321 > ig221 > ds221 > ig331 > t331 > rm331 > ig341 > t341 > mr341 ds112 > ig212 > ds212 > ig312 > t312 > mr312 > ig322 > t322 > mr322 > ig222 > ds222 > ig332 > t332 > rm332 > ig342 > t342 > rm342 ds113 > ig213 > ds213 > ig313 > t313 > ru313 > ig323 > t323 > mr323 > ig223 > t223 > ru223 ds114 > ig214 > ds214 > ig314 > t314 > rm314 > ig324 > t324 > mr324 > ig224 > ds224 > ig334 > t334 > mr334 > ig344 > t344 > mr344
Recycling Policy 2	ds111 > ds211 > ds221 > ig311 > t311 > ru311 > ig321 > t321 > rm321 > ig331 > t331 > rm331 > ig341 > t341 > mr341 ds112 > ds212 > ds222 > ig312 > t312 > mr312 > ig322 > t322 > mr322 > ig332 > t332 > rm332 > ig342 > t342 > rm342 ds113 > ds213 > ds223 > ig313 > t313 > ru313 > ig323 > t323 > mr323 > ig333 > t333 > ru333 > ig343 > t343 > ru343 ds114 > ds214 > ds224 > ig314 > t314 > rm314 > ig324 > t324 > mr324 > ig334 > t334 > mr334 > ig344 > t344 > mr344
PPS	IG111 > ds111 > ds211 > t311 > ru311 > t321 > rm321 > ds221 > t331 > rm331 > mr341 IG112 > ds112 > ds212 > mr312 > mr322 > ds222 > t332 > rm332 > t342 > rm342 IG113 > ds113 > ds213 > t313 > ru313 > mr323 > t223 > ru223 IG114 > ds114 > ds214 > t314 > rm314 > mr324 > ds224 > mr334 > mr344

* Legends: ds(disassembly), ig(identification & grading), t(testing)
IG(identification & grading in the proposed system)
ru(reuse), rm(remanufacture), mr(material recovery)

The number of components for disassembly, identification and grading, and testing is calculated for each recycling policy. The result, as listed in <Table 6.2>, shows that the proposed system is more efficient than the others, and that *Recycling Policy 2* is better than *Recycling Policy 1* in terms of total number of jobs.

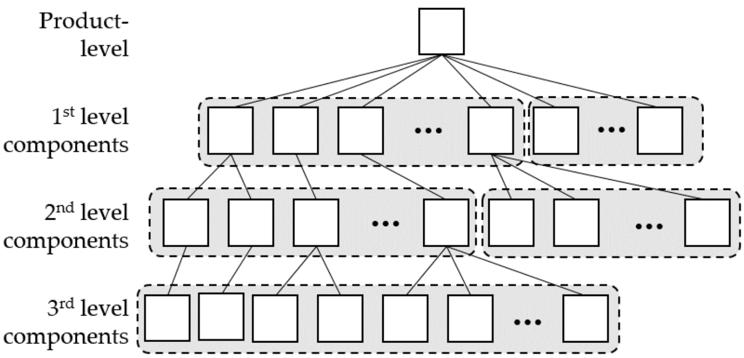
<Table 6.2> Number of jobs by type of process for each recycling policy

Recycling policy	***Recycling Policy 1***				***Recycling Policy 2***				***PPS***			
Type of Process	**ds**	**ig**	**t**	**subtotal**	**ds**	**ig**	**t**	**subtotal**	**ds**	**IG**	**t**	**subtotal**
Product 111	3	6	4	13	3	4	4	11	3	1	3	7
Product 112	3	6	4	13	3	4	4	11	3	1	2	6
Product 113	2	4	3	9	3	4	4	11	2	1	2	5
Product 114	3	6	4	13	3	4	4	11	3	1	1	5
Total	11	22	15	**48**	12	16	16	**44**	11	4	8	**23**

However, considering processing cost or time, *Recycling Policy 2* is the worst scenario due to disassembly cost, which is more than the costs of other processes. Moreover, *Recycling Policy 2* is worse than the others in terms of resource efficiency and opportunity cost, because remanufacturable or reusable upper-level components are disassembled rather than remanufactured or reused. In addition, it entails additional costs for unnecessary disassembly jobs. For the illustrative example, the unnecessary disassembly job is occurred in recycling product 113. Component 223 was dismantled even though component 223 is reusable as previously indicated. Hence, it concludes that *Recycling Policy 1* is optimistic to the probabilities of reuse and remanufacturing; *Recycling Policy 2* is pessimistic to the probabilities.

6.2. A Requisite for Enhancement

Until now, performance of presented recycling policies is compared by the number of jobs only. From now on, recycling policies are evaluated in consideration of processing time of each process. Before evaluation, it is presented how to calculate expected number of recycling jobs for modular products which have a BOM structure presented in <Figure 6.4>.



For the 1st level components	# of branching nodes = p_1, # of terminal nodes = p_2 Probability of branching = α
For the 2nd level components	# of branching nodes = q_1, # of terminal nodes = q_2 Probability of branching = β
For the 3rd level components	# of terminal nodes = r Probability of material recovery = γ

<Figure 6.4> BOM structure of modular products

Let assume that there is a product that consists of (p_1 + p_2) 1st level components, ($q_1 + q_2$) 2nd level components, and r 3rd level components. p_1 in the 1st level components, and q_1 in the 2nd level components have no child; and probability of branching, which means that probability of disassembly or material recovery, is identical within a BOM level. For this products, expected number of recycling jobs for each recycling policy is presented in <Table 6.3>.

<Table 6.3> Expected number of recycling jobs for each recycling policy

Recycling policy	**BOM level**	**Type of process**	**Expected number of jobs**
Recycling Policy 1	1st level	ig	$p_1 + p_2$
		ds	αp_1
		t	p_2
	2nd level	ig	$\alpha(q_1 + q_2)$
		ds	$\alpha\beta q_1$
		t	q_2
	3rd level	ig	$\alpha\beta r$
		t	$\alpha\beta r$
Recycling Policy 2	Whole level	ig	$p_2 + q_2 + r$
		ds	$p_1 + q_1$
		t	$p_2 + q_2 + r$
RP3	Initial	IG	1
	1st level	ds	αp_1
		t	$(1-\alpha)p_2$
	2nd level	ds	$\alpha\beta q_1$
		t	$(1-\beta)q_2$
	3rd level	t	$\alpha\beta(1-\gamma)r$

Let the unit costs of each type of recycling process, including the cost of simultaneous identification and grading which is from the proposed system, are presented as follows. Also, it is assumed that the cost of each process is identical to the type of products and components.

- cost of disassembly: c_d
- cost of identification and grading: c_{ig}
- cost of testing: c_t
- cost of simultaneous identification and grading: c_{IG}

Then, the expected total cost for each policy are given as follows.

$$
\begin{aligned}
TC_{RP1} &= c_{ig}\{p_1 + p_2 + \alpha(q_1 + q_2) + \alpha\beta r\} + c_d\alpha(p_1 + \beta q_1) \\
&\qquad + c_t(p_2 + q_2 + \alpha\beta r) \\
TC_{RP2} &= c_{ig}(p_2 + q_2 + r) + c_d(p_1 + q_1) + c_t(p_2 + q_2 + r) \\
TC_{PPS} &= c_{IG} + c_d(\alpha p_1 + \alpha\beta q_1) \\
&\qquad + c_t\{(1-\alpha)p_2 + (1-\beta)q_2 + \alpha\beta(1-\gamma)r\}
\end{aligned}
$$

To ensure profitability of the proposed system, following two inequalities should be held for any situation.

$$TC_{RP1} \geq TC_{PPS} \; and \; TC_{RP2} \geq TC_{PPS}$$

It can be concluded that the proposed system is more efficient than other recycling systems when following conditions, which are derived by reorganizing above conditions in terms of costs, are satisfied.

$$c_{IG} \leq c_{ig}\{p_1 + p_2 + \alpha(q_1 + q_2) + \alpha\beta r\} + c_t(\alpha p_2 + \beta q_2 + \alpha\beta\gamma r) \qquad \text{(Eq. 1)}$$

$$c_{IG} \leq c_{ig}(p_2 + q_2 + r) + c_d\{(1-\alpha)p_1 + (1-\alpha\beta)q_1\} + c_t[\alpha p_2 + \beta q_2 + \{1 - \alpha\beta(1-\gamma)\}r] \qquad \text{(Eq. 2)}$$

Also, it is found that the right side of inequalities is a monotonic increasing function for the number of components, which means that the proposed system would be more powerful as structural complexity of the product increases.

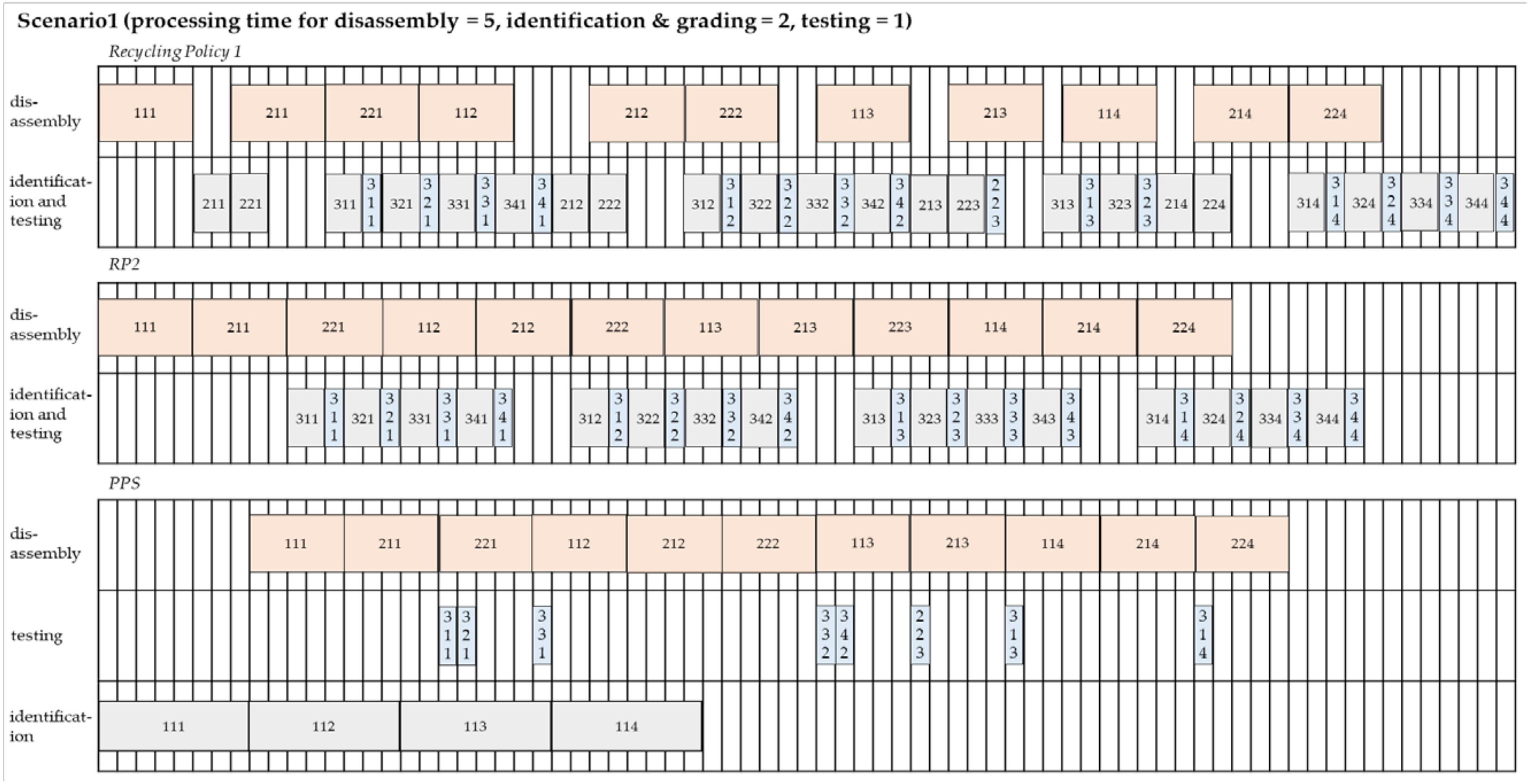
Job sequences are then presented for consideration of the costs, with various assumptions of disassembly processing time. Disassembly is known to be a labor intensive and expensive job. However, in the near future, many efforts, which can be found in literatures [131-134], to make disassembly easier, such as DfD (design for disassembly) may reduce disassembly time. In consideration of these circumstances, different disassembly times for each scenario are assumed.

Based on the assumption that $c_{ig} = 2$, $c_{IG} = 8$, and $c_t = 1$, the value that satisfies (Eq. 1) and (Eq. 2) is 5 for the example product structure in <Figure 6.3>. Accordingly, disassembly times for each scenario are 5 for scenario 1, 3 for scenario 2, and 1 for scenario 3. If disassembly time is increased more than 5, there is no change of the results. Then, job sequences are derived as depicted in <Figure 6.5> to <Figure 6.7> based on following assumptions:

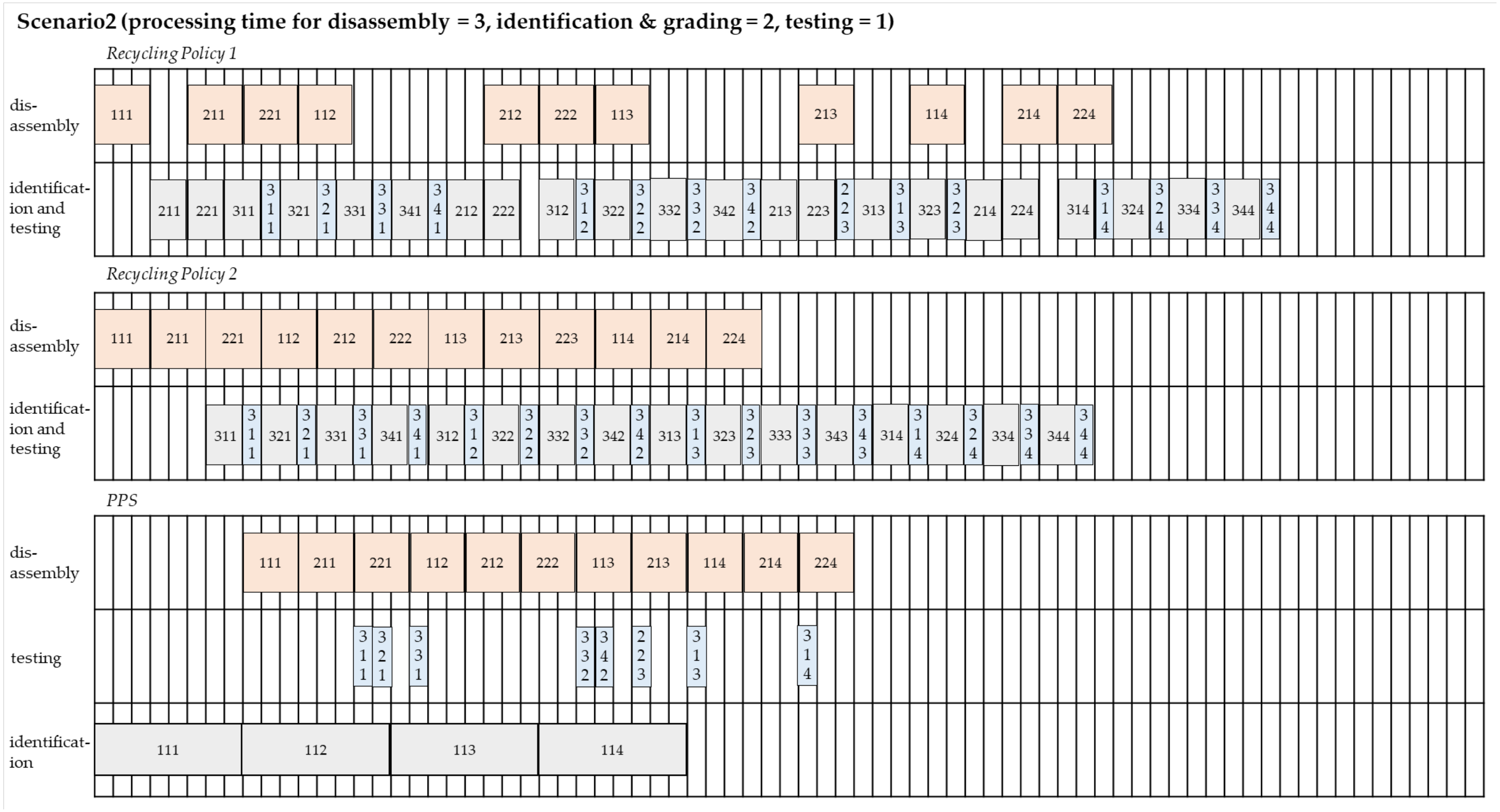
- Returned products are processed in a FIFS (First-In-First-Served) basis;
- Disassembly jobs are dispatched to single independent disassembly line;
- Identification, grading, and testing jobs are dispatched to single independent line for *Recycling Policy 1* and *Recycling Policy 2*;

- For *PPS*, identification and grading is executed when a returned product arrives;
- Identification and grading jobs are treated as a single unit of jobs.

And performance measures by scenarios are listed in <Table 6.4>.

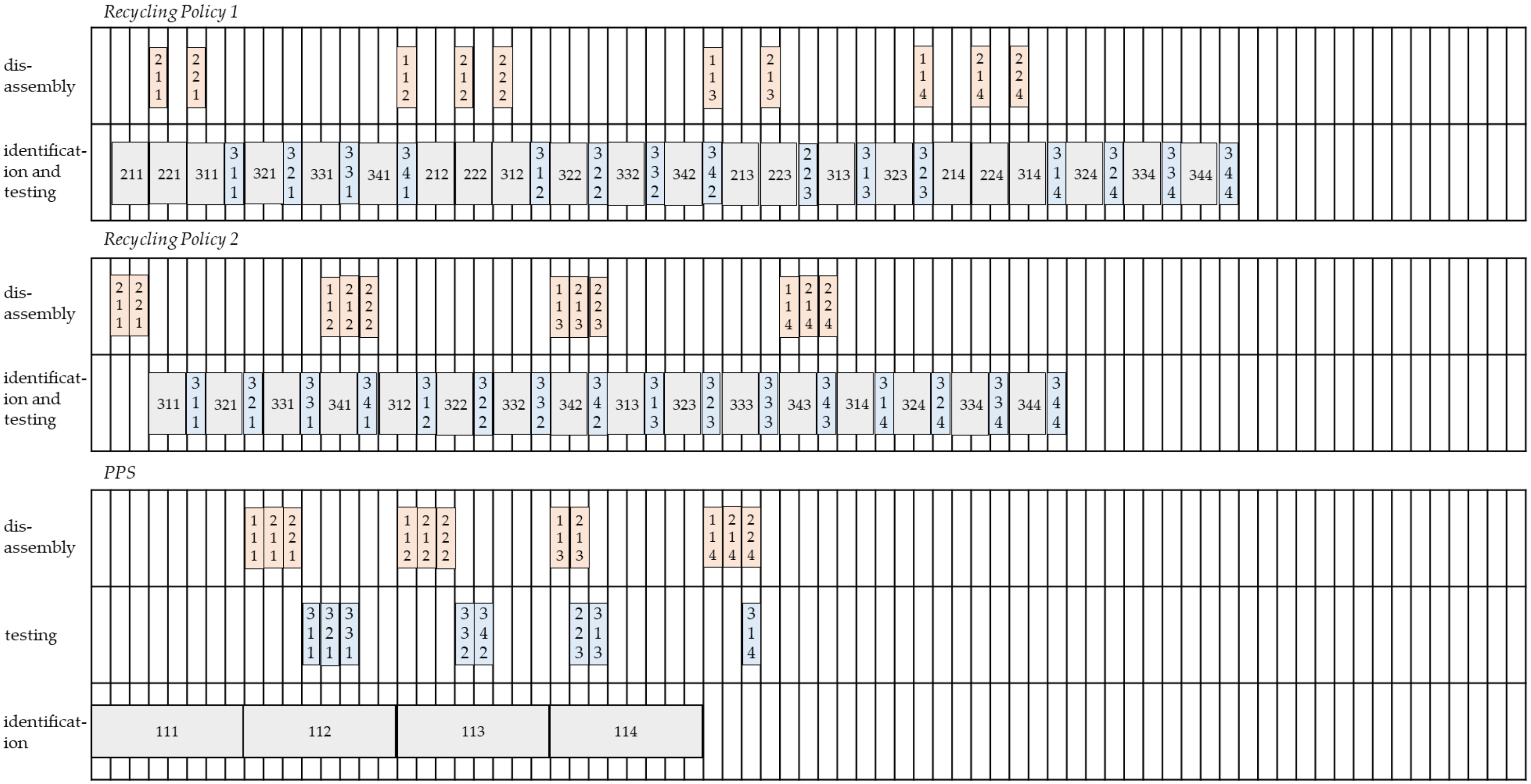


<Figure 6.5> Job sequence chart for scenario 1



<Figure 6.6> Job sequence chart for scenario 2

Scenario3 (processing time for disassembly = 1, identification & grading = 2, testing = 1): as an extreme case



<Figure 6.7> Job sequence chart for scenario 3

<Table 6.4> Performance measures for each recycling policy and each scenario

Scenario	Processing time			Performance measures			
	ds	ig	t	Recycling policy	Makespan	Total idle time	Idle ratio
Scenario 1	5	2	1	*Recycling Policy 1*	75	36	0.240
	5	2	1	*Recycling Policy 2*	67	26	0.194
	5	8*	1	*PPS*	63	94	0.497
Scenario 2	3	2	1	*Recycling Policy 1*	64	36	0.281
	3	2	1	*Recycling Policy 2*	54	24	0.222
	3	8*	1	*PPS*	41	49	0.398
Scenario 3	1	2	1	*Recycling Policy 1*	60	50	0.417
	1	2	1	*Recycling Policy 2*	51	42	0.412
	1	8*	1	*PPS*	35	54	0.514

* Note that processing time of ig is 8 for *PPS*

Due to the long times and precedence rules in remanufacturing processes, completion time of the job and the makespan of a set of jobs are important likewise the other manufacturing processes. Then makespan is introduced to evaluate the given schedules. *PPS* shows that it performs better than the conventional systems in terms of makespan because the proposed system separates the identification and grading processes from the conventional identification-grading-testing process loop, which is executed in a single line. To evaluate the schedules under a different aspect, idle ratio, which is the average ratio of idle time to makespan, is introduced as follows.

$$\text{Idle ratio} = \frac{Total\ idle\ time}{makespan \times number\ of\ lines}$$

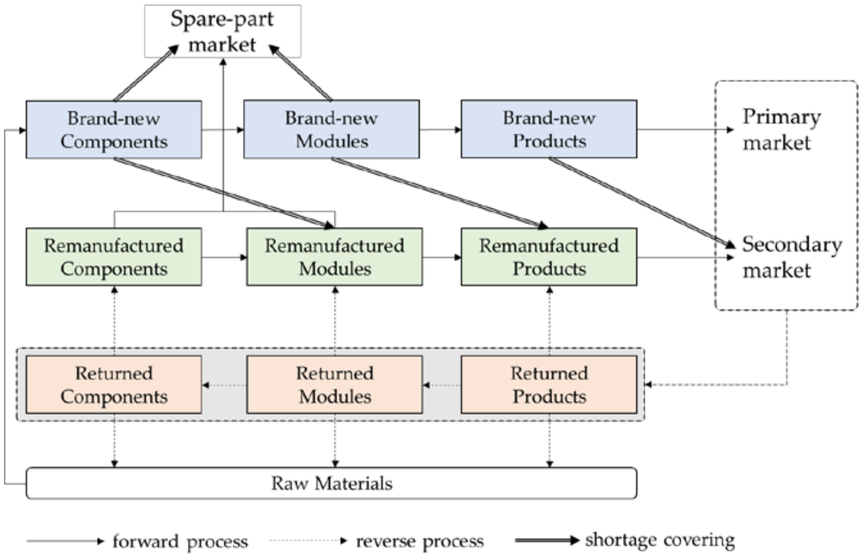
Number of lines has the value of 2 for *Recycling Policy 1* and *Recycling Policy 2*, or 3 for *PPS*. For the idle ratio, *PPS* seems to be worse than the others. However, the greatest portion of idle time is from the testing line due to line separation, which can be found in the figures of the results. This means that the system has surplus time to further tests for returned items.

7. Hybrid Production Planning for a Remanufacturing/Manufacturing System

The proposed system draws appropriate recycling option for each product as well as each component by using data driven decision support with lifecycle information. In previous chapter, it is shown that the proposed system leads not only to reduce the lead time for remanufacturing process, but also to gain time to further tests. In this chapter, positive value of the proposed system will be illustrated in terms of production planning which is one of major CLSC operations. Multi-period production planning model for a remanufacturing/manufacturing system (RMS) will be proposed based on integer linear programming (ILP) approach. And numerical experiment will follow to prove the value of real-time information gathering.

7.1. Conceptual Modeling

Customer market is segmented in three markets, namely primary, secondary and spare-part, in consideration of different type of customers. Unlike Ferrer and Swaminathan [135] divided customers to three groups according to the customer preferences, customer market is divided to two groups as follows. Customers in the primary market only purchase newly manufactured products. Customers in the secondary market only purchase remanufactured products with cheaper price as a result of market diversification. Finally, spare-part market covers situations that remanufactured components are used as substitutes to cope with component failure during product lifecycle. Also it is assumed that a manufacturer has to fulfill the demand of each market, which means that if quantity of remanufactured components is not enough to fulfill the demand of the secondary market and the spare-part market, newly manufactured components should be used.

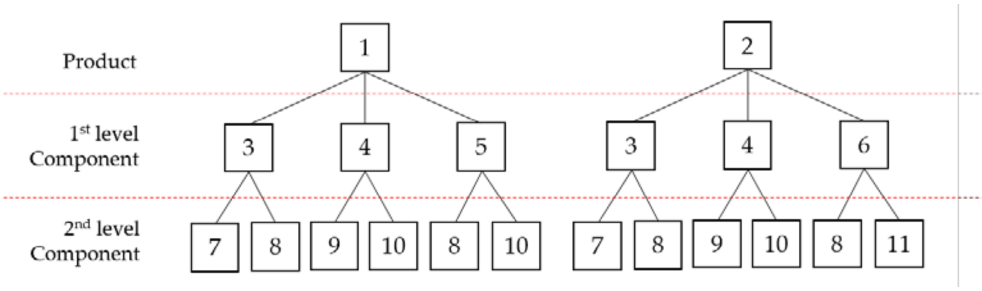


<Figure 7.1> Market segmentation and material flow

Before building a production planning model, it should be considered that how to handle components within multi-level BOM. As stated above, operations in modular product CLSCs are executed not only in a product-level, but also in a module/component level. Furthermore, if there are different types of products, the complexity of the model will inevitably increase because the components that make up the product are all different.

To handle events within various BOM levels efficiently in terms of mathematical modeling, an assembly matrix is introduced.

An assembly matrix that indicates product structure consists of binary elements. If product i is a parent of component j, an element (i,j) has the value of 1; otherwise, 0. To represent structures of two types of product as presented in <Figure 7.2>, corresponding assembly matrix is described in <Table 7.1>.



<Figure 7.2> Example: different BOM structure for two types of product

However, organizing the assembly matrix only in 2-dimensional way as presented in the example, is at risk for excessive expansion when the level of BOM or the number of components increase. To cope with this problem, the assembly matrix can be decomposed as presented in <Table 7.2> and <Table 7.3>. It might be helpful for reducing computational complexity.

<Table 7.1> Assembly matrix for the example

AM(i,j)		***i***										
		1	2	3	4	5	6	7	8	9	10	11
j	1	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0
	3	1	1	0	0	0	0	0	0	0	0	0
	4	1	1	0	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	0	0	0	0
	6	0	1	0	0	0	0	0	0	0	0	0
	7	0	0	1	0	0	0	0	0	0	0	0
	8	0	0	1	0	1	1	0	0	0	0	0
	9	0	0	0	1	0	0	0	0	0	0	0
	10	0	0	0	1	1	0	0	0	0	0	0
	11	0	0	0	0	0	1	0	0	0	0	0

<Table 7.2> Decomposed assembly matrix for product-module level

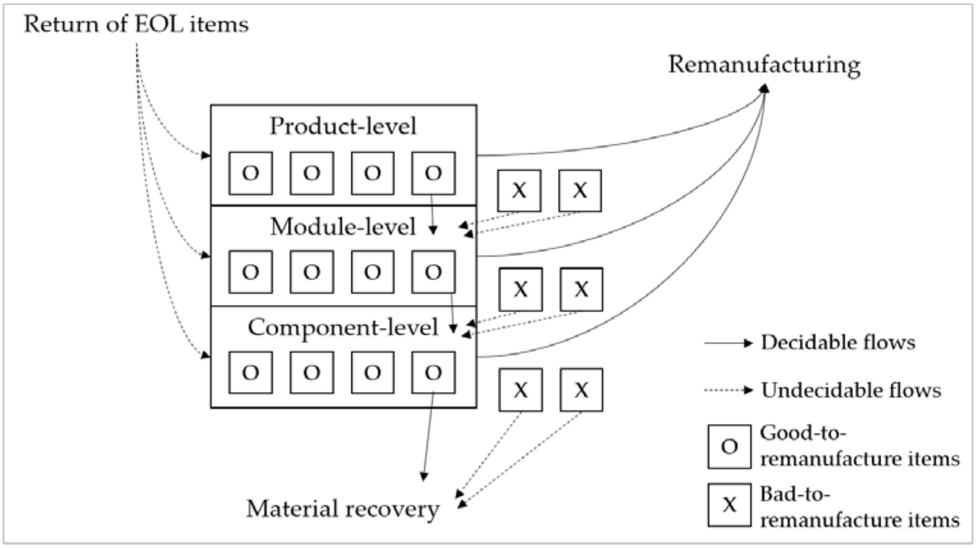
$AM_{PM}(i,j)$		***Product (i)***	
		1	2
Module (j)	3	1	1
	4	1	1
	5	1	0
	6	0	1

<Table 7.3> Decomposed assembly matrix for module-component level

AMMC(j,k)		***Module (j)***			
		3	4	5	6
Component (k)	7	1	0	0	0
	8	1	0	1	1
	9	0	1	0	0
	10	0	1	1	0
	11	0	0	0	1

EOL return of modular products can be occurred not only in a product level, but also in a module or a component level due to component/module substitution in the MOL phase. If condition of the returned item is good-to-remanufacture, it will be remanufactured. Otherwise, it will be dismantled or recovered as natural resources. The proposed production planning model has following assumptions for material flow:

- Bad-to-remanufacture products are disassembled to modules;
- Bad-to-remanufacture modules are disassembled to components;
- Bad-to-remanufacture components are recovered as natural resources;
- Recovered resource from material recovery is used to manufacture new items;
- Remanufactured items are used to manufacture refurbished products for secondary market demand or to manufacture spare parts;
- Returned items can be dismantled to lower level items or be recovered as resources to fulfill every kind of demands even if they are good-to-remanufacture.

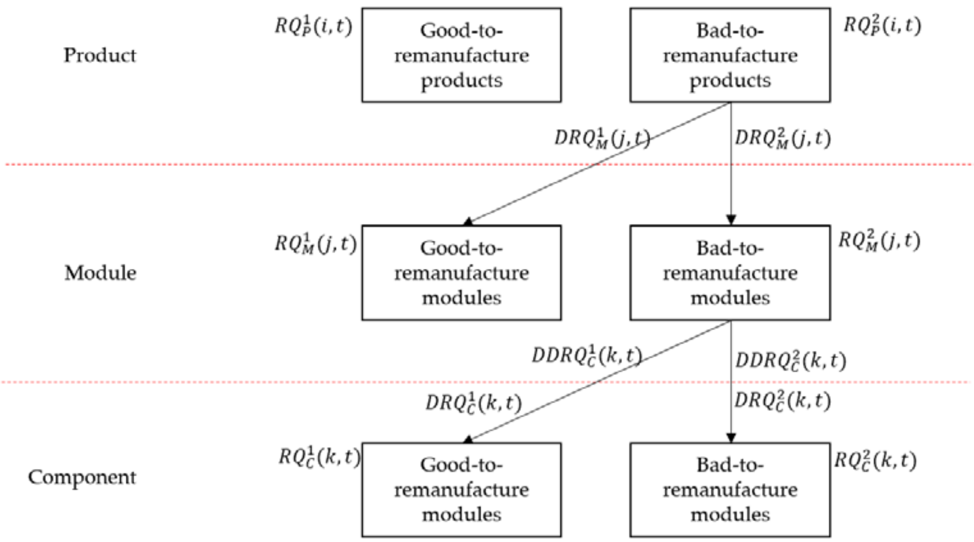


<Figure 7.3> Material flow of the proposed model

Product return quantity and quality are not decidable. Hence, the objective of this model is to control decidable flows considering undecidable flows in <Figure 7.3>, in terms of cost optimization. Characteristics including basic assumptions of the proposed model are presented as follows:

- Multi-period planning;
- Multiple product with multiple components within more than 3-level BOM;
- An OEM observes quantity and quality of returned items in real time by using IoT technology;
- An OEM observes demands of primary, secondary and spare-part markets;
- An OEM predefines the price of products and components for each market with an appropriate market segmentation strategy;
- All inventories are uncapacitated with initial value of zeros;
- There is no backorder.

Based on the assumption that a manufacturer observes quantity and quality of returned items in real-time, available resources for remanufacturing include inventories of a period before as well as returned items in the period.



<Figure 7.4> Waterfall structure of available resource

Sequence of that the returned item becomes available resource has a waterfall structure as depicted in <Figure 7.4>. Although bad-to-remanufacture products cannot be used to remanufacture, they can be used by disassembly if they have good-to-remanufacture modules or components. The proposed system is able to identify which module or component can be remanufactured before disassembly. Hence, accurate quantity of available good-to-remanufacture items can be figured out.

Costs and benefits that should be considered to optimize the model are listed as follows:

- Manufacturing cost including shortage covering;
- Remanufacturing cost;
- Material recovery cost;
- Disassembly cost;
- Inventory cost;
- Benefit from material recovery.

7.2. Mathematical Modeling

7.2.1. Notations

Indices:

t	planning horizon, t = 1,2,…,T
i	index for products, i = 1,2,…,I
j	index for modules, j = 1,2,…,J
k	index for components, k = 1,2,…,K

Parameters:

$c_n^P(i)$	unit manufacturing/assembly cost for product i
$c_n^M(j)$	unit manufacturing/assembly cost for module j
$c_n^C(k)$	unit manufacturing/assembly cost for component k
$\mathrm{c_r}^P(i)$	unit remanufacturing cost for product i
$\mathrm{c_r}^M(j)$	unit remanufacturing cost for module j
$\mathrm{c_r}^C(k)$	unit remanufacturing cost for component k
c_{MR}	unit material recovery cost
$\mathrm{c_d^{PM}}$	unit disassembly cost of products
$\mathrm{c_d^{MC}}$	unit disassembly cost of modules
$c_h^P(i)$	unit inventory holding cost for product i
$c_h^M(j)$	unit inventory holding cost for module j
$c_h^C(k)$	unit inventory holding cost for component k

ER	unit expected value of material recovery
$RQ_P^1(i,t)$	returned quantity of good-to-remanufacture product *i* at period *t*
$RQ_P^2(i,t)$	returned quantity of bad-to-remanufacture product *i* at period *t*
$RQ_M^1(j,t)$	returned quantity of good-to-remanufacture module *j* at period *t*
$RQ_M^2(j,t)$	returned quantity of bad-to-remanufacture module *j* at period *t*
$RQ_C^1(k,t)$	returned quantity of good-to-remanufacture component *k* at period *t*
$RQ_C^2(k,t)$	returned quantity of bad-to-remanufacture component *k* at period *t*
$DRQ_M^1(j,t)$	returned quantity of good-to-remanufacture module *j* at period *t* which come from returned bad-to-remanufacture products at period *t*
$DRQ_M^2(j,t)$	returned quantity of bad-to-remanufacture module *j* at period *t* which come from returned bad-to-remanufacture products at period *t*
$DRQ_C^1(k,t)$	returned quantity of good-to-remanufacture component *k* at period *t* which come from returned bad-to-remanufacture modules at period *t*
$DRQ_C^2(k,t)$	returned quantity of bad-to-remanufacture component *k* at period *t* which come from returned bad-to-remanufacture modules at period *t*
$DDRQ_C^1(k,t)$	returned quantity of good-to-remanufacture component *k* at period *t* which come from bad-to-remanufacture product at period *t*
$DDRQ_C^2(k,t)$	returned quantity of bad-to-remanufacture component *k* at period *t* which come from bad-to-remanufacture product at period *t*

$AM_{PM}(i, j)$	assembly matrix of product-module relationship
$AM_{MC}(j, k)$	assembly matrix of module-component relationship

Decision Variables:

$X^P(i, t)$	remanufactured quantity of product *i* at period *t*
$X^M(j, t)$	remanufactured quantity of module *j* at period *t*
$X^C(k, t)$	remanufactured quantity of component *k* at period *t*
$Y_P(i, t)$	disassembled quantity of product *i* at period *t*
$Y_M(j, t)$	disassembled quantity of product *i* at period *t*
$Y_C(k, t)$	disassembled quantity of product *i* at period *t*
$Z^P(i, t)$	newly manufactured quantity of product *i* at period *t* for shortage covering
$Z^M(j, t)$	newly manufactured quantity of module *j* at period *t* for shortage covering
$Z^C(k, t)$	newly manufactured quantity of component *k* at period *t* for shortage covering
$I_P(i, t)$	inventory level of product *i* at the end of period *t*
$I_M(j, t)$	inventory level of module *j* at the end of period *t*
$I_C(k, t)$	inventory level of component *k* at the end of period *t*

7.2.2. Objective Function

The objective of this model is to minimize total cost. Incurred costs and benefits for each period are as follows:

- Cost for remanufacturing:

$$C_1(t) = \sum_{i=1}^{I} c_r^P(i)X^P(i,t) + \sum_{j=1}^{J} c_r^M(j)X^M(j,t) + \sum_{k=1}^{K} c_r^M(k)X^C(k,t) \tag{1}$$

where $i = 1,2,\dots,I, j = 1,2,\dots,J, k = 1,2,\dots,K$

- Cost for disassembly:

$$C_2(t) = c_d^{PM}\sum_{i=1}^{I}\{RQ_P^2(i,t) + Y_P(i,t)\} + c_d^{MC}\sum_{j=1}^{J}\{RQ_M^2(j,t) + DRQ_M^2(j,t) + Y_M(j,t)\} \tag{2}$$

where $i = 1,2,\dots,I, j = 1,2,\dots,J$

- Cost for material recovery:

$$C_3(t) = c_{MR}\sum_{k=1}^{K}\{RQ_C^2(k,t) + DRQ_C^2(k,t) + DDRQ_C^2(k,t) + Y_C(k,t)\} \tag{3}$$

where $k = 1,2,\dots,K$

- Cost for inventory holding:

$$C_4(t) = \sum_{i=1}^{I} c_h^P(i)I_P(i,t) + \sum_{j=1}^{J} c_h^M(j)I_M(j,t) + \sum_{k=1}^{K} c_h^C(k)I_C(k,t) \tag{4}$$

where $i = 1,2,\dots,I, j = 1,2,\dots,J, k = 1,2,\dots,K$

- Cost for shortage covering:

$$C_5(t) = \sum_{i=1}^{I} c_n^P(i)Z^P(i,t) + \sum_{j=1}^{J} c_n^M(j)Z^M(j,t) + \sum_{k=1}^{K} c_r^C(k)Z^C(k,t) \tag{5}$$

where $i = 1,2,\dots,I, j = 1,2,\dots,J, k = 1,2,\dots,K$

- Benefit from material recovery:

$$B(t) = ER \sum_{k=1}^{K} c_n^C(k)\{RQ_C^2(k,t) + DRQ_C^2(k,t) + DDRQ_C^2(k,t) + Y_C(k,t)\} \quad \text{where } k = 1,2,\dots,K \tag{6}$$

It is assumed that production plan for each period should fulfill every kind of demands. Accordingly, cost for fulfilling primary market demand, which comes from manufacturing of new items only, remains unaffected in any circumstance. Then, only shortage covering for secondary market and spare-part market is considered as described in (5). The objective function of this model is given in (7).

$$\text{Minimize} \sum_{t=1}^{T} \{C_1(t) + C_2(t) + C_3(t) + C_4(t) + C_5(t) - B(t)\} \quad \text{where } t = 1,2,\dots,T \tag{7}$$

7.2.3. Constraints

Following constraints should be satisfied for every product $i \in \{1,2,\dots,\mathrm{I}\}$, module $j = \{1,2,\dots,\mathrm{J}\}$, component $k = \{1,2,\dots,\mathrm{K}\}$, and period $t = \{1,2,\dots,\mathrm{T}\}$.

$$I_P(i,t) = I_P(i,t-1) + RQ_P^1(i,t) - X_P(i,t) - Y_P(i,t) \quad \text{where } i = 1,2,\dots,I, t = 1,2,\dots,T \tag{8}$$

$$I_M(j,t) = I_M(j,t-1) + RQ_M^1(j,t) + DRQ_M^1(j,t) + \sum_{i=1}^{I} AM_{PM}(i,j)Y_P(i,t) - X_M(j,t) - Y_M(j,t) \tag{9}$$

where $i = 1,2,\dots,I, j = 1,2,\dots,J, t = 1,2,\dots,T$

$$I_C(k,t) = I_C(k,t-1) + RQ_C^1(k,t) + DRQ_C^1(k,t) + DDRQ_C^1(k,t) + \sum_{j=1}^{J} AM_{MC}(j,k)Y_M(j,t) - X_C(k,t) - Y_C(k,t) \tag{10}$$

where $j = 1,2,\dots,J, k = 1,2,\dots,K, t = 1,2,\dots,T$

Constraints (8)-(10) are the inventory level of good-to-remanufacture products, modules, and components, respectively.

$$X_P(i,t) + Y_P(i,t) \leq I_P(i,t-1) + RQ_P^1(i,t) \tag{11}$$

where $i = 1,2,\dots,I, t = 1,2,\dots,T$

$$X_P(i,t) + Z_P(i,t) = D_S(i,t) \tag{12}$$

where $i = 1,2,\dots,I, t = 1,2,\dots,T$

Constraints (11) and (12) are about remanufacturing activity in a product level. Especially, constraint (11) indicates that the sum of good-to-remanufacture quantity and sacrifice disassembly quantity cannot exceed the sum of inventory level of a period before and returned quantity of good-to-remanufacture products. And constraint (12) indicates the sum of remanufacturing quantity and shortage covering quantity should be the same as secondary demand of each period.

$$X_M(j,t) + Y_M(j,t) \leq I_M(j,t-1) + RQ_M^1(j,t) + DRQ_M^1(j,t) + \sum_{i=1}^{I} AM_{PM}(i,j)Y_P(i,t) \tag{13}$$

where $i = 1,2,\dots,I, j = 1,2,\dots,J, t = 1,2,\dots,T$

$$X_M(j,t) + Z_M(j,t) = \sum_{i=1}^{I} AM_{PM}(i,j)D_S(i,t) + D_{SP}^M(j,t) \tag{14}$$

where $i = 1,2,\dots,I, j = 1,2,\dots,J, t = 1,2,\dots,T$

$$X_C(k,t) + Y_C(k,t) \leq I_C(k,t-1) + RQ_C^1(k,t) + DRQ_C^1(k,t) + DDRQ_C^1(k,t) + \sum_{j=1}^{J} AM_{MC}(j,k)Y_M(j,t) \tag{15}$$

where $i = 1,2,\dots,I, j = 1,2,\dots,J, k = 1,2,\dots,K, t = 1,2,\dots,T$

$$X_C(k,t) + Z_C(k,t) = \sum_{j=1}^{J}\sum_{i=1}^{I} AM_{PM}(i,j)AM_{MC}(j,k)D_S(i,t) + D_{SP}^M(j,t) \tag{16}$$

where $i = 1,2,\dots,I, j = 1,2,\dots,J, k = 1,2,\dots,K, t = 1,2,\dots,T$

Likewise, constraints (13) and (14) are for module level remanufacturing; constraints (15) and (16) are for component level remanufacturing. Constraints (13) and (15) indicate that remanufacturing quantity and sacrifice disassembly quantity should not exceed available resource quantity including sacrifice disassembly in the upper level. Constraints (14) and (16) indicate that the sum of remanufacturing quantity and shortage covering quantity should be the same as the sum of spare-part market demand and required quantity to fulfill the secondary demand.

$$X^P(i,t), X^M(j,t), X^C(k,t), Y_P(i,t), Y_M(j,t), Y_C(k,t),$$
$$Z^P(i,t), Z^M(j,t), Z^C(k,t), I_P(i,t), I_M(j,t), I_C(k,t) \geq 0 \tag{17}$$
$$\text{where } i = 1,2,\dots,I, j = 1,2,\dots,J, k = 1,2,\dots,K, t = 1,2,\dots,T$$

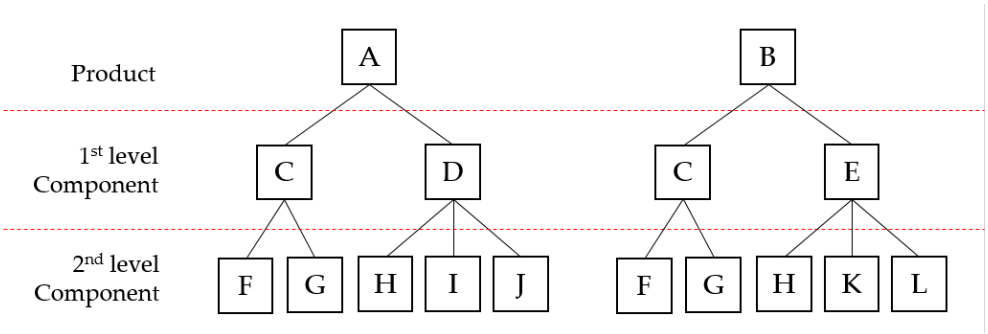
Constraint (17) ensures that all decision variables are non-negative integer.

$$I_P(i,0) = I_M(j,0) = I_C(k,0) = 0 \tag{18}$$
$$\text{where } i = 1,2,\dots,I, j = 1,2,\dots,J, k = 1,2,\dots,K$$

Finally, constraint (18) ensures that the initial inventory levels equal to zero.

7.3. Computational Results

Let assume that there is a manufacturer that manufactures two kinds of products with different components as depicted in <Figure 7.5>. There is a common module C for both products; and there is a common component H for module D and module E.



<Figure 7.5> BOM structure of example products

Then, corresponding assembly matrices are given as follows.

$$\mathrm{AM}_{\mathrm{PM}}(i,j) = \begin{bmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix}$$

$$\mathrm{AM}_{\mathrm{MC}}(j,k) = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 \end{bmatrix}$$

Periodic return quantities, periodic demands for each market, and parameters related to cost including manufacturing, remanufacturing, inventory holding, and material recovery are given in Appendix.

<Table 7.4> Inventory level for each item per period

INV.	1	2	3	4	5	6	7	8	9	10	11	12	sub total1	sub total2	Total
A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	853
B	0	0	0	0	0	0	0	0	0	0	0	0	0		
C	0	0	0	0	0	0	0	0	0	0	0	0	0	55	
D	0	0	0	0	0	0	0	0	0	0	0	0	0		
E	0	11	21	12	11	0	0	0	0	0	0	0	55		
F	26	0	31	46	103	34	1	0	0	22	0	0	263	798	
G	15	0	50	82	114	64	9	9	18	44	0	0	405		
H	0	0	0	0	0	0	0	0	0	0	0	0	0		
I	0	0	0	0	73	31	0	6	1	18	0	0	129		
J	0	0	0	1	0	0	0	0	0	0	0	0	1		
K	0	0	0	0	0	0	0	0	0	0	0	0	0		
L	0	0	0	0	0	0	0	0	0	0	0	0	0		

<Table 7.5> Remanufactured quantity for each item per period

X	1	2	3	4	5	6	7	8	9	10	11	12	sub total1	sub total2	Total
A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34055
B	0	0	0	0	0	0	0	0	0	0	0	0	0		
C	277	261	275	266	248	233	224	216	258	281	237	270	3046	5667	
D	106	83	111	86	50	107	112	127	135	102	55	119	1193		
E	107	118	114	128	130	116	113	118	131	123	106	124	1428		
F	454	476	456	464	414	478	458	466	452	454	474	442	5488	28388	
G	464	488	434	446	440	472	500	454	442	462	474	442	5518		
H	460	476	434	486	426	432	494	450	410	484	456	428	5436		
I	332	354	292	356	288	342	340	296	288	312	362	312	3874		
J	318	286	278	344	328	270	310	274	262	316	330	254	3570		
K	172	170	136	164	150	140	148	192	180	154	156	200	1962		
L	172	230	216	186	208	242	220	188	194	220	216	248	2540		

<Table 7.6> Sacrifice disassembly quantity for each item per period

Y	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**sub total1**	**sub total2**	**Total**
A	0	0	0	0	0	0	0	1	0	1	1	0	3	6	3486
B	0	0	0	0	1	1	0	0	0	0	1	0	3		
C	0	0	0	0	0	0	0	29	0	0	0	0	29	429	
D	39	66	27	46	78	10	8	0	0	41	72	13	400		
E	0	0	0	0	0	0	0	0	0	0	0	0	0		
F	33	0	32	0	0	0	0	0	2	32	0	32	131	3051	
G	14	0	0	0	0	0	0	0	0	0	0	60	74		
H	113	60	41	47	71	44	2	41	47	37	33	41	577		
I	0	0	0	0	0	0	0	0	0	0	0	0	0		
J	43	52	64	0	0	0	10	6	35	0	48	19	277		
K	66	125	114	112	118	117	141	109	114	118	106	56	1296		
L	92	57	53	88	59	32	25	91	71	54	48	26	696		

<Table 7.7> Shortage covering quantity for each item per period

Z	1	2	3	4	5	6	7	8	9	10	11	12	sub total1	sub total2	Total
A	158	156	122	164	132	140	166	144	114	156	160	116	1728	2320	4625
B	46	46	42	44	48	46	46	54	50	60	54	56	592		
C	33	51	1	62	52	127	162	92	38	67	91	68	844	2305	
D	104	137	81	130	146	83	122	97	33	140	171	53	1297		
E	25	0	0	0	0	6	5	18	9	35	44	22	164		
F	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
G	0	0	0	0	0	0	0	0	0	0	0	0	0		
H	0	0	0	0	0	0	0	0	0	0	0	0	0		
I	0	0	0	0	0	0	0	0	0	0	0	0	0		
J	0	0	0	0	0	0	0	0	0	0	0	0	0		
K	0	0	0	0	0	0	0	0	0	0	0	0	0		
L	0	0	0	0	0	0	0	0	0	0	0	0	0		

Computational results for the proposed model are presented in <Table 7.4> to <Table 7.7>. To evaluate a production plan derived from the ILP model, self-sufficiency (SS) and sacrifice ratio (SR) are introduced. Self-sufficiency indicates how much required remanufactured parts are made from returned items. Sacrifice ratio indicates how much good-to-remanufacture items are disassembled to fulfill periodic demand. The higher the self-sufficiency, the better production plan; the lower the sacrifice ratio, the better. They can be calculated by following formula respectively.

$$SS(p,t) = \frac{X(p,t)}{X(p,t) + Z(p,t)} \tag{19}$$

$$SS(p_1 \sim p_2, t_1 \sim t_2) = \frac{\sum_{p=p_1}^{p_2} \sum_{t=t_1}^{t_2} X(p,t)}{\sum_{p=p_1}^{p_2} \sum_{t=t_1}^{t_2} \{X(p,t) + Z(p,t)\}} \tag{20}$$

$$SR(p,t) = \frac{Y(p,t)}{X(p,t) + Y(p,t)} \tag{21}$$

$$SR(p_1 \sim p_2, t_1 \sim t_2) = \frac{\sum_{p=p_1}^{p_2} \sum_{t=t_1}^{t_2} Y(p,t)}{\sum_{p=p_1}^{p_2} \sum_{t=t_1}^{t_2} \{X(p,t) + Y(p,t)\}} \tag{22}$$

For single item or single period use, SS and SR can be calculated by using (19) and (21). Otherwise, for multiple item or multi-period use, (20) and (22) derive the value of them.

<Table 7.8> Self-sufficiency (*SS*) results

<table>
<tr><th>SS</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>avg. SS (item)</th><th>avg. SS (BOM Level)</th><th>avg. SS (Total)</th></tr>
<tr><th>A</th><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td rowspan="2">0</td><td rowspan="12">88.04</td></tr>
<tr><th>B</th><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><th>C</th><td>89.35</td><td>83.65</td><td>99.64</td><td>81.10</td><td>82.67</td><td>64.72</td><td>58.03</td><td>70.13</td><td>87.16</td><td>80.75</td><td>72.26</td><td>79.88</td><td>78.30</td><td rowspan="3">71.09</td></tr>
<tr><th>D</th><td>50.48</td><td>37.73</td><td>57.81</td><td>39.81</td><td>25.51</td><td>56.32</td><td>47.86</td><td>56.70</td><td>80.36</td><td>42.15</td><td>24.34</td><td>69.19</td><td>47.91</td></tr>
<tr><th>E</th><td>81.06</td><td>100</td><td>100</td><td>100</td><td>100</td><td>95.08</td><td>95.76</td><td>86.76</td><td>93.57</td><td>77.85</td><td>70.67</td><td>84.93</td><td>89.70</td></tr>
<tr><th>F</th><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td rowspan="7">100</td></tr>
<tr><th>G</th><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td></tr>
<tr><th>H</th><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td></tr>
<tr><th>I</th><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td></tr>
<tr><th>J</th><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td></tr>
<tr><th>K</th><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td></tr>
<tr><th>L</th><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td></tr>
<tr><th>avg. SS (period)</th><td>88.66</td><td>88.30</td><td>91.78</td><td>87.97</td><td>87.65</td><td>87.57</td><td>85.35</td><td>87.29</td><td>91.86</td><td>86.39</td><td>84.64</td><td>90.01</td><td>--</td><td>--</td><td>--</td></tr>
</table>

<Table 7.9> Sacrifice ratio (*SR*) results

	1	2	3	4	5	6	7	8	9	10	11	12	avg. *SR* (item)	avg. *SR* (BOM level)	avg. *SR* (Total)
A	0	0	0	0	0	0	0	100	0	100	100	0	100	100	9.69
B	0	0	0	0	100	100	0	0	0	0	100	0	100		
C	0	0	0	0	0	0	0	11.84	0	0	0	0	0.94	7.86	
D	26.90	44.29	19.57	34.85	60.94	8.55	6.67	0	0	28.67	56.69	9.85	25.11		
E	0	0	0	0	0	0	0	0	0	0	0	0	0		
F	6.78	0	6.56	0	0	0	0	0	0.44	6.58	0	6.75	2.33	36.02	
G	2.93	0	0	0	0	0	0	0	0	0	0	11.95	1.32		
H	19.72	11.19	8.63	8.82	14.29	9.24	0.40	8.35	10.28	7.10	6.75	8.74	9.60		
I	0	0	0	0	0	0	0	0	0	0	0	0	0		
J	11.91	15.38	18.71	0	0	0	3.125	2.14	11.78	0	12.70	6.96	7.20		
K	27.73	42.37	45.6	40.58	44.03	45.53	48.79	36.21	38.78	43.38	40.46	21.88	39.78		
L	34.85	19.86	19.70	32.12	22.10	11.68	10.20	32.62	26.79	19.71	18.18	9.49	21.51		
avg. *SR* (period)	0	10.90	10.76	9.10	10.87	6.72	6.00	9.06	8.90	8.87	9.73	8.00	--	--	--

7.4. Sensitivity Analysis

In this subsection, sensitivity analysis is presented to analyze the impact on performance measures by changing parameters of the model.

7.4.1. Impact of Information Visibility

Proposed system observes recycling options for each product and component through information visibility. Accordingly, modules and components can be remanufactured or disassembled as needed right after their return. In other words, remanufactured components or recovered resources can be used in the same period when they returned.

Assume that the returned products need time of a period to become available resources for the RMS. This means that returned components are ready for remanufacturing after a period. Under this circumstance, the mathematical model is changed as follows. A changed model is called generic model from now on.

$$\text{Minimize} \sum_{t} (C_1'(t) + C_2'(t) + C_3'(t) + C_4'(t) + C_5'(t) - B'(t) \tag{19}$$

where

$$C_1'(t) = \sum_{i=1}^{I} c_r^P(i) X^P(i,t) + \sum_{j=1}^{J} c_r^M(j) X^M(j,t) + \sum_{k=1}^{K} c_r^M(k) X^C(k,t) \tag{20}$$

$$C_2{}'(t) = c_d^{PM} \sum_{i=1}^{I} \{RQ_P^2(i,t) + Y_P(i,t)\} + c_d^{MC} \sum_{j=1}^{J} \{RQ_M^2(j,t) + DRQ_M^2(j,t) + Y_M(j,t)\} \tag{21}$$

$$C_3{}'(t) = c_{MR} \sum_{k=1}^{K} \{RQ_C^2(k,t) + DRQ_C^2(k,t) + DDRQ_C^2(k,t) + Y_C(k,t)\} \tag{22}$$

$$C_4{}'(t) = \sum_{i=1}^{I} c_h^P(i) I_P(i,t) + \sum_{j=1}^{J} c_h^M(j) I_M(j,t) + \sum_{k=1}^{K} c_h^C(k) I_C(k,t) \tag{23}$$

$$C_5{}'(t) = \sum_{i=1}^{I} c_n^P(i) Z^P(i,t) + \sum_{j=1}^{J} c_n^M(j) Z^M(j,t) + \sum_{k=1}^{K} c_r^C(k) Z^C(k,t) \tag{24}$$

$$B'(t) = ER \sum_{k=1}^{K} c_n^C(k) \{RQ_C^2(k,t) + DRQ_C^2(k,t) + DDRQ_C^2(k,t) + Y_C(k,t)\} \tag{25}$$

Subject to: (for all products, modules, components, and periods)

$$I_P(i,t) = I_P(i,t-1) + RQ_P^1(i,t) - X_P(i,t) - Y_P(i,t) \tag{26}$$

$$I_M(j,t) = I_M(j,t-1) + RQ_M^1(j,t) + DRQ_M^1(j,t) + \sum_{i=1}^{I} AM_{PM}(i,j) Y_P(i,t) - X_M(j,t) - Y_M(j,t) \tag{27}$$

$$I_C(k,t) = I_C(k,t-1) + RQ_C^1(k,t) + DRQ_C^1(k,t) + DDRQ_C^1(k,t) + \sum_{j=1}^{J} AM_{MC}(j,k) Y_M(j,t) - X_C(k,t) - Y_C(k,t) \tag{28}$$

$$X_P(i,t) + Y_P(i,t) \le I_P(i,t-1) + RQ_P^1(i,t) \tag{29}$$

$$X_P(i,t) + Z_P(i,t) = D_S(i,t) \tag{30}$$

$$X_M(j,t) + Y_M(j,t) \le I_M(j,t-1) + RQ_M^1(j,t) + DRQ_M^1(j,t) + \sum_{i=1}^{I} AM_{PM}(i,j) Y_P(i,t) \tag{31}$$

$$X_M(j,t) + Z_M(j,t) = \sum_{i=1}^{I} AM_{PM}(i,j) D_S(i,t) + D_{SP}^{M}(j,t) \tag{32}$$

$$\begin{aligned} X_C(k,t) + Y_C(k,t) & \\ \le I_C(k,t-1) &+ RQ_C^1(k,t) + DRQ_C^1(k,t) \\ &+ DDRQ_C^1(k,t) + \sum_{j=1}^{J} AM_{MC}(j,k) Y_M(j,t) \end{aligned} \tag{33}$$

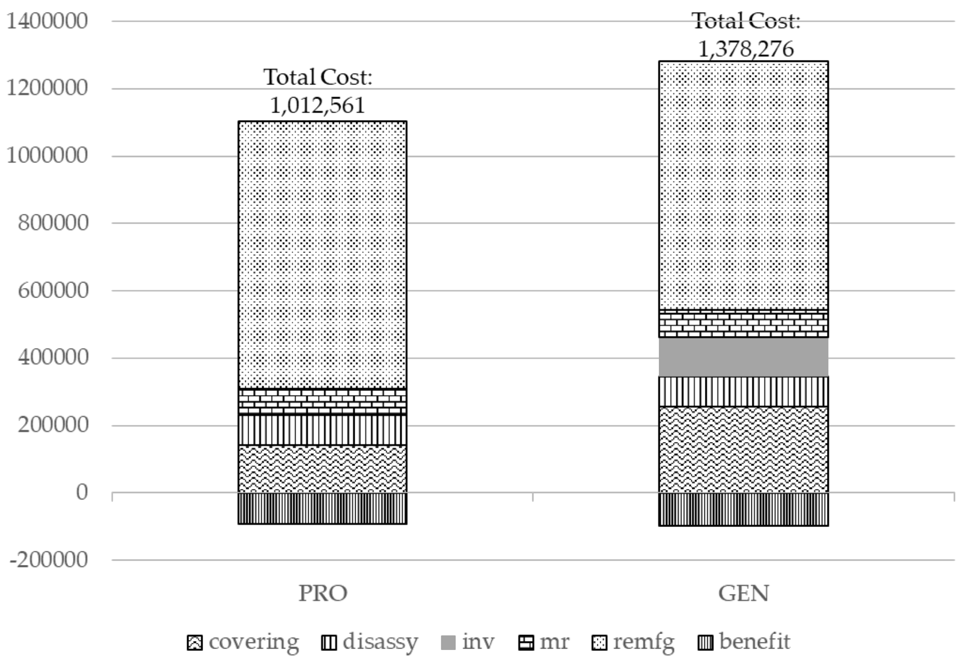
$$\begin{aligned} X_C(k,t) + Z_C(k,t) & \\ = \sum_{j=1}^{J}\sum_{i=1}^{I} & AM_{PM}(i,j) AM_{MC}(j,k) D_S(i,t) + D_{SP}^{M}(j,t) \end{aligned} \tag{34}$$

Constraints about non-negative integer and initial inventory are the same as the proposed model. Note that there are changes for return quantity related terms. By solving both model based on the baseline dataset, the results are given in <Figure 7.6> and <Table 7.10>.

<Table 7.10> Results of baseline dataset

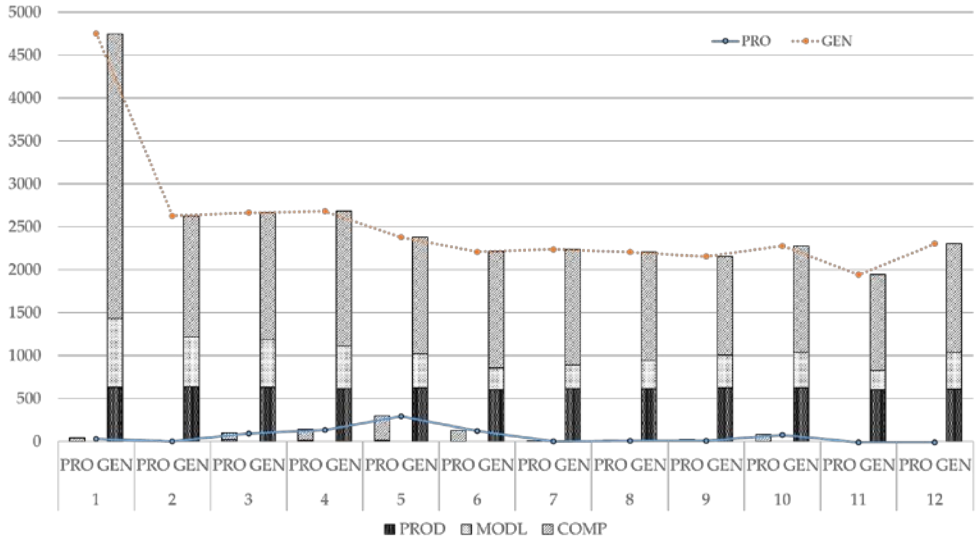
	Cov[1]	**Ds**[2]	**Inv**[3]	**MR**[4]	**Remfg**[5]	**Benefit**	**Total cost**	***SS***	***SR***
PRO	141200	90831	1761	75204	795810	92245	1012561	88.04	9.29
GEN	256200	89915	117000	79428	738310	97423	1378276	81.99	12.39

[1] Shortage Covering; [2] Disassembly; [3] Inventory holding; [4] Material recovery; [5] Remanufacturing

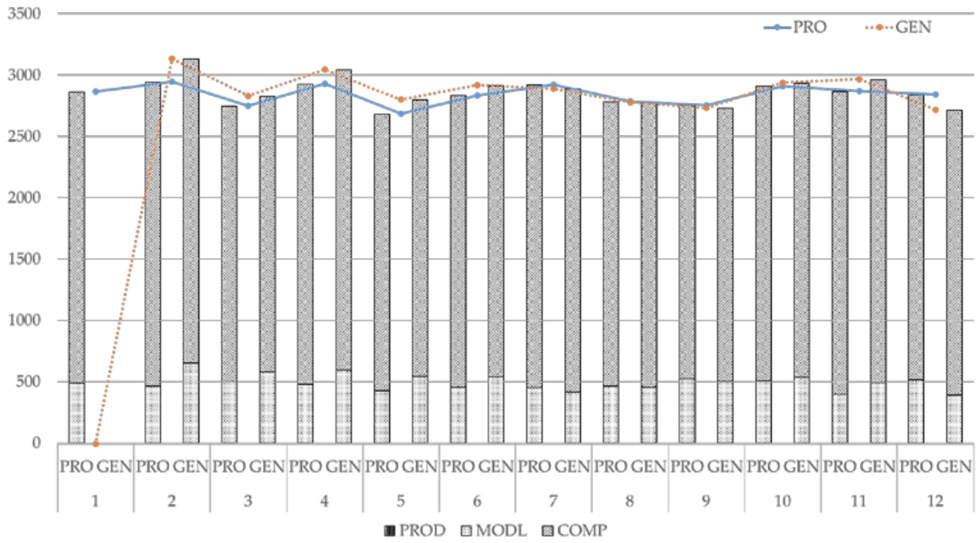


<Figure 7.6> Total cost breakdown for baseline dataset

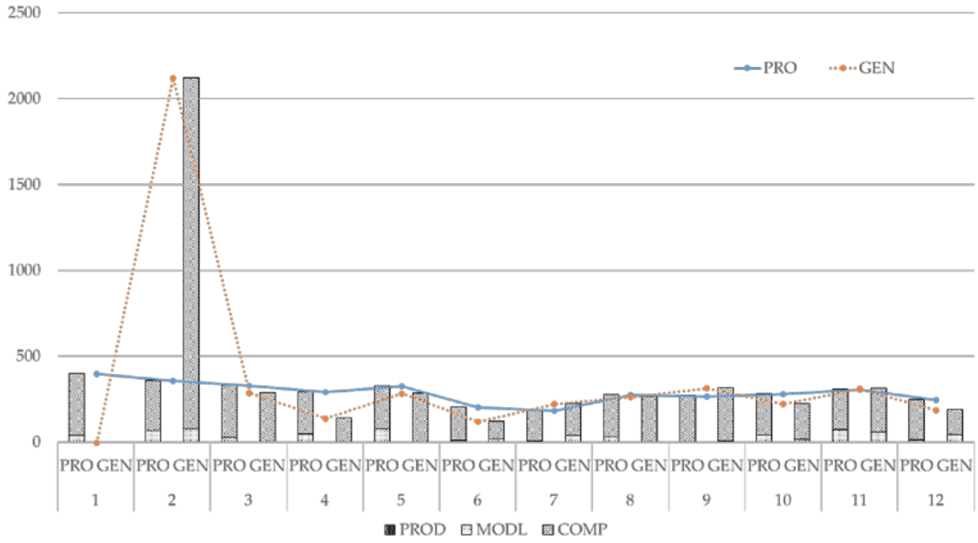
<Table 7.10> shows that the proposed system performs better than the generic system in terms of cost, *SS*, and *SR*. The main causes of the result are shortage covering and inventory cost. This discrepancy is due to the lack of using returned items in the first period. For more detailed analysis, observations of decision variables for each period are given in <Figure 7.7> to <Figure 7.10>.



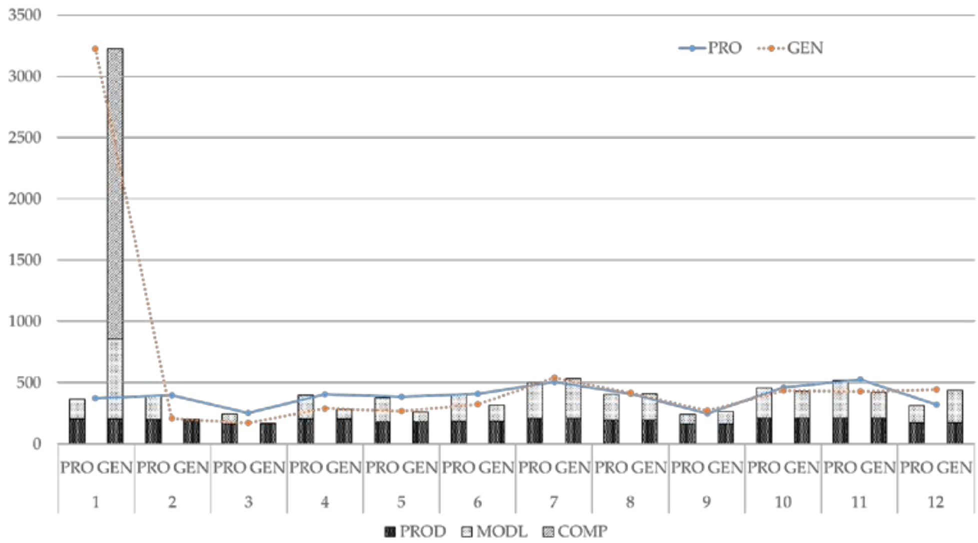
<Figure 7.7> Inventory levels for each period



<Figure 7.8> Remanufactured quantity for each period

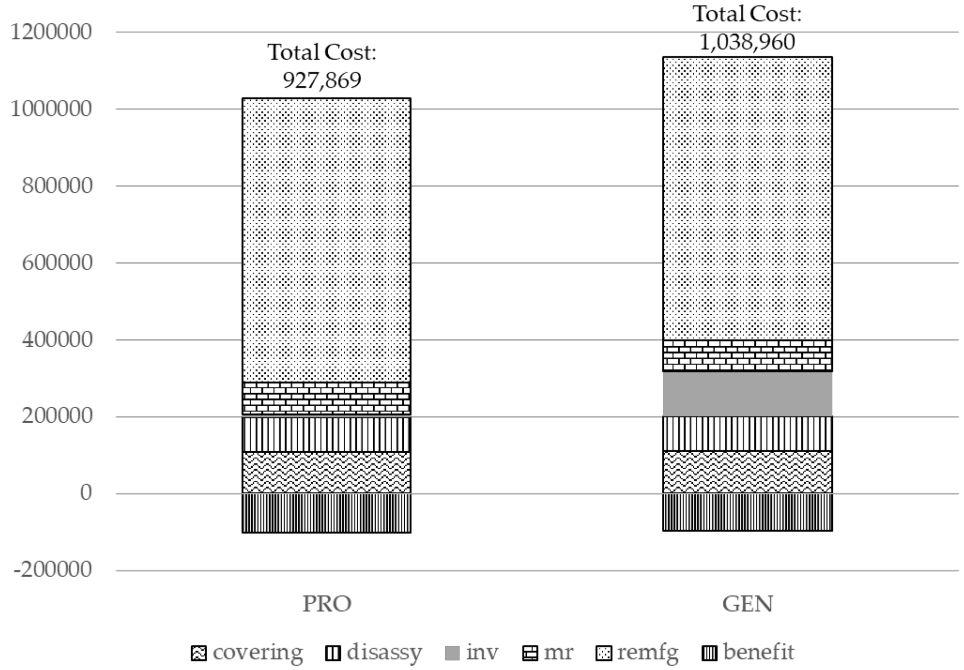


<Figure 7.9> Sacrifice disassembly/shredding quantity for each period



<Figure 7.10> Shortage covering quantity for each period

The generic system should covers shortage for secondary and spare-part demands in the first period, because it is not capable to recycle returned items in the period when they are returned. This fact shows that there is a big impact on performance. Hence, quantities of secondary and spare-part demands are set to zeros to eliminate this ‘first period effect’.

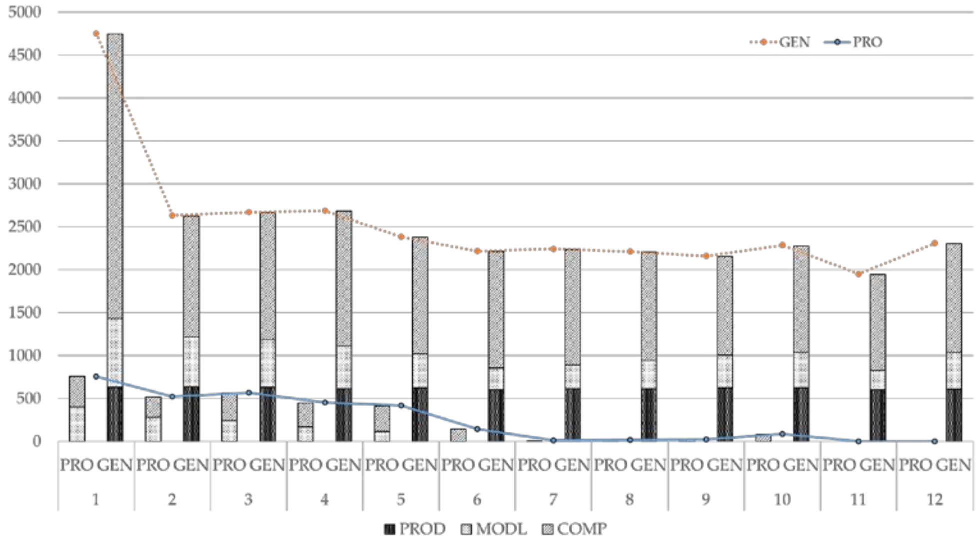


<Figure 7.11> Cost breakdown excluding demand of the first period

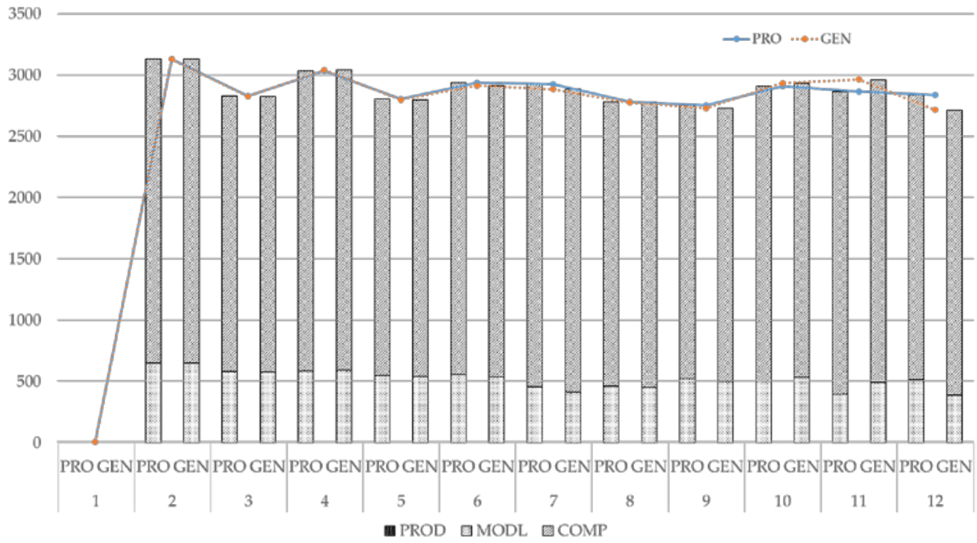
<Table 7.11> Results excluding demand of the first period

	Cov[1]	Ds[2]	Inv[3]	MR[4]	Remfg[5]	Benefit	Total cost	*SS*	*SR*
PRO	108570	90115	8028	82716	739890	101450	927869	89.72	14.42
GEN	111730	89915	117000	79428	738310	97423	1038960	89.46	12.39

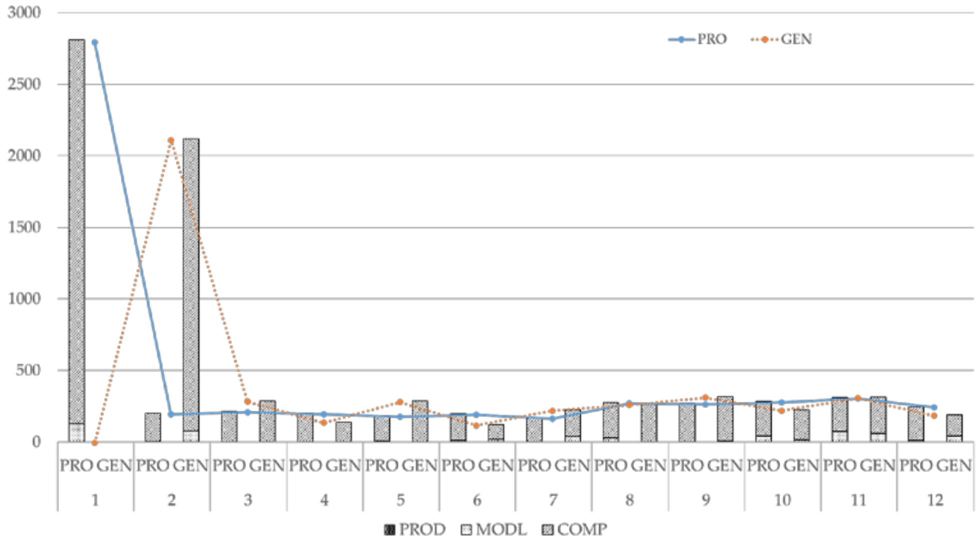
[1] Shortage Covering; [2] Disassembly; [3] Inventory holding; [4] Material recovery; [5] Remanufacturing



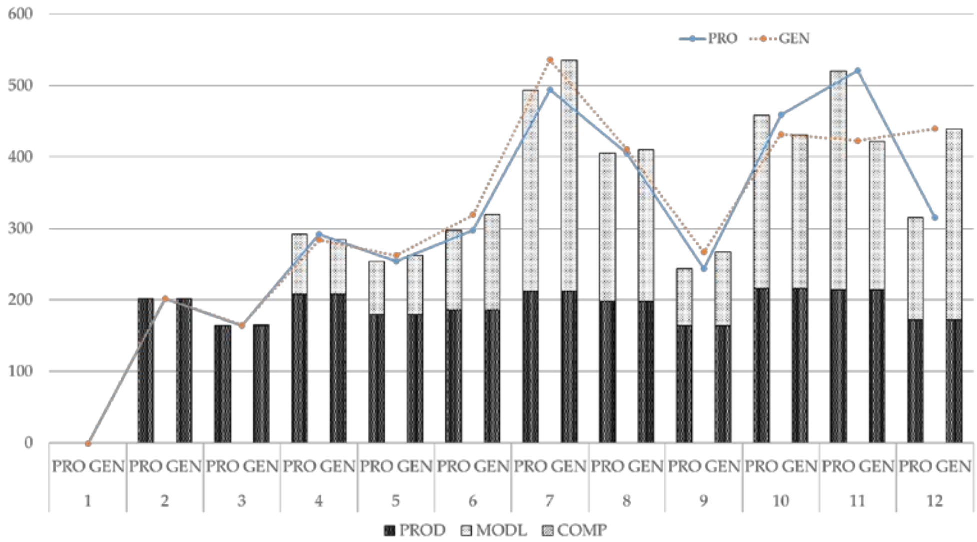
<Figure 7.12> Inventory levels excluding demand of the first period



<Figure 7.13> Remanufactured quantity excluding demand of the first period



<Figure 7.14> Sacrifice disassembly/shredding quantity excluding demand of the first period



<Figure 7.15> Shortage covering quantity excluding demand of the first period

The results excluding the first period also show that there is a significant difference in inventory level, even though the other decision variables are similar to each other. Hence, it is concluded that information visibility provides more profit, because response to the return is faster in terms of the fact that the proposed system recognizes how returned items can contribute to RMS as a raw material immediately.

7.4.2. Impact of Changes in Secondary Demands

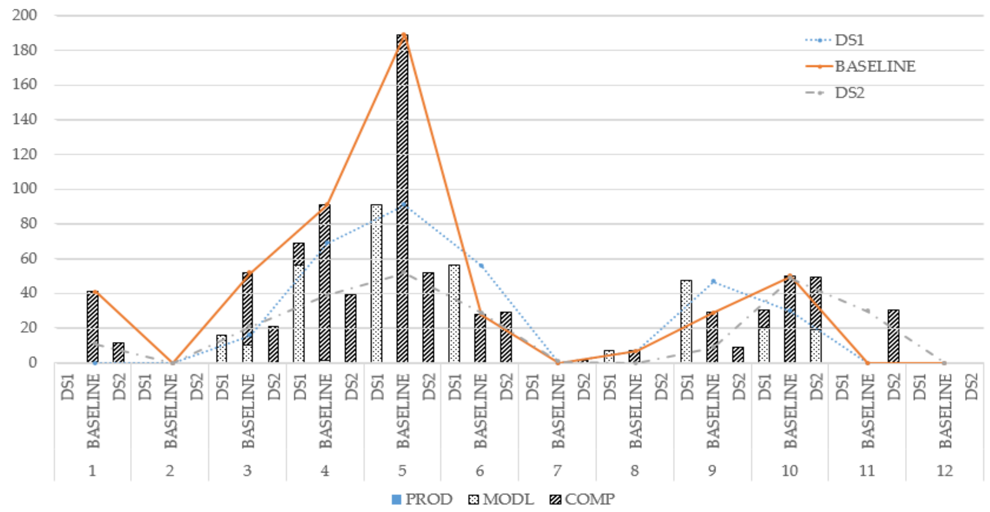
The formation of secondary market in which remanufactured components can be used is essential to establish a sustainable culture. To prove this statement, sensitivity analysis for various secondary demand is executed. The result is listed in <Table 7.12>.

<Table 7.12> Results of sensitivity analysis on secondary demand

Data set	Cov[1]	Ds[2]	Inv[3]	MR[4]	Remfg[5]	Benefit	Total cost	*SS*	*SR*
DS1	34958	90917	1263	97684	650860	119780	755902	95.8	24.83
BASE LINE	141200	90831	1761	75204	795810	92245	1012561	88.04	9.29
DS2	317130	98187	443	70356	905920	86271	1305765	79.03	10.16

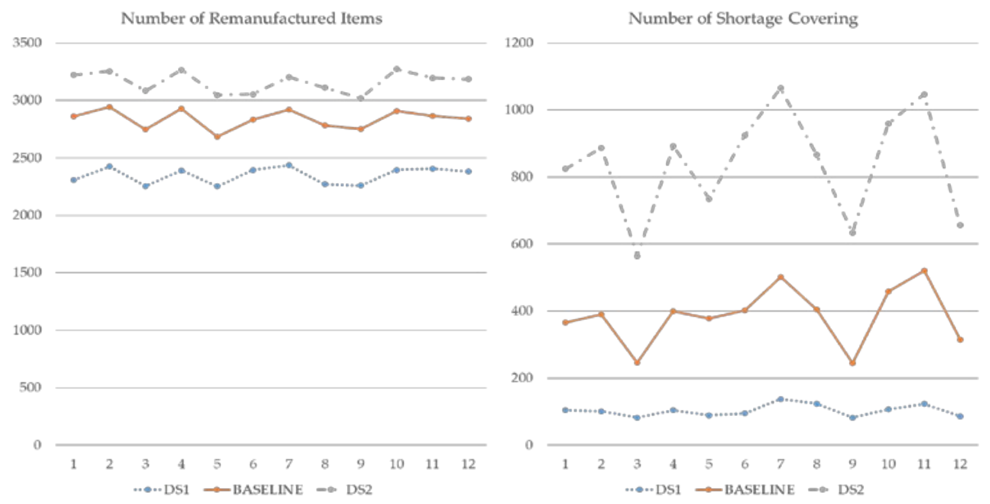
[1] Shortage Covering; [2] Disassembly; [3] Inventory holding; [4] Material recovery; [5] Remanufacturing

DS1 has a half of secondary demand that BASELINE has; DS2 has 1.5 times more demand than BASELINE. The fact that *SS* and *SR* of DS1 are both high, shows that the shortage covering can be less, and since the sufficient amount of good-to-remanufacture items is left, it can be seen that it tends to be used as resources after sacrifice shredding. Only in terms of cost, it seems good to have less secondary demand, but if secondary demand increases, the price of remanufactured items in the market will also increases, so benefit should be considered. <Figure 7.16> and <Figure 7.17> present changes in decision variables.



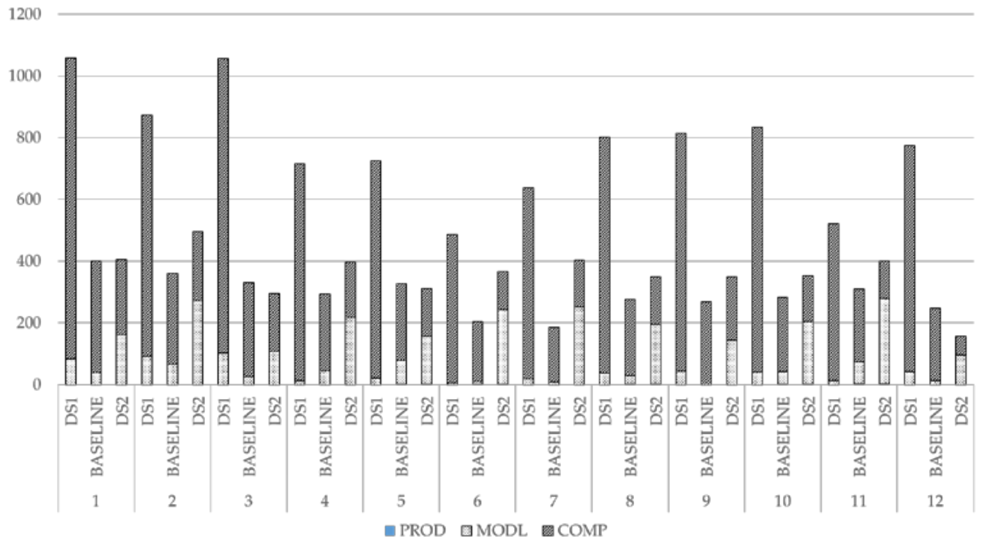
<Figure 7.16> Inventory levels for each dataset

The results show that remanufactured quantity is proportional to secondary demand, and sacrifice disassembly/shredding is more likely to do in DS1.



<Figure 7.17> Changes in X and Z for each dataset

As the right side of <Figure 7.17> indicates that sacrifice disassembly/shredding quantity of DS2 is more than BASELINE. The reason can be found in <Figure 7.18>. This is done to meet the balance because there are more modules and fewer components than needed on the available resources.



<Figure 7.18> Changes in available resources for each dataset

The lesson learned from this analysis is that it is generally good to have a lot of secondary demand, but in terms of the resource circulation efficiency represented by *SR*, there is an appropriate quantity of secondary demand.

7.4.3. Impact of Changes in Remanufacturing Cost

Sensitivity analysis of remanufacturing cost is executed to show the behavior of RMS system changes as the remanufacturing cost changes. Unit remanufacturing cost is assumed that 50% of manufacturing cost for

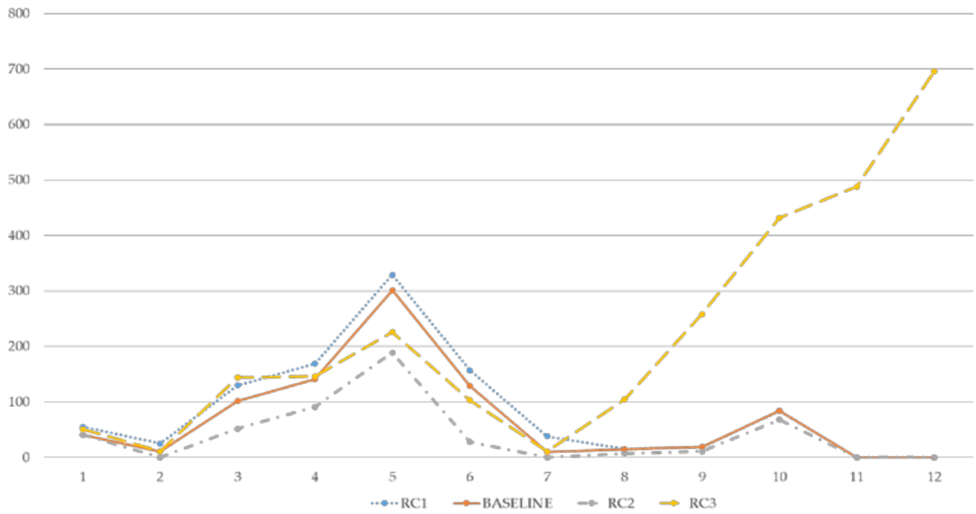
BASELINE dataset; 25% for RC1, 70% for RC2, 90% for RC3 as an extreme case. Cost breakdown for each dataset is given in <Table 7.13>.

<Table 7.13> Results of sensitivity analysis of remanufacturing cost

Data set	Cov[1]	Ds[2]	Inv[3]	MR[4]	Remfg[5]	Benefit	Total cost	*SS*	*SR*
RC1	138550	90559	2115	74616	398570	91524	612886	88.08	9.18
BASE LINE	141200	90831	1761	75204	795810	92245	1012561	88.04	9.29
RC2	141040	90815	937	75172	1114200	92205	1329959	87.91	9.69
RC3	157550	444350	4089	259740	1417700	170000	2113429	87.62	4.74

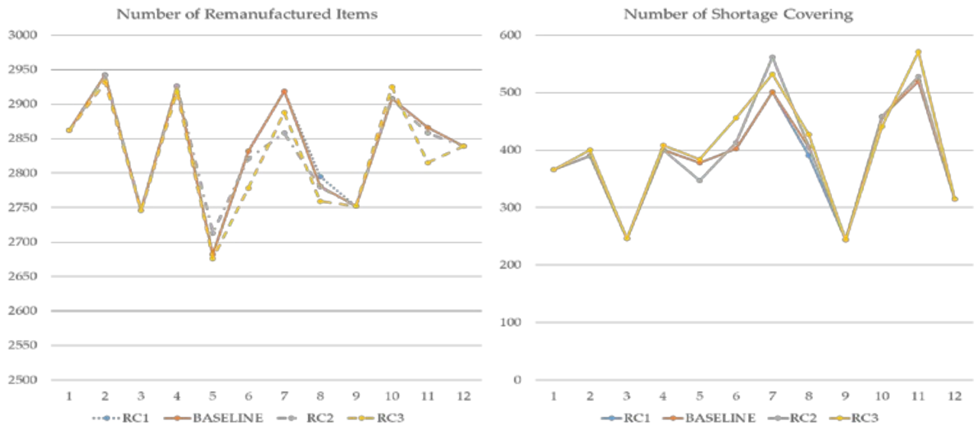
[1] Shortage Covering; [2] Disassembly; [3] Inventory holding; [4] Material recovery; [5] Remanufacturing

<Figure 7.19> shows periodic inventory levels for each dataset. Most of them show similar trends, but in the case of RC3, the inventory level increases in the latter half.



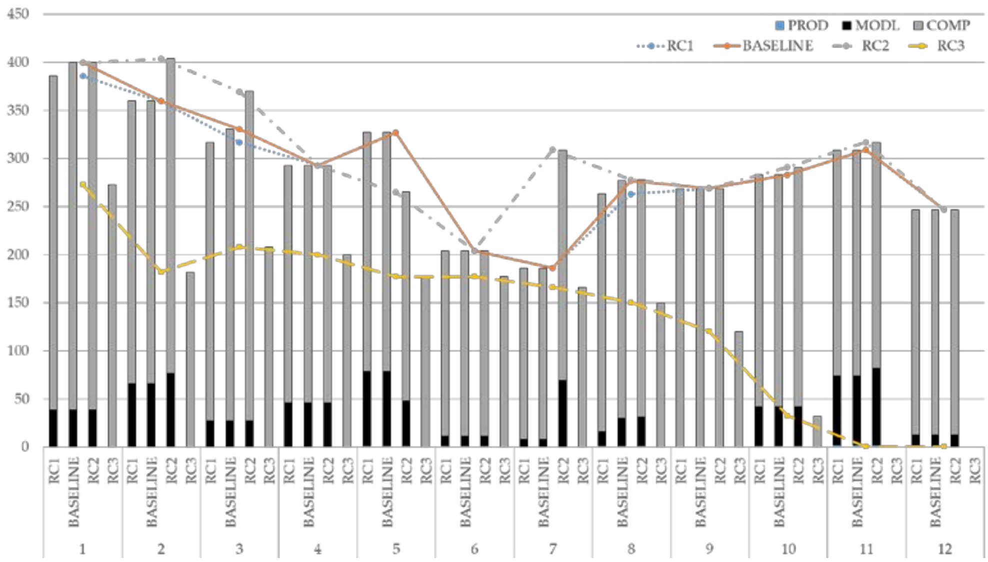
<Figure 7.19> Inventory level for each dataset

Observation for decision variables is needed to make a diagnosis of this situation. For remanufactured quantity and shortage covering quantity, there is no significant difference, and also trend is similar as shown in <Figure 7.20>. It indicates that remanufacturing at a lower cost is preferred, even if the cost increases. The reason why the inventory level of RC3 increases can be found in <Figure 7.21>.



<Figure 7.20> Changes in X and Z for each dataset

From period 9, when inventory level has begun to increase, it can be seen that any sacrifice disassembly/shredding in RC3. For this periods, the major components of the inventory are the component K and L. What we can find at this point is that it is more economical to manufacture new components with newly sourced resources than recovered resources from the returned items, in consideration of incurred costs including material recovery cost, disassembly cost, and so forth. By this reason, sacrifice disassembly for returned modules are not appeared. It also can be found in terms of *SS* and *SR* as listed in <Table 7.14>. Particularly in the case of RC3, shortage covering in a component level occurs.



<Figure 7.21> Changes in sacrifice disassembly/shredding

<Table 7.14> *SS* and *SR* by BOM levels for each dataset

Dataset	*SS*			*SR*		
	Product	Module	Component	Product	Module	Component
RC1	0	71.26	100	100	6.81	9.62
BASELINE	0	71.09	100	100	7.04	9.70
RC2	0	70.46	100	100	7.86	10.02
RC3	0.26	76.32	97.93	0	0	5.71

Based on the results, it can be concluded that the unit remanufacturing cost should be minimized through the development of remanufacturing technology.

7.4.4. Impact of Remanufacture-ability

Sensitivity analysis of good-to-remanufacture portions of the returned quantity is conducted to highlight the change in the characteristics of the RMS.

<Table 7.15> Results of sensitivity analysis of good-to-remanufacture portions

Data set	**Cov[1]**	**Ds[2]**	**Inv[3]**	**MR[4]**	**Remfg[5]**	**Benefit**	**Total cost**	***SS***	***SR***
RQ1	761090	113300	375	164880	485870	202170	1323345	51.24	11.04
BASE LINE	141200	90831	1761	75204	795810	92245	1012561	88.04	9.29
RQ2	75298	82777	1272	54724	828760	67157	975674	93.08	16.00

[1] Shortage Covering; [2] Disassembly; [3] Inventory holding; [4] Material recovery; [5] Remanufacturing

In this case, as expected, as the number of potentially good-to-remanufacture components increases, remanufactured quantity can be increased. *SS* and *SR* also increases because returned good-to-remanufacture quantity is sufficient to meet secondary and spare-part demands.

8. Conclusion

8.1. Summary

This dissertation presents a comprehensive approach for closed-loop supply chain management in order to achieve industrial sustainability. As the interest for environmental conservation grows, the importance of CLSC management, which enables to maximize the lifecycle value creation while satisfying the needs of product recycling, has increased. What is the most important in operation of CLSC is achieving visibility to eliminate chronic problems caused by lack of real-time information.

Problems caused by lack-of-visibility are extracted from surveys of the domestic ELV remanufacturing industry, and they classified into three classes according to the problem characteristics, namely, social, environmental, and technical. Technical problems can be solved by achieving information visibility by using the IoT technologies, including RFID, thereby a CLSC management framework is presented. What is different from existing RFID-based CLSC management approaches is examining the possibility that applying new features provided by Gen2 protocol, which is the most recent RFID protocol.

Proposed system framework includes information system design in order to derive various positive effects throughout whole product lifecycle.

Design of backend database and RFID tag encoding scheme is given while focusing on how to manage numerous information generated in the IoT environment. In particular, the design of the RFID tags follows current GS1 standards strictly to ensure compatibility with the subsequent application. Component-level individual tagging which enables more detailed lifecycle information management also makes difference to existing approaches. Family relations among the components of modular products, which is a part of identity of the objects, is stored in user memory space in the RFID tags. To satisfy fixed-length constraint for software products, partial ring structure is proposed. With the proposed structure, any kind of tree structured product can be represented with uniform-length records.

The latter part of this dissertation comprehensively illustrates potential effects throughout product lifecycle which can be derived when the proposed system implemented. In the MOL phase, RMM and counterfeit prevention, which are intangible effects in terms of product service, are examined. For the valuable products such as aerospace, maintenance methodologies that gather operational data with RFID-based sensor integration and analyze it has been applied. In this dissertation, the possibility of extension of the scope to the consumer product sector was examined. There are two kinds of counterfeits; historical counterfeit which conceals historical failures to make unfair profits in the second-hand market; structural counterfeit which use non-genuine parts. The proposed system offers solutions to deal with these counterfeits. Networked RFID system stores MRO events to prevent the historical counterfeits. And for the structural counterfeits, two approaches, sweeping scan and cross checking, are proposed by using family relations stored in RFID tags and backend database.

The proposed system also has potential effects in the EOL phase in terms of remanufacturing activities. There exists an unnecessary loop that consists of testing, grading, and disassembly, because of lack of detailed component-level lifecycle information management. The proposed system eliminates the unnecessary loop by enabling the proposed system to make recycling decisions for each component by using family relations in the user memory, without any disassembly. This is proved that the proposed system enhances the remanufacturing process in terms of number of jobs and makespan, with the illustrative example. Hybrid production planning model for a RMS is given based on the integer linear programming. This model is to make a decision for each period about how much returned items should be remanufactured, disassembled, and recovered as natural resources to fulfill every kind of market demands, namely, primary market, secondary market, and spare-part market. Also how much newly manufactured items to cover shortages for each market demand is determined. Unlike existing models relating to hybrid production planning, multi-level product structure, which has more than 3 levels, is considered. The value of information visibility achieved from the proposed system is proved by comparing the proposed model and the generic model with the numerical experiment. It is shown that achieving information visibility in order to aware the available resource for the RMS makes response speed faster, thereby reduces inventory level as well as total cost. Also, sensitivity analysis is executed to recognize the characteristics of the RMS. By doing this, requisites for healthy remanufacturing environment is extracted.

8.2. Limitations and Future Research Direction

The proposed system is possible to function only when component-level decision of recycling option based on accurate estimation of residual value with lifecycle information is available. While data-driven methods for achieving these objectives are actively developed, the accuracy and performance should be guaranteed. Furthermore, this kind of methodologies using sensors have been developed for valuable product such as aerospace products. Potential value should be higher in terms of cost, to spread these methodologies into the customer products, which is the same prerequisite for RMM.

Although the proposed system is expected to be helpful for operating CLSC for modular products that consist of various types of components, comprehensive discussion with domain experts is required for application of the proposed system, since key factors that represent the product lifecycle and the information required to estimate residual value are all different. Also, cost-benefit analysis should precede system implementation even though the economic feasibility of automated identification technology on end-of-life management processes has been proved.

This dissertation provides numerical studies to prove the value of the proposed system for the remanufacturing shop floor and the hybrid production planning. However, it should be considered that line balancing for remanufacturing process streamlining, and stochastic demand and return for the production planning. It will show that the proposed system is applicable to various environments. Worker support on the remanufacturing shop floor is considered briefly. Theoretically, it is examined that displaying predefined work instructions for each job will help workers to concentrate, and to reduce human errors in complex remanufacturing environment. It can be considered that applying the augmented reality techniques to enhance understanding.

Appendix. Numerical Experiment Settings

1. Cost for manufacturing

$c_n^P(i) = \{30, 24\}$

$c_n^M(j) = \{40, 26, 34\}$

$c_n^C(k) = \{55, 43, 46, 51, 50, 51, 50\}$

2. Cost for remanufacturing

$c_r^P(i) = \{15, 12\}$

$c_r^M(j) = \{20, 13, 17\}$

$c_r^C(k) = \{27.5, 21.5, 23, 25.5, 25, 25.5, 25\}$

3. Unit inventory holding cost

$c_h^P(i) = \{9, 8.5\}$

$c_h^{M}(j) = \{4, 5, 4.5\}$

$c_h^C(k) = \{2, 2, 2, 1.5, 1.5, 1.5, 1\}$

4. Other cost parameters

$c_{MR} = 4$

$ER = 0.1$

$c_d^{PM} = 5$

$c_d^{MC} = 4$

5. Demands

$D_P(i)$	1	2	3	4	5	6	7	8	9	10	11	12
A	506	557	568	589	582	576	491	478	539	525	445	475
B	320	330	359	308	315	317	314	330	310	318	362	336

$D_S(i)$	1	2	3	4	5	6	7	8	9	10	11	12
A	158	156	122	164	132	140	166	144	114	156	160	116
B	46	46	42	44	48	46	46	54	50	60	54	56

$D_{SP}^{M}(j)$	1	2	3	4	5	6	7	8	9	10	11	12
C	106	110	112	120	120	174	174	110	132	132	114	166
D	52	64	70	52	64	50	68	80	54	86	66	56
E	86	72	72	84	82	76	72	82	90	98	96	90

$D_{SP}^{C}(k)$	1	2	3	4	5	6	7	8	9	10	11	12
F	250	274	292	256	234	292	246	268	288	238	260	270
G	260	286	270	238	260	286	288	256	278	246	260	270
H	256	274	270	278	246	246	282	252	246	268	242	256
I	174	198	170	192	156	202	174	152	174	156	202	196
J	160	130	156	180	196	130	144	130	148	160	170	138
K	126	124	94	120	102	94	102	138	130	94	102	144
L	126	184	174	142	160	196	174	134	144	160	162	192

6. Periodic return quantities

$RQ_{P}^{1}(i,t)$	0	1	2	3	4	5	6	7	8	9	10	11	12
A	0	0	0	0	0	0	0	0	1	0	1	1	0
B	0	0	0	0	0	1	1	0	0	0	0	1	0

$RQ_{P}^{2}(i,t)$	0	1	2	3	4	5	6	7	8	9	10	11	12
A	0	350	334	350	315	315	319	332	316	330	343	316	315
B	0	283	307	283	299	309	281	284	297	297	282	288	296

$DRQ_M^1(j,t)$	0	1	2	3	4	5	6	7	8	9	10	11	12
C	0	207	216	204	201	188	192	186	202	205	209	195	199
D	0	112	117	119	101	108	99	100	98	109	121	102	111
E	0	88	99	97	90	109	85	89	93	104	94	87	95

$DRQ_M^2(j,t)$	0	1	2	3	4	5	6	7	8	9	10	11	12
C	0	426	425	429	413	436	408	430	411	422	416	409	412
D	0	238	217	231	214	207	220	232	218	221	222	214	204
E	0	195	208	186	209	200	196	195	204	193	188	201	201

$DDRQ_C^1(k,t)$	0	1	2	3	4	5	6	7	8	9	10	11	12
F	0	311	302	314	298	323	286	301	309	313	312	299	289
G	0	303	319	318	294	319	298	306	288	313	300	291	309
H	0	321	307	298	306	296	307	309	311	291	297	295	294
I	0	174	155	165	157	156	157	172	164	162	167	161	143
J	0	177	157	171	152	145	161	172	153	162	167	155	145
K	0	145	154	138	157	142	146	141	151	143	141	151	147
L	0	141	154	131	149	146	140	147	149	143	140	143	143

$DDRQ_C^2(k,t)$	0	1	2	3	4	5	6	7	8	9	10	11	12
F	0	115	123	115	115	113	122	129	102	109	104	110	123
G	0	123	106	111	119	117	110	124	123	109	116	118	103
H	0	112	118	119	117	111	109	118	111	123	113	120	111
I	0	64	62	66	57	51	63	60	54	59	55	53	61
J	0	61	60	60	62	62	59	60	65	59	55	59	59
K	0	50	54	48	52	58	50	54	53	50	47	50	54
L	0	54	54	55	60	54	56	48	55	50	48	58	58

$RQ_M^1(j,t)$	0	1	2	3	4	5	6	7	8	9	10	11	12
C	0	70	45	71	65	59	40	38	42	53	71	40	71
D	0	33	32	19	31	20	18	20	28	26	21	24	21
E	0	19	30	27	29	19	19	24	25	27	29	18	29

$RQ_M^2(j,t)$	0	1	2	3	4	5	6	7	8	9	10	11	12
C	0	157	99	154	148	132	90	92	91	115	171	90	169
D	0	74	73	45	68	48	42	46	68	63	51	52	51
E	0	43	65	63	66	44	48	55	55	68	65	40	64

$DRQ_C^1(k,t)$	0	1	2	3	4	5	6	7	8	9	10	11	12
F	0	118	73	116	106	97	66	66	67	82	125	65	122
G	0	114	74	114	110	93	67	69	64	87	129	65	119
H	0	88	101	80	95	68	66	74	88	94	85	66	85
I	0	55	52	32	48	36	32	35	50	45	38	38	39
J	0	54	54	32	49	35	32	33	51	45	38	39	36
K	0	32	49	45	49	33	35	42	41	49	49	29	48
L	0	33	46	45	47	31	36	39	41	51	46	30	48

$DRQ_C^2(k,t)$	0	1	2	3	4	5	6	7	8	9	10	11	12
F	0	39	26	38	42	35	24	26	24	33	46	25	47
G	0	43	25	40	38	39	23	23	27	28	42	25	50
H	0	29	37	28	39	24	24	27	35	37	31	26	30
I	0	19	21	13	20	12	10	11	18	18	13	14	12
J	0	20	19	13	19	13	10	13	17	18	13	13	15
K	0	11	16	18	17	11	13	13	14	19	16	11	16
L	0	10	19	18	19	13	12	16	14	17	19	10	16

$\mathrm{RQ}_{\mathrm{C}}^{1}(k,t)$	0	1	2	3	4	5	6	7	8	9	10	11	12
F	0	84	75	89	75	51	57	58	60	59	71	88	63
G	0	76	80	52	74	60	57	70	73	51	59	74	74
H	0	125	62	70	86	55	93	105	92	72	98	56	77
I	0	64	81	68	105	91	101	94	88	76	83	73	117
J	0	91	61	112	98	69	67	107	76	90	70	112	79
K	0	61	92	67	70	93	76	106	109	102	82	82	61
L	0	90	87	93	78	90	98	59	89	71	88	91	83

$\mathrm{RQ}_{\mathrm{C}}^{2}(k,t)$	0	1	2	3	4	5	6	7	8	9	10	11	12
F	0	63	44	57	52	36	39	40	35	37	42	61	40
G	0	83	74	57	79	66	60	72	76	56	57	79	82
H	0	197	92	109	140	82	140	150	127	108	152	87	114
I	0	46	60	48	77	69	59	63	59	46	57	49	88
J	0	97	55	106	104	69	66	116	83	94	73	117	81
K	0	43	57	44	52	64	54	73	80	60	51	59	44
L	0	124	127	131	127	140	160	96	138	102	137	142	125

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국문초록

생산자책임재활용제도는 제조업 측면에서의 환경 문제에 대한 해결책으로, 이것의 도입과 함께 자동차, 전기 및 전자제품의 최종생산자들의 책임은 생산, 유통을 넘어 회수 및 재활용까지로 확장되었다. 특히 재활용의 경우에는 질량 기준 일정한 비율 이상의 재활용을 강제하는 법적 제도가 도입되었다. 이러한 시대적 배경에서 일명 정방향 프로세스로 일컬어지는 소싱, 생산, 판매로 이루어지던 전통적인 공급망 관리의 범위가 회수와 재활용을 포함하는 역방향 판매를 통합한 범위로 확장되었다. 이는 한 번 생태계에 투입된 자원을 지속적으로 사용한다는 측면에서 폐쇄루프 공급망이라고 부르며 이것의 적절한 운영을 통해 환경 법제를 준수하는 것뿐만 아니라 제품 생애주기에 따른 가치 창출을 최대화함으로써 경제적인 가치를 극대화할 수 있다. 그러나 회수에서 재활용으로 이어지는 역방향 프로세스는 불확실성을 지니고 있어 전체 폐쇄루프 공급망의 성과 측면에서 비효율을 야기하고 있다. 물리적인 흐름 측면에서 회수의 시점 및 수량에 대한 예측이 힘든데다 회수 후 재활용은 수많은 공급망 내 참여자들에 의해 발생하기 때문에 그 복잡도가 매우 높다. 뿐만 아니라 제품 수명주기 측면에서 제품들은 사용 환경과 사용자의 사용 행태 및 수많은 인자에 의해 회수되었을 시 그 잔존가치가 천차만별로 나타날 수 있으며 제품을 구성하는 부품 단위로 더 자세하게 보면 이 문제는 더 심하게 나타나게 된다. 많은 연구들에서 이러한 문제들에 대한 해결책으로 실시간 정보의 취득 및 활용을 제시해 왔다. 이러한 맥락에서 이 논문은 RFID를 포함한 사물인터넷 기술을 활용하여 물리적 흐름, 제품 수명주기 측면에서 발생하는 정보 부족에 따른 불확실성을

최소화하고 전 수명주기에 걸쳐 다양한 효과를 파생시킬 수 있는 시스템 프레임워크를 제안하고 시스템 운영에 필요한 정보시스템에 대한 설계를 진행한다. 제안하는 시스템은 제품 단위로만 태그를 부착하는 기존 연구들과는 다르게 제품을 구성하는 부품 단위까지 태그를 부착하여 더 세부적인 수명주기 정보관리를 할 수 있도록 한다. 특히 초고주파 대역 RFID 기술의 최신 표준인 Gen2 프로토콜이 제공하는 새로운 기능인 유저 메모리를 활용하여 부품들 간의 가족관계를 기록함으로써 다음과 같은 전수명주기에서의 다양한 효과들을 포괄적으로 도출한다. RFID 태그 인코딩 체계를 비롯한 정보시스템 설계는 현재 수립된 표준을 철저히 준수하여 설계함으로써 향후 동일 산업군 내 호환성을 보장하고자 한다.

제안한 시스템의 운영을 통해 MOL 단계에서의 실시간 모니터링 기반 제품 유지보수 체계, 위조 방지 체계와 같은 제품 서비스 측면에서의 무형적인 효과에 대해 제시하며 특히 가족관계 인코딩을 활용한 위조 방지 체계인 스위핑 스캔 방법론을 제시한다. 또한 EOL 단계에서 제안하는 시스템이 제공하는 세부적인 수명주기 정보를 활용하여 재제조 프로세스 및 제조/재제조 통합 생산계획에 있어 효과를 보일 수 있음을 수리적 예제를 통해 증명하고자 한다.

주요어 : 재활용, 폐쇄루프 공급망, 제품수명주기관리, 생산계획, RFID, 산업지속가능성

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