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Resource Conservative Manufacturing
A New Generation of Manufacturing

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To those who believed in me

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I would never be in my current position without the love and support of my parents and siblings and this work would have not been possible without the sacrifice and love of my wife Fiza and my daughter Arushi.

Abstract

The question of resource scarcity and emerging pressure of environmental legislations have put the manufacturing industry with a new challenge. On the one side, there is a huge population that demands a large quantity of commodities, on the other side, these demands have to be met by minimum resources and with permissible pollution that the earth's ecosystem can handle. In this situation, technologic breakthrough that can offer alternative resources has become essential. Unfortunately, breakthroughs do not follow any rule of thumb and while waiting for a miracle, the manufacturing industry has to find ways to conserve resources. Within this research the anatomy of a large body of knowledge has been performed to find the best available practices for resource conservation. Critical review of the research revealed that none of the available solutions are compatible with the level of resource conservation desired by the manufacturing industry or by society. It has also been discovered that a large gap exists between the solutions perceived by the scientists and the applicability of those solutions. Through careful evaluation of the state-of-the-art, the research presented in this thesis introduced a solution of maximizing resource conservation i.e., material, energy and value added, as used in manufacturing. The solutions emerged from the novel concept named as Resource Conservative Manufacturing, which is built upon the concept of Multiple Lifecycle of product. Unlike other research work, the research documented in this thesis started with the identification of the problem and from which a 'wish to do' list was drawn. The seriousness of the problem and potential of adopting the proposed concept has been justified with concrete information. A great number of arguments have been presented to show the existing gaps in the research and from that, a set of solutions to conserve resources has been proposed. Finally, one of the prime hypotheses concerning closed loop supply chain has been validated through the system dynamics modeling and simulation.

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Asif, F. M. A.; Semere, D. T. & Nicolescu, C. M., (2009). A Novel Concept for End-of-life Vehicles (ELV). *Proceeding of the International 3'rd Swedish Production Symposium*, *pp* 325-331, ISBN-978-91-633-6006-0, 2-3 December 2009, Göteborg, Sweden.

Paper-B

Asif, F. M. A.; Semere, D. T.; Nicolescu, C. M. & Haumann, M., (2010). Methods Analysis of Remanufacturing Options for Repeated Lifecycle of Starters and Alternators. *The Proceeding of the 7th International DAAAM Baltic Conference, "Industrial Engineering", pp* 340-345, ISBN-978-9985-59-982-2, 22-25 April 2010, Tallinn, Tallinn University of Technology, Estonia.

Paper-C

Asif, F. M. A. & Nicolescu, C. M, (2010). Minimizing Uncertainty Involved in Designing the Closed-loop Supply Network for Multiple-lifecycle of Products. *Annals of DAAAM for 2010 & Proceeding of the 21st International DAAAM Symposium, "Intelligent Manufacturing and Automation: Focus on Interdisciplinary Solutions", pp* 1055-1056, ISSN 1726-9679, 20-23 October 2010, Zadar, Croatia.

Abbreviations

DFE	Design for Environment
DFX	Design for X
ELV	End-of-Life vehicles
EoL	End-of-Life
EoU	End-of-Use
EPR	Extended Producer Responsibility
OEM	Original Equipment Manufacturer
RCL	Resource Conservation Level
RCP	Resource Conservative Product
ResCoM	Resource Conservative Manufacturing
WEE	Waste Electrical and Electronic Equipment

Chapter I

1. Introduction

This chapter contains background of the research, motivation for conducting the research, research questions, hypothesis and overview of the contents of the thesis report.

1.1. Background

Due to the worldwide population boost, economic growth and increase in standards of living, the current reserves of natural resources are proven to be insufficient and the earth's ecosystems are on the edge of collapsing. The current growth indicates that the worldwide population will be doubled by 2072 [1]. This double population size will result in a five times increase in the GDP per capita, with a ten times increase in resource consumption and waste generation [2]. By contributing 30.7 % to the total world GDP and employing a 0.7 billion workforce worldwide (estimated in 2010) [3], the manufacturing industry serves as one of the main driving forces in economic growth and improvement of living standard. Indeed, at the same time, the manufacturing industry is contributing to resource consumption and waste generation on a large scale. It indicates that the manufacturing industry are in the dilemma of either, grow as the society demands at the cost of the earth and the ecosystem or of halting growth and setting the civilization back to the Stone Age to save the earth. However, neither of these alternatives seem practical. This problem is further elaborated on the proceeding sections in terms of four dimensions, resources scarcity, waste generation, energy consumption and value added.

It is estimated that the worldwide iron ore resources are 800,000 million metric tons (mmt) [4]. By having an approximate ratio of 3:1, this amount of iron ore can produce about 267,000 mmt of steel. The steel consumption has increased by 69% since 2000, and reached the consumption of 1,282 mmt in 2010. If other things stay the same, with the growth remaining at an average of 7% a year the current reserves of iron ore will run out by 2089. This figure is even more frightening if the increase in the steel consumption rate of developing countries such as China is considered. In the past 10-years, the consumption rate of steel in China has increased by 181% [5]. If China continues to grow at the same pace as today, the reserves of iron ore will run out even faster. Moreover, due to high demand, the price of iron ore is increasing proportionally making the situation even more volatile. As the manufacturing industry is one of the biggest consumers of steel, these figures are a matter of concern. Furthermore it can certainly be stated that, other materials used by the manufacturing industry in a large scale have a similar picture. However, there is no reason to panic yet because a substantial portion of steel is reused. In recent years (2006-2010) the global scrap used in steel making has been an average of 512 mmt per annum, with an increase of 6% since 2006 [6]. Reuse of scrap materials not only saves the natural resources but with each ton of steel scrap reused, 1.8 tons CO_2 emission and energy consumption equivalent to 0.53 tons of anthracite coal can be avoided [7]. It is worth mentioning that, if the reuse rate and recycling process efficiency is not increased the problem of resource scarcity will hit us in another 50 years.

Resource scarcity is thus the 1st dimension of the problem. The 2nd dimension of the problem faced by the manufacturing industry is waste management. The manufacturing industry is one of the largest contributors to waste generation. In 2008 approximately 363 million tons of solid waste (account for 14% of the total waste) was generated by the manufacturing industry in the EU-27 [8]. In additions to this, through Extended Producer Responsibility (EPR) regulation manufacturers are now fully or partially accountable for End-of-Life (EoL) products that are sold in the market. The problem has become more serious with an increase in tax and restrictiona on landfilling of solid waste. Nevertheless, large portions of the manufacturing solid waste and EoL product waste are avoided through recycling, reducing the amount to be landfilled. Even though, in general, reuse of steel can save up to 75% of energy, depending on the complexity of the alloy's composition, the energy intensity of material recovery can be quite high. There are situations where the reuse of material is more energy intensive than the buying or producing of new material. As energy consumption is directly linked to CO_2 emission, and often the consumption of other natural resources, the manufactures have to think twice before making their choice. Unfortunately, the source of energy is not unlimited and energy is produced at the cost of the environment. There are regulatory pressures on manufacturers on both energy consumption and $C0_2$ emission. Thus, the 3rd dimension of the problem that manufacturers are facing is the reduction of energy consumption or becoming more energy efficient.

The 4th dimension of the problem is not that well debated and understood. It is agreed that a product is the output of a certain manufacturing system where inputs are mainly material, energy and value added (in terms of labor, machine, overhead etc.). The inputs that do not fall in the category of energy or material are mostly parts of the value added. In many cases, the value added is the largest part of the manufacturing costs. It is true that values that are added during the manufacturing are lost or used during the use phase of the product. At EoL, those values are completely used. In this case, it makes sense (if it does not oppose the 3rd dimension of the problem discussed above) to reuse materials from the used product as nothing else i.e., energy or value added can be recovered.

However, the matter of concern is that in the fast-growing and evolving consumer market, products seldom reach EoL when a consumer decides to shift to the next generation of products. In this case, products end up in scrap yards although they retain some values. Recovering only material from a product when it could be possible to recover other values is not the best practice both from a manufacturing and an environmental point of view. This issue is getting growing attention, and that is why legislative bodies are stepping up to improve the situation. In the European Union, there are at least five directives (see section 2.1 for further details) issued, which are directly or indirectly trying to promote reuse of products or components where feasible.

In summary, the manufacturing industry is facing four major problems. Manufacturers have to grow in the same proportion as the market demands with limited resource, higher-energy efficiency, near to zero emission and solid waste (both during manufacturing and at a product's EoL) and with maximum value recovery from a product. The irony is that these problems are highly interconnected, and it is therefore inappropriate to treat them independently and optimize each individually. The manufacturing industry needs solutions that can solve entirely, or partially, all the problems. Resource conservative Manufacturing (ResCoM) is a holistic concept which will balance the system to a great extent, as shown in Figure 1-1.

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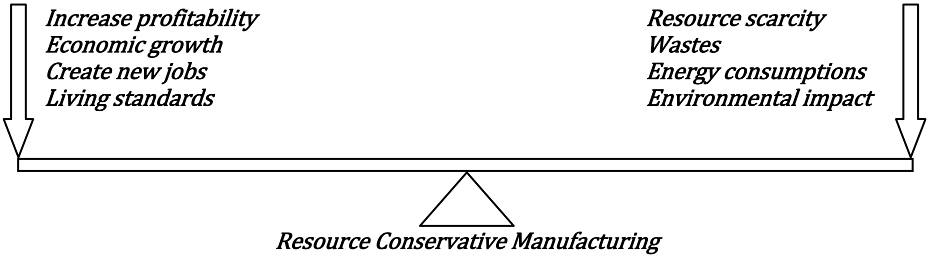

Figure 1-1: The balancing characteristic of resource conservative manufacturing.

It needs to be admitted that these are not the only challenges that the manufacturing industry is facing, but other problems are not within the scope of this research.

1.2. Research motivation

The primary motivation for this research came from the above mentioned four dimensions of the problem that the manufacturing industry is facing. As we have only one earth, and its resources are limited, there is a lot to do to keep this earth inhabitable for future generations. Being part of the manufacturing and production engineering community my research focus is naturally justified.

The business part of the manufacturing industry cares less about the earth or the ecosystem, and more about profitability, unless they are legislatively obliged or such considerations provide strategic advantages. As the center of business is profitability, the manufacturing industry needs to be proactive with future resource crisis and environmental toll, to keep profitability optimum. However, every action that is taken to increase profitability should not only be economically justified for one community but should also be justified within other dimensions in a global respect. The current practices (shown in Figure 1-2) toward resource conservation are placed in a comparative scale, and compared with manufacturing in respect to economy, value recovery, energy consumption and environmental impact. The most desirable position in the scale is the upper left corner. Indeed, the manufacturing industry tends to move to the upper left corner, but there is a huge gap between what is being done and could be done. The minimization of this gap is the secondary motivation for the research.

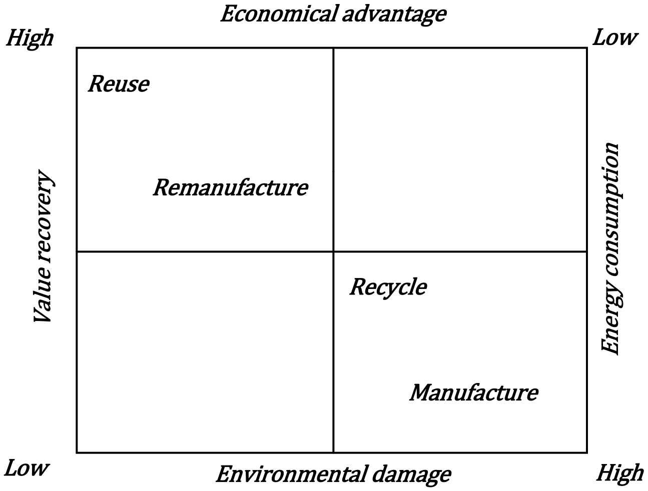

Figure 1-2 : Comparison of different resource conservation approaches[1] to manufacturing in respect of economy, value recovery, energy consumption and environmental impact.

It is equally important to support the claims in terms of quantifiable data. It should be noted that the data (such as cost, energy consumption, labor and overhead cost) related to different approaches to resource conservation varies widely. The data is mainly product oriented and different for different products. An overview of value of a product reclaimed; remanufacturing *vs.* recycling in terms of material, energy, labor and partial overhead (plant and equipment) is shown in Figure 1-3. [9]

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[1] It should be noted that the term reuse and remanufacture can be interchangeable depending on how they are defined. In this case, reuse refers to component. A used component (having same functional quality as new or upgraded to as the new component) is reused as spare part or reused to remanufacture a product. On the other hand, remanufacture refers to product that consists of more than one component. During remanufacturing functionally disordered components are upgraded or replaced with new components.

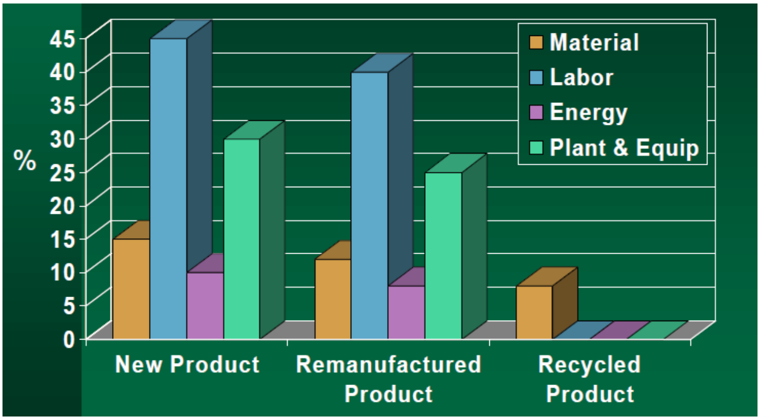


Figure 1-3: Value of a product reclaimed: Remanufacturing *vs.* Recycling.

Moreover, due to the lower consumption of material and energy, and the reuse of materials, similar levels of environmental benefits, in terms of reduced waste and CO_2 emission, are achieved. The benefits of reusing and remanufacturing are not limited to the above mentioned, though these are the easily identifiable ones. Asif *et al* [10] have identified and categorized the different drivers of remanufacturing and reuse (in other words, product's multiple lifecycle) as basic and tactical. These drivers go beyond the economic and environmental benefits. There is a great potential both in terms of profitability and sustainability, which is the tertiary motivation for this research.

Despite such potential remanufacturing has not achieved its desired status and its application is fairly limited. It can be easily assumed that there are a number of pitfalls. As the concept of resource conservative manufacturing proposes product's multiple lifecycles (which is more complicated than single time remanufacturing) it is important to understand those pitfalls. Identifying and understanding these pitfalls is the final motivation for this research.

To summarize the motivations for this research work are,

1. The problems faced by the manufacturing industry with resource scarcity, waste, energy and value recovery.
2. Existing gap between research effort and implementation of conventional resource conservation approach.

3. Pitfalls that lies behind the adoption and economical success of conventional resource conservation approach

1.3. The concept of resource conservative manufacturing in brief

The concept of resource conservation manufacturing is presented elaborately in section 2.2. As the term has already been used in above sections, it has become necessary to briefly describe the concept for the convenience of readers. Resource conservative manufacturing neither criticizes nor takes the side of conventional forms of resource conservation, such as recycling or remanufacturing. Instead, this approach considers them as enabling support. However, it highly criticizes the distinct approach of decision making (and not validate decision making by combination of cost, resource consumption, recoverable value and environmental protection analysis) whether a product should be remanufactured or recycled, and does not either support blindly following any of the alternatives.

Resource conservative manufacturing proposes a careful analysis of products'/components' n^{th} (n representing any value 1, 2, 3….n as long as it ensures optimum resource conservation) lifecycle considering cost, resource consumption, value recovery and environmental protection to determine the optimum number of lifecycles. Once the number of lifecycle(s) is determined, a product/component is designed accordingly. The product recollection interval(s) is also determined in the design phase. In addition, it proposes to feature products with embedded smart components that keep a record of critical parameters that determine components'/products' lifecycle (for instance, number of revolutions, loads, operating temperature etc. in case of mechanical bearing). The product is also proposed to be designed with the support of information technology that stores all necessary information (for example, information concerning product identification, disassembly, testing etc) that might be needed throughout the multiple lifecycle. At predetermined intervals, products are recalled through a closed loop supply chain, components are then upgraded, replaced or recycled (as suggested by the lifecycle analysis done in the early phase and the products' current state at the time of return), and remanufacturing is performed. In resource conservative manufacturing this approach has been named as Product's Multiple Lifecycle. Resource conservative manufacturing recommends this entire approach to be part of regular manufacturing systems. Therefore, it does not only propose the technological solution but also incorporate the supply chain and business aspect. Resource conservative manufacturing is not just a tool but a holistic approach that provides a complete solution towards maximum resource conservation and minimum environmental damage.

1.4. Research questions and hypothesis

This thesis contains four chapters and three conference publications which all together aim to answer the following three research questions,

A. Is it possible to create economic growth at the company level (local level) and sustain the worldwide economic (global level) growth by conserving (or without destroying) the earth's resources and ecosystems, reducing pollution, increasing consumption and creating job opportunities?
B. How the proposed resource conservative manufacturing differs from existing ones in terms of energy and material savings and value recovery?
C. What are the cornerstones of resource conservative manufacturing?

The question for the future research work has already been formulated as follows,

A. Is it possible to use the resource conservative manufacturing concept to analyze the system at a global level using time and space dimension to find an optimum point to satisfy all the conditions and still create profit for a company and at the same time maintaining sustainability of the system?

Addition to answering the above mentioned question the thesis aims to validate the following hypothesis,

A. By adopting the resource conservative manufacturing approach a well functioning closed loop supply chain can be designed.

It is important to observe that the chapters in the report and publications attached are not structure according (or in chronological order) to research questions or hypothesis, e.g., chapter ‘1’ answers question ‘A’. Instead, more than one chapter and publication bring up more than one question and try to answer it. For the convenience of the readers, a mapping of relevance of the contents of this report with research questions and hypothesis is included in the section 1.5.

1.5. Thesis overview

Following the introductory chapter, the research framework, chapter 2, briefly presents the state-of-the-art relevant to the concept of resource conservative manufacturing with a comparative analysis. Chapter 3 describes an essential cornerstone of resource conservative manufacturing; the closed-loop supply chain. It also includes designing, modeling and simulation of a generic closed-loop supply chain using the system dynamics principles. The result of the simulation with discussion is added at the end of the chapter. Chapter 4 is the concluding chapter which includes direction of the future work.

In addition to the above mentioned four chapters, the following three conference publications have been added to the thesis,

A. Asif, F. M. A.; Semere, D. T. & Nicolescu, C. M., (2009). A Novel Concept for End-of-life Vehicles (ELV). *Proceeding of the International 3'rd Swedish Production Symposium*, *pp* 325-331, ISBN-978-91-633-6006-0, 2-3 December 2009, Göteborg, Sweden.

B. Asif, F. M. A.; Semere, D. T.; Nicolescu, C. M. & Haumann, M., (2010). Methods Analysis of Remanufacturing Options for Repeated Lifecycle of Starters and Alternators. *The Proceeding of the 7th International DAAAM Baltic Conference, "Industrial Engineering", pp* 340-345, ISBN-978-9985-59-982-2, 22-25 April 2010, Tallinn, Tallinn University of Technology, Estonia.

C. Asif, F. M. A. & Nicolescu, C. M, (2010). Minimizing Uncertainty Involved in Designing the Closed-loop Supply Network for Multiple-lifecycle of Products. *Annals of DAAAM for 2010 & Proceeding of the 21st International DAAAM Symposium, "Intelligent Manufacturing and Automation: Focus on Interdisciplinary Solutions", pp* 1055-1056, ISSN 1726-9679, 20-23 October 2010, Zadar, Croatia.

A mapping of the relevance of the contents of this report with the research questions and hypothesis mentioned in section1.4, is shown in Table 1-1.

Table 1-1: Mapping of the contents of the thesis report and publications with research questions and hypothesis.

Research questions & hypothesis	Chp. 1	Chp. 2	Chp. 3	Chp. 4	Chp. 5	Publ. A	Publ. B	Publ. C
Question A	X	X				X	X	
Question B	X	X				X	X	
Question C		X	X			X	X	X
Question D	Research question for the future work							
Hypothesis A			X					X

Chapter II

2. Research framework

In this chapter the state-of-the-art with a critical review is presented. The concept of resource conservative manufacturing is elaborately discussed with a brief implementation method.

2.1. A review of state-of-the art towards resource conservation

In recent times an effort towards resource conservation is quite noticeable in the manufacturing industry. At the same time, it is well known that approaches used by industries to conserve resources are diverse. This is the result of research conducted in past centuries, and it is not realistic to include all the resource conservation approaches. The aim is to briefly present the state-of-the-art researches and industrial practices relevant to the proposed concept of resource conservative manufacturing described in section 2.2.

Remanufacturing for resource conservation

The core idea behind resource conservation is to use a product multiple times (each time by adding minimum energy, resources and material), with remanufacturing as one of the enabling tools. Therefore, it is important to discuss remanufacturing. Exactly when the method of sustaining a product/component for more than one lifecycle was given the name remanufacturing and became a topic of research is not known. The earliest publication that is traceable was published by Robert T. Lund in the early 80s. Two significant milestones of R. T. Lund work were to try to industrialize remanufacturing and highlight the quality and standard issues of a remanufactured product [11]. Sundin [12], by combining the definitions of influential authors in the field of remanufacturing, formulated the definition of remanufacturing as,

'Remanufacturing is an industrial process whereby products referred as cores are restored to useful life. During this process, the core passes through a number of remanufacturing steps, e.g., inspection, disassembly, part

replacement/refurbishment, cleaning, reassembly and testing to ensure it meets the desired product standards.'

The process of remanufacturing is relatively simple compared to manufacturing and limited to the steps mentioned in the above definition. However, the actual techniques of performing these steps vary considerably depending on the types of product. The research regarding remanufacturing technology mainly emphasized how remanufacturing can be made viable for industries, e.g., product design (focusing on remanufacturing, disassembly, assembly and reassembly), supply chain management and logistics design, and strategies and business models for remanufacturing.

An equal amount of research or even greater compared to technological issues in remanufacturing, was carried out to justify why remanufacturing is the best way to achieve sustainability i.e., material and resources conservation, preserve value-added from a product, reduce the environmental impact and boost economic benefits.

Despite all these efforts and benefits, insignificant maturity has been gained when it comes to industrialization of remanufacturing. A few names appear repeatedly in literature as examples of successful remanufacturers. Among them, Caterpillar, Xerox, Kodak, IBM, HP and BMW are most discussed names. Nevertheless, in reality, remanufacturing is done by many small and medium sized industries all over the world, but the market is rather tiny compared to its potential.

As an argument to the existing gap between research and industrial application, several hypothesizes are available. The leading hypothesis (and most influential) is that remanufacturing cannot utilize its full potential unless Original Equipment Manufacturer (OEM) is involved or closely controls the remanufacturing business. This hypothesis is directly or indirectly validated by many researchers. Nasr and Thruston [13] stated that full potential of remanufacturing cannot be achieved unless the product is design for it, which refers to OEM's involvement. Giuntini and Gaudette [14] stated ten points as the reasons for remanufacturing not being successful; most of these points are in some way related to OEM's involvement in remanufacturing business. Kumar *et al* [2] stated that combined efforts from all stakeholders i.e., OEMs, regulatory bodies, consumers and product's EoL/EoU facilitators are required to improve the current situation of product recover, and achieve the vision of product multi-use.

Besides these, the drawbacks of remanufacturing can be summarized in the following three categories,

1. *Technological drawbacks*

- Highly customized products with very many variants and short technology-life and lifecycle.
- Products are not designed to facilitate remanufacturing.
- The remanufacturing process technology is not matured.
- Remanufacturing and manufacturing are two separate worlds and have no mutual interest to facilitate each other.

2. *Economic drawbacks*

- Cost vs. benefit of remanufacturing is not well understood.
- Fear of market cannibalization.
- Performance and success of any firm is only measured in terms of cost and profit.

3. *Societal drawbacks*

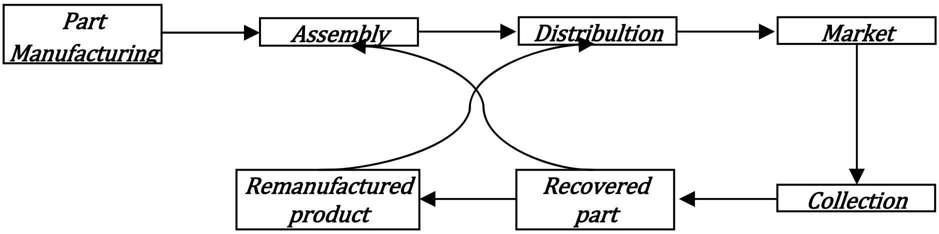
- Major stakeholder's negative attitude towards remanufacturing.

Supply chain for resource conservation

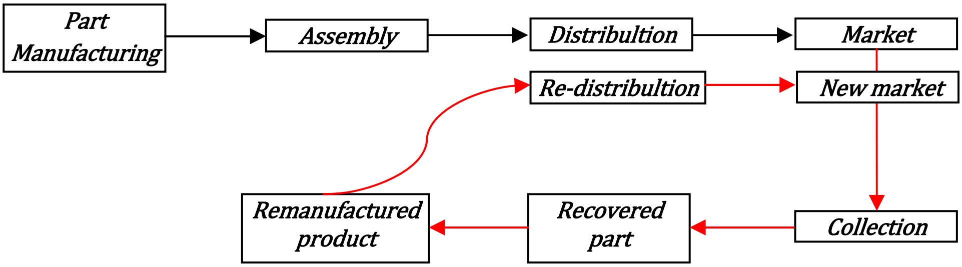
Designing and managing a supply chain to ensure collection of used products (usually addressed as 'Core') is one of the essential elements for making products' multiple lifecycles viable. A supply chain of this kind is usually addressed as a reverse supply chain, or closed loop supply chain. Nevertheless, both refer to the same activities which are related to the collection of return products or cores and remarketing of remanufactured products. A significant difference can be observed when defining these two terms. It is appropriate to call the chains of core collection as the reverse supply chain, if the cores are collected for single event remanufacturing and if the recovered cores do not enter the main stream of the forward supply chain or the recovered contents of the original products used by other firms to manufacture products serving a different purpose [15] [16]. If the core is collected once or more through the same channel to perform remanufacturing, and the cores are used in the same products or sold in the same market, then it is more appropriate to call it a the closed loop supply chain. It should also be noted that core collection activities can only be referred to as a closed loop supply chain if the following conditions are fulfilled,

- The core is collected by the OEM or the 3rd party remanufacturer that acts as the supplier to the OEM.
- The core enters (and is used) in the main stream of a manufacturing forward material flow.
- The remanufactured product is sold in the same way as the new, i.e., the remanufactured product is not considered as a different product variant and order-supply is not handled separately.

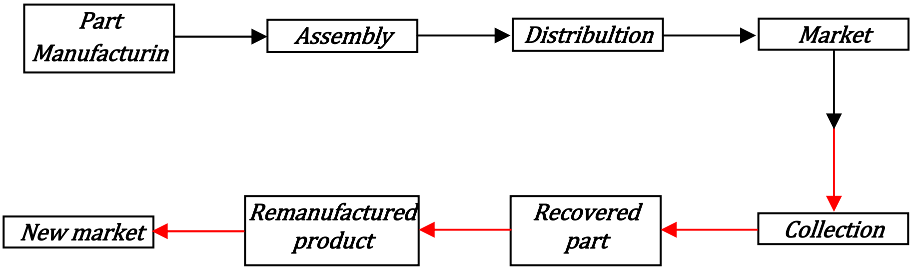
If all of the above-mentioned conditions are not fulfilled, then the supply chain is not closed and technically it should not be addressed as a closed loop supply chain. Figure 2-1 (a, b, c) describes the material flow in different types of supply chain.



a. Remanufacturing is performed by the OEM or a 3rd party but the product is distributed through the same channel and to the same market (ideal closed loop supply chain)



b. Remanufacturing is performed by the OEM or a 3rd party but the product is distributed through a different channel and to a different market (reverse supply chain with an open end, often mistaken as a closed loop supply chain).



c. Remanufacturing is performed by the 3rd party and the product is distributed to a different market (entirely open system, two forward supply chains, one for the manufacturer and the other for the remanufacturer).

Figure 2-1 (a, b, c): Material flow in different types of supply chain.

The ideal closed loop supply chain, which is essential to the success of the product's multiple lifecycle, is shown in Figure 2-1 (a). By clarifying the existing misconceptions, closed loop supply chain management can be defined as [17],

"The design, control, and operation of a system to maximize value creation over the entire lifecycle of a product with dynamic recovery of value from different types and volumes of returns over time".

In the remanufacturing system the core acts as raw material and seamless operation of the system entirely depends on the efficiency of the core collection. It becomes especially challenging as the core is not supplied by one or a few suppliers in a periodic and systematic manner. Instead, the suppliers of the core are the end consumers who own one or a few products and return those products whenever they need or want. In addition to this, the consumers' geographic locations could be anywhere on the globe. The supply chain becomes further complicated with product variety, return time, quality of the core, product lifecycle, technology lifecycle, cost of collection and so on.

The research in the area of the closed loop supply chain seeks answers for many questions. Therefore, the branches of research in the closed loop supply chain can be traced in pure design and management of the supply chain, processes and operations management of manufacturing and remanufacturing system, design, manage and coordinate logistics support, consumer's role in managing the supply chain and technological issues related to product tracing etc. Guide and Van [17] have put together the past 15 years' research evolution in the closed loop supply chain which pointed out the above-mentioned research topics.

All researchers who have worked with the closed loop supply chain have more or less acknowledged the problem of uncertainty related to timing and quantity of the returned core, quality of the core and mismatch between the supply-demand of the core and remanufactured product. This problem was mentioned in the early research done by Thierry *et al* [18] and it was described in the most-recent work done by Guide and Van [17] that the problem still exit. Along the way, these problems have been brought up by several authors, among them the contributions of Gungor and Gupta [19], Seitz and Peattie [20] and Toffel [21] are worth mentioning. Through review of this research, the underlying reasons of uncertainty have been identified as,

- The return of the core occurs for different reasons in different period of time, which causes uncertainty. Parlikad and McFarlane [22] and Östlin *et al* [23] have described different types of return as follows,
    - Commercial returns- consumer's right to return the product and get refund within the agreed period.
    - Warranty returns- consumer's right to get repair, service or replacement tied with failure of the product within the warranty period.

    - End-of-lease returns- consumer returns product when leasing period is over.
    - End-of-use returns- consumer's perception of acquiring a new model of the product while the current product is fully functional.
    - End-of-life returns- returns tied with functional failure and fulfillment of the optimum lifecycle.
    - Re-usable components- consumer returns part of the product tied with consumption, e.g., toner cartridges.
    - Legislative obligations- regulations to return the product at the EoL/EoU
- A product's EoL is the result of the complex relationships between age and pattern of use (user conditions, user interactions, levels of service and maintenance etc.) of a product. [24]
- Some products never return as the products move out of the region where legislative or other obligations are not valid and return is not economically feasible.
- The product's information is lost, thus, the core collection from the product is done manually on the basis of trial and error, which often causes destruction of cores.
- Remanufacturing is treated as a separate business, therefore, demand and supply is tackled independently.
- The products are not designed for efficient recovery.

Business model for resource conservation

From the discussion in the above sections, it is clear that to sustain a product's multiple lifecycles remanufacturing is a viable tool and to enable it, proper management of the closed loop supply chain is vital. However, the management of the closed loop supply chain suffers from multiple problems related to the uncertainty of getting the core and variable quality level of the core.

In this section, the effort to minimize the uncertainties in core collection at the business level is discussed. To ensure core returns, some sort of agreement between OEMs, consumers and remanufacturers needs to be established. It is important that a win-win situation is created for all stakeholders involved. There are several business models that have been adopted by the OEMs pioneering in remanufacturing. Östlin *et al* [23]have discussed some of the relationships and core acquisition strategies often used by the OEMs. Those relationships are described as follows,

Ownership-based- products are owned by the OEMs and operated by the consumers in the form of lease or product-service offer.
Service-contract- based on the contract between the OEMs and customers which includes remanufacturing.
Direct-order- the consumers return the used product to the remanufacturer and get the same product back (if remanufacturing is possible).
Deposit-based- consumers are obliged to return a similar product when they buy a remanufactured product.
Credit-based- consumers get credit points by returning used products. Collected credits provide discounts when consumers purchase a new product from the OEM.
Buy-back- the OEMs or remanufacturers buy old products from the suppliers, consumers or scrap yard.
Voluntary-based- suppliers or consumers return the used products on a voluntary basis.

Kumar and Malegeant [25] pointed out that strategic alliance between the OEMs and eco-non-profit organizations in the collection process not only helps to acquire cores at EoL /EoU but also creates value for the firm. Among all these, the most commonly used business models are ownership-based and buy-back. However, from the publication of Lifset and Lindhqvist [26] it is understood that the ownership-based business model is not straightforward, and its success depends upon careful analysis of the profit and loss. In other words, the ownership-based business model is not always feasible. Buy-back is not as efficient as it is supposed to be, if the consumers are not concerned and motivated.

Moreover, this solves half of the problem. It is true, that these kind of business models bring a certain level of certainty to the timing of the core returns, but uncertainty related to the quality of the core remains unsolved [15]. At the same time, the above mentioned business models aim to bring cores back at the EOL/EoU, at which point value recovery becomes extremely difficult. It is also important to consider the consumer's perception about newness of the product, as it influences return of the core. Most of the business models will fail to fulfill its purpose if the consumers have a negative impression of the remanufactured product. The rest of the business models will fail if the customers wish to change brand or manufacturer.

Product design for resource conservation

In addition to other factors, product design plays a crucial role to the success of resource conservation manufacturing. As mentioned earlier, Nasr and Thruston [13] pointed out that the full potential of remanufacturing cannot be achieved unless the product is designed for it. Moreover, from the above discussions it is clear that the conventional approach of resource conservation is reactive and tries to solve the problem at product's EoL/EoU. The remanufactures try to remanufacturer a product when the core is returned at the EoL/EoU without any prior knowledge of the product, starting with disassembly and testing to find out if it is worth and/or possible to remanufacture. In this approach, resources in terms of manpower, energy, transportation etc. are often invested in the collection, disassembly and testing process to find out that remanufacturing is not possible [27]. Considering remanufacturing or other EoL/EoU strategies at the design phase has evolved as a research topic evolving for quite a long time. In this section issues related to design are discussed.

There are a large number of methodologies and standards available to support product design in respect to resources conservation. Most of the design tools belong to the Design for X (DFX) paradigm where 'X' represents the ability (such manufacturability, assembly-ability etc.). A brief overview on how to develop a DFX tool is discussed by Huang and Mak [28]. Among all the DFX tools, the most relevant design tool is Design for Environment (DFE), which covers a relatively large number of issues concerning safety, environment, resource conservation and EoL etc. A general overview of the DFE practices has been illustrated by Zhang *et al* [29]. Ironically, conflict and overlap of interests is often evident in different design tools. For example, in some cases design for assembly has opposite design requirements to design for recycling and remanufacturing [30] and to some extent, disassembly. On the other hand, design for remanufacturing, disassembly, recycling and serviceability/maintainability share similar goals and requirements to a large extent. Figure 2-2 gives an overview of different design tools in respect to their relationships with each other.

	Design for assembly	Design for manufacturing	Design for remanufacturing	Design for disassembly	Design for recycling	Design for serviceability/maintenance
Design for assembly		(+)(○)	(-)(●)	(-)(●)	(-)(○)	(-)(●)
Design for manufacturing			(-)(Δ)	(-)(Δ)	(+)(Δ)	(-)(○)
Design for remanufacturing				(+)(●)	(+)(●)	(+)(●)
Design for disassembly					(+)(●)	(+)(●)
Design for recycling						(+)(Δ)
Design for serviceability/maintenance						

Figure 2-2: An overview of relationships of different design tools with each others.

In the matrix the (+) and (-) signs represents positive and negative relationships i.e., does the use of a certain design tool facilitate or impede the requirements of other tools. The symbols '(●), (○) and (Δ)' represent the strength, i.e, strong, moderate and weak, respectively, of the positive or negative relationships. For example, design for assembly has a negative relationship with design requirements of all other design tools except design for manufacturing. On the other hand, design for remanufacturing has a positive relationship with design for disassembly, recycling and serviceability/maintainability. There are a large number of requirements to fulfill while designing a product and at the same time requirements positively or negatively influence each others, therefore, designers cannot depend on one or a few tools, which means that tradeoffs become necessary. There is a lack of methodologies that integrate different design tools and reliable data on material, component, ecological footprint etc. to support tradeoffs among different design requirements [31].

For remanufacturing, it is not enough just to consider design for remanufacturing or disassembly as the component of a product needs to be reassembled. Bras [32] has suggested to follow the common design for assembly guidelines in case of reassembly. In this case, the design will suffer as design for reassembly is counterproductive to design for assembly. If the product is to be disassembled and reassembled (as a product's multiple lifecycle requires) multiple times during the lifecycle, then the traditional tools are not enough. Moreover, the current design tools that suggest considering the product's EoL/EoU at the design phase are developed mainly for products that are meant to be used for a single, or a maximum of two lives. Therefore, its efforts are usually limited to part recovery and separation before recycling or landfilling. These tools are not well equipped for a product's multiple lifecycle. Material recovery (through recycling) is the main objective of most of the tools; as a result, destructive disassembly is often permitted. The product's lifecycle information is another issue upon which the success of these design tools largely depends. For some products, the lifecycle duration is quite long. As a result, during the lifecycle the requirements and criteria on which the design was done may be lost. Due to the lack of information disassembly cannot be planned. Moreover, during the lifecycle product/component may be upgraded and maintained which makes the situation worse [33]. In addition to this, determining the disassembly sequence is another critical issue [34], information with regards to the disassembly sequence is not generally available at the product's EoL.

Dahlström [35] has reported that the design for environment tools are not applied in industries in exactly the same way as it is emphasized in research and literature. Most of the design improvements in industries are incremental and the result of legislative push, direct consumers' requirement, and the market trend of that particular time. Often, industries have their own design standards, which are somehow compatible with international and local standards, but above all provide a competitive edge. Industries' main priority is not long-term environmental sustainability. There is a lack of proactive approaches to resources scarcity and environmental sustainability in design methodologies implemented by industries.

Legislative efforts towards resource conservation

Legislation plays an important role in resource conservation and controlling waste generation of manufacturing. The reason automobiles now-a-days are made of 85% recyclable material is not because the manufacturers foresaw the problem of solid waste management or resource limitation a decade ago. This is just the consequence of End-of-Life vehicles (ELV) directive issued by the European Commission in 2000, which urged that by no later than the 1st January 2015, for all EoL vehicles, the reuse and recovery shall be increased to a minimum of 95 % by an average weight per vehicle and year [36]. The year prior to the issue of the ELV directive, the directive on the Landfill of Waste was issued, which already advocated to promote prevention, recycling and recovery of waste and the use of recovered material and energy to safeguard natural resources and obviate the wasteful use of land [37]. A similar directive was issued on the Waste Electrical and Electronic Equipment (WEEE) which directed that the recoverability and recyclability of the products should be between 50%-80% by an average weight per appliance according to defined category [38]. This explains why OEM’s in the electrical and electronic equipment manufacturing industry are more efficient in recycling and remanufacturing than others.

It should be noted that the mentioned directives have emphasized recycling as the ultimate solution to manage EoL/EoU waste. However, from the discussion presented in section 1.2, it is clear that in many cases, recycling is not the optimum solution, if one considers energy required, and environmental impact. Stakeholders have already started to realize that energy consumption and environmental impact are also essential issues to be considered during the lifecycle of a product (cradle-to-grave or cradle -to-cradle). To support this statement the most recent directive on establishing a framework for the setting of eco-design requirements for energy-related products and the European Commission’s Communication entitled ‘Integrated Product Policy — Building on Environmental Life-Cycle Thinking’, [39] can be mentioned. It can certainly be said that similar kinds of regulations are available in other developed continents and countries apart from Europe.

Legislations evolve with time and are introduced based up on predictions of the future. How the OEMs will act in the future is greatly influenced by these legislations. It is clear from discussions that future legislations will be much stricter for the OEMs, and emphasis will be on maximum value recovery from product while avoiding recycling to as a greater degree as possible. he

There is a considerable delay between the introduction of a new legislation and OEM's adaptation of the new regulation. Those who act fast on the change or are proactive always get the strategic advantage. It is important for OEMs to be proactive to gain the competitive advantages through resource conservation. As it can already be predicted, now that future legislations will focus on resource conservation, it would be unwise to wait until new legislations come into action and force a change in manufacturer's strategies.

Critical review of the sate-of-the-art

The idea of resource conservation by remanufacturing is at least three-decades old, and the benefits of adopting it are quite evident. Unfortunately, only limited numbers of OEMs are interested in remanufacturing [11]. As the key to success of remanufacturing lies behind the involvement of OEMs, limited progress has been made. Due to this, even though the concept is three decades old, the research around remanufacturing is still trying to solve its basic problems i.e., convincing stakeholders, proposing strategies and solutions. The research in solving technological barriers in remanufacturing is limited since technology depends largely on the specific product and on how OEMs want to go about it. However, sufficient knowledge has been gathered around remanufacturing, and it has become well accepted that integration and implementation of that knowledge in the related fields i.e., product design, closed loop supply chain, business model and societal perception in remanufacturing are the necessary keys to success.

There is a misconception concerning closed loop supply chain. Supply chains designed to collect cores and developed to sell remanufactured products in the secondary market (by- passing OEMs) are not necessarily closed. Apart from this fact, more or less all researchers agreed that the main problem of the closed loop supply chain is the uncertainty in timing of core return and the quality of the returned cores. A fundamental, but rarely discussed, truth is that most of the researchers suggest implementing the closed loop supply chain concept where the product, or the business model, is not designed for it. In the conventional way the closed loop supply chain is usually designed based on a particular product, and it changes from product to product in time. In reality, it should be fixed, and the product should follow the pre-designed closed loop supply chain.

The product design also suffers from several problems. There are no tools available to facilitate remanufacturing without violating requirements of other design tools. Moreover, there is no evidence that those tools have been applied by any OEM. The research in this area is still in the conceptual phase and lacks the consideration of basic design requirements, e.g., capturing a product's lifecycle information, storing product information and information required at EoL/EoU to facilitate one or multiple lifecycles.

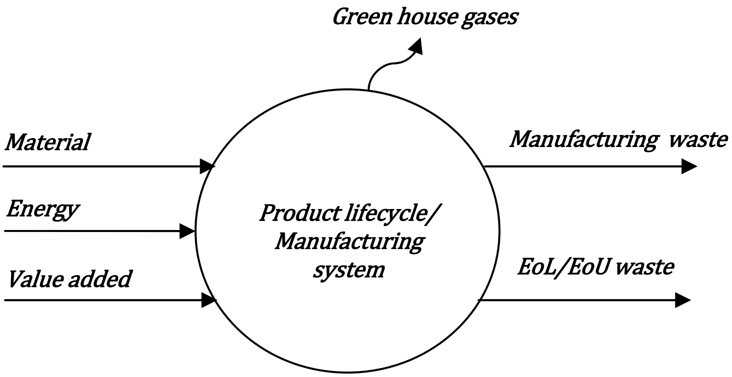
There is a lack of research effort in improving consumer's perception in respect to accepting remanufactured products as part of their lifestyle. There is no integration and cooperation between OEMs, consumers and regulating bodies to reinforce resource conservation as a vital part of society. Legislations come into action and others try to cope with them, in spite of lack of willingness. Thus, making a minimum effort to fulfilling legislative requirements has become the usual trend. Things would go much smoother if the necessity of resource conservation came from consumers as a product requirement.

2.2. Resource conservative manufacturing

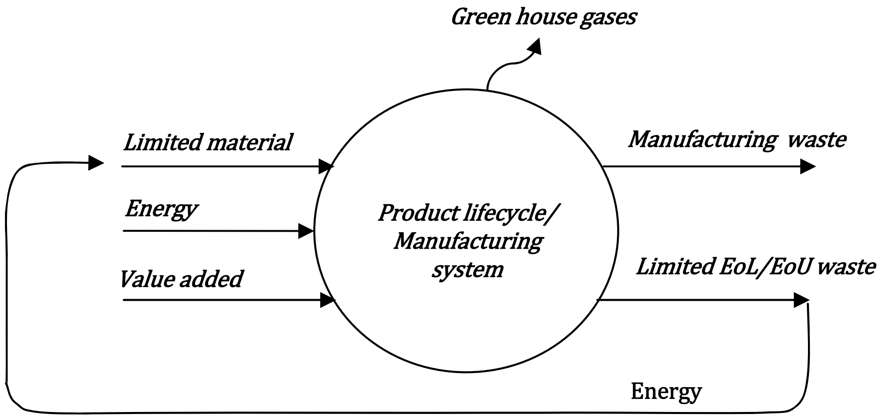
As briefly described in section 1.3 the resource conservative manufacturing is not just a tool but a holistic approach that provides a complete solution to maximize resource conservation and minimize environmental damage with respect to a product. Resource conservative manufacturing is built upon the concept of the product's multiple lifecycle, which is supported by design of the product, management of the closed loop supply chain and the business model. In this section, the resource conservative manufacturing approach is presented elaborately in relevance to the state-of-the art described in section 2.1.

The level of resources conserved during the lifecycle of a product is not a static measure. Same product, with the same lifecycle parameters, but manufactured, operated, collected and remanufactured at two different times will have different levels of resource conservation (or consumption). Similarly, this measure will differ with geographical locations, regulations in that particular location and how people in that location perceive the seriousness of resource conservation. Therefore, resource conservative manufacturing anticipates this as a complex dynamic system that is extended in time and space. The lifecycle analysis that resource conservative manufacturing aims to undertake will include every detail of the lifecycle parameters and plot them over the time and in accordance with the geographical locations.

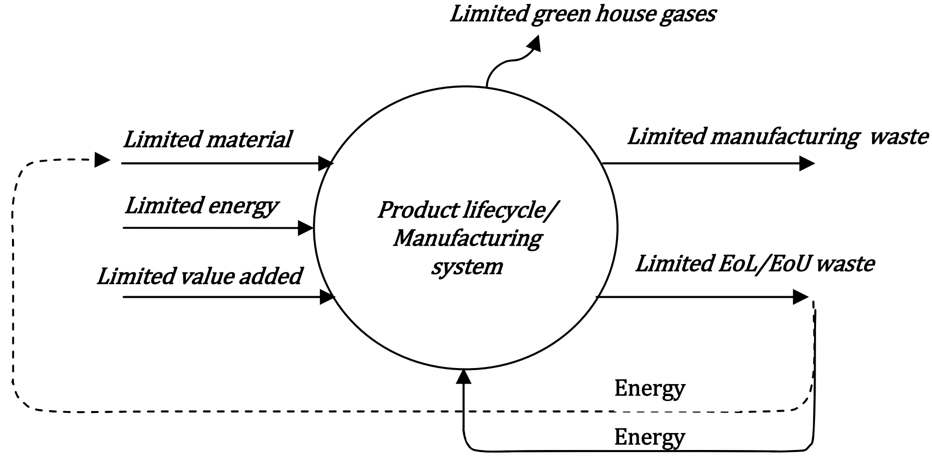
Keeping this in mind, resource conservative manufacturing strives to conserve mainly three types of resources, which are material, energy and value added. In fact, the proposed resource conservative manufacturing approach is two steps ahead of the classic product lifecycle and manufacturing systems, as illustrated in Figure 2-3 [a, b & c].



a. Classic product lifecycle and manufacturing systems where sources of resources are unlimited and the capacity of the environment is unlimited to take on wastes.



b. Contemporary product lifecycle and manufacturing systems where the sources of material is limited but other resources are unlimited and the capacity of the environment is moderately limited to take on wastes.



c. Product lifecycle and manufacturing systems under the resource conservative thinking where resources are limited and the capacity of the environment is limited to take on wastes.

Figure 2-3 (a, b, c): Resource flow models in classic, contemporary and resource conservative manufacturing and product lifecycle systems [2].

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[2] The model used in Figure 2-3 is based on the concept presented by Nasr and Thurston [13].

Figure 2-3 (a) represents an open loop product system where raw materials are extracted and manufacturing is performed. Products are then landfilled at EoU/EoL. This type of system requires a huge amount of new material, energy and value added and results in a huge waste.

Figure 2-3 (b) represents a semi closed loop product system where only material is recovered at EoU/EoL by recycling, minimizing the generation of solid wastes. However, additional energy (often equal or more energy is used compared to material extraction) is input, which contributes to additional green house gases. The only benefit of this type of model is that, it can continue with limited raw material and generates less solid wastes.

Figure 2-3 (c) represents an ideal closed loop product system, as proposed by resource conservative manufacturing where product/component is reused, upgraded and remanufactured as long as it is economically viable and environmentally sustainable. If not, the product then follows the model shown in Figure 2-3 (b) i.e., material is recovered. Each time a product/component is reused, conservation of material, energy and value added is achieved, and at the same time wastes, both solid and green house gases, are reduced. If product/component can be used for multiple times, the overall benefits are increased, with this, the idea of the product's multiple lifecycle is introduced, which is elaborated below.

Simply put, the lifecycle of a product (that contains more than one part) is generally equal to the lifecycle of the component that has the shortest life. For example, a product consists of three parts X, Y and Z; each has the designed life of one, two and three years respectively, basically, the product will reach its EoL when one of the components fails. Considering other factors does not affect, the component 'X' will fail at the age of one and eventually the product will be considered to have reached the EoL. It is to be noted that, components 'Y' and 'Z' have equal and twice as many remaining lives compared to 'X', respectively. If the entire product is discarded (as in the case of the traditional product lifecycle and manufacturing systems thinking shown in Figure 2-3 [a, b]) the potential recoverable values are lost. Instead, if component 'X' can be replaced or upgraded at the age of one year and component 'X' is replaced or upgraded again along with 'Y' at the age of two years, the product can sustain three lifecycles. Alternatively, the ideal case is to design a product that contains components that have the same duration of life. Of course, in reality, it is not as straightforward as it has been explained, particularly if the product is big in terms of the number of components in it. Automotives are a typical example. However, if the subassemblies (such as starter and alternator) of an automobile are considered as product/component, then it can fit in the product's multiple lifecycle contexts. It is important to highlight that the lifecycle of product/component is not time dependent, meaning, at which point the product/component will reach its EoL is not deterministic. The lifecycle duration of a product is the result of a complex relationship between mainly age, operating conditions, service and maintenances during the lifecycle and the user locations. It is not possible to determine the exact interval of each lifecycle. Therefore, the interval will be determined based on what is most likely to happen. It may be that when a product returns on a predetermined interval the component(s) that is predicted to have reached the EoL has not, or the component(s) that is designed for two or more lifecycles has reached the EoL already at the end of the first lifecycle. The level of remanufacturing needed to be performed will be based on the best solution that can be offered at that particular time. These uncertainties are considered and will be reduced to a large extent through product design in resource conservative manufacturing.

In resource conservative manufacturing, product is named as Resource Conservative Product (RCP) which is used as a 'brand' name. Each lifecycle of RCP is labeled with Resource Conservation Level (RCL). The concept is illustrated in Figure 2-4. In principle, RCL_0 means a new RCP that contains all new components, and is at the start of its first lifecycle, having several lifecycles ahead. Component at a certain level is called RCL_i (where i= 0,1,2…) components such as RCL_0 components, RCL_1 components and so on. At the end of lifecycle 1 (i.e., end-of-resource conservation level 0, $EoRCL_0$) when desired performance reaches the minimum allowable, product is recalled and upgrading, replacement of complements is done and remanufacturing is performed. At RCL_1, which is the beginning of the second lifecycle, contains new components of RCL_0, upgraded components of RCL_0 and may contain some new components. This approach continues until the product finishes its pre-determined number of lifecycles. At the end of each lifecycle product is restored to the desired performance level. This so far explains the lifecycle at the product or subassembly level. The lifecycle of the component is slightly different and illustrated in Figure 2-5.

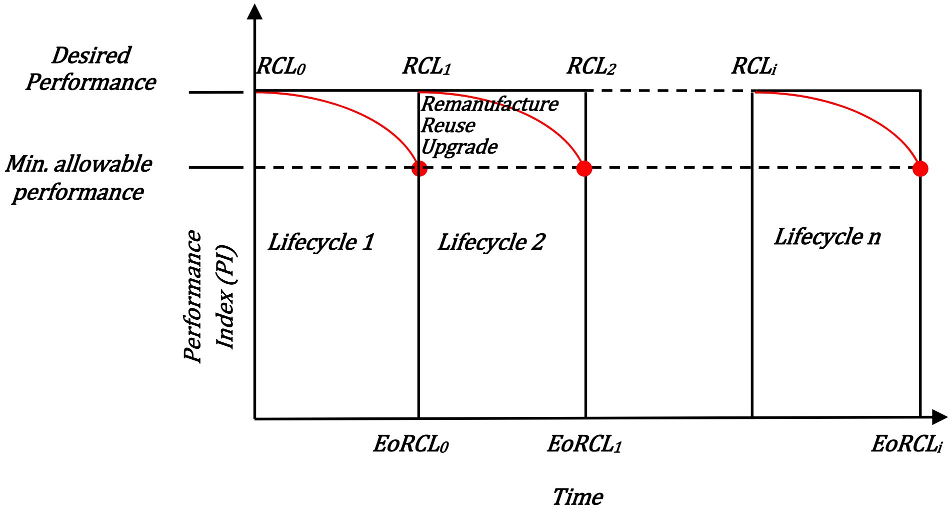


Figure 2-4: Product's lifecycle in resource conservative manufacturing.

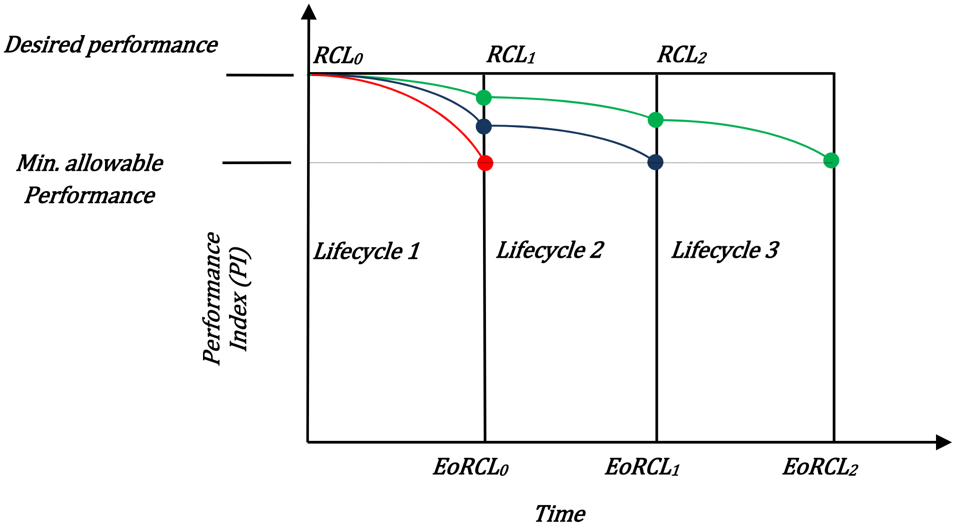


Figure 2-5: Component's lifecycle in resource conservative manufacturing.

Let's assume that a product is assembled with three components X (--), Y (--) and Z (--) and their performance index over time is shown in the Figure 2-5 with red, blue and green curves respectively. In this particular case, the lifecycle (i.e., three lifecycles) of the product is determined based on the component which has longest design life i.e., component Z. At RCL_0 the product contains three new components. At $EoRCL_0$ component 'X' reaches the minimum allowable performance, which is then either replaced with a new component or upgraded for the next life. It means at RCL_1 the product will have two RL_0 components. Similarly, at RCL_2 the product will have components from RCL_0 and RCL_1, if the component is upgraded. The purpose of labeling the product with RCLi level is further illustrated later in this section.

So far, the core concept of resource conservative manufacturing and product's multiple lifecycle has been presented. Up to this point, the readers may not find anything unique in the concept and may consider this another buzz word of remanufacturing. As mentioned earlier resource conservative manufacturing is not just a tool but a complete solution. There is no disgrace in admitting that product's multiple lifecycle cannot stand alone, or it will face similar problems (as discussed in section 2.1) that remanufacturing is facing, if it is not integrated with design and supply chain issues. It will also not work unless it is implemented with conventional manufacturing or remanufacturing business model. The implementation of the concept will seriously suffer if all stakeholders are not involved. In the following sections, the additional enablers of resource conservative manufacturing are discussed with some implementation guidelines.

Determining the optimum number of lifecycle for product/component

Before going into the detail of how to determine the optimum number of lifecycle for a given product, if is important to answer two basic questions,

1. Is there any particular product or product category that is appropriate for multiple lifecycle approach?
2. What determines whether a product is to be considered for multiple lifecycle?

The answer to the first question is not straightforward and has a contradictory answer. This question is particularly important to OEMs, who may think their product is not appropriate for multiple lifecycle. Gray and Charte [**40**] referred to Ron Giuntini, who said *'any product that can be manufactured can also be remanufactured. However, some products are remanufactured more than the others'*. The Remanufacturing Institute [**41**] and the Automotive Parts

Remanufacturers Association [42] has listed a number of industries on their website where remanufacturing is being practiced. Parker [43] has investigated a number of industries where remanufacturing exits. Both these examples confirm the claim of Ron Giuntini. Hence, it can be said that any product that can be remanufactured is a potential candidate for multiple lifecycles and this is applicable to a wide range of products.

The second question is relatively easy to answer at this point as a lot of discussions around it have already been covered in chapter 1 and in the beginning of this section. In brief, the decision of whether a product is to be consider for multiple lifecycle has to be justified from economic, environmental and societal perspectives over a long period of time. In one of the publications by Asif *et al* [10] it was attempted to determine factors that affect the decision of whether a product should be considered for multiple lifecycle or not at EoL/EoU. However, the factors that affect the decision of whether a product should be considered for multiple lifecycle or not at design phase are much wider and decision-making is much more complex. In Table 1-1 possible factors that influence the determining of the number of lifecycles are listed.

Table 2-1 : Factors needed to be analyzed to determine product's multiple lifecycles.

Cost	Value added	Environment	Energy
- Cost of resource conservative manufacturing - Cost of manufacturing - Cost of operation - Cost of remanufacturing and upgrade - Cost of ladfilling	- Recoverable value in each lifecycle	- Green house gas emission equivalent to energy usage - Avoided amount of raw material extraction - Saved landfill area	- Energy required for manufacturing - Energy required for remanufacturing in each lifecycle - Energy required for upgrading in each lifecycle - Energy required for recycling

Considering all these factors the optimum number of lifecycles will depend on the ratio between new material, energy and resources in each lifecycle and the quantity of material, energy and resources required to produce an entirely new product. In case of a particular product, if the analysis is favorable and better than other alternatives, only then product's multiple lifecycle should be considered.

It is to be noted that for some products, it may be more sustainable to have one lifecycle, and for others more than one. For the first lifecycle the value recovery and environmental protection may be more and energy usage less. For the next lifecycle, it may not be the same, and not linearly proportional with successive lifecycles. So the analysis has to be done for several scenarios and summarized to make the decision.

Designing product/component

As discussed earlier, the lifecycle of a product containing multiple components are mainly determined based on the component that has the shortest design life. If a product completes the life of the component that has shortest design life and the product fails, in principle, it is considered that the product has reached its EoL. At that point, the owner may consider repairing the product only if it is convenient and attractive. This is particularly the case in with fast evolving consumer goods. Resource conservative manufacturing proposes an opposite approach. A component that has the longest design life with relatively high residual value (recoverable value) throughout the lifecycle is the one that should determine the life of the product. In addition to fulfilling conventional design requirements such as functionality, performance, quality, aesthetic, ergonomic etcetera the proposed design will consider,

- Extended product durability
- Adding intelligence for monitoring critical lifecycle parameters
- Adding information storage mechanism

Under the extended durability requirements, critical components in terms of functionality, cost, value added, environmental impact and energy intensity of manufacturing, will be designed for an extended life. To what extent the durability of the component is improved has to be reasonable and in accordance to the analysis of determining the optimum lifecycle.

The parameters that influence the lifecycle of a product/component will be monitored, and information about it will be stored by using smart components to determine the physical and functional condition of the product throughout the lifecycle. This information will be accessed and analyzed at return to determine the course of action that needs to be taken. For example, if the component exceeds the design life due to excessive use or other extreme conditions, the component will not sustain the predetermined number of lifecycles. In those extreme situations, the component will be sent either for upgrading or recycling (if no value is recoverable). If the component is operated under normal conditions and follows normal lifecycle patterns the condition monitoring device will provide information that the component is functionally fine to continue with the rest of its lifecycles. This information will help to reduce the time required for testing the physical functional condition of the component extensively at return, as compared to the conventional system.

Information storage system will store pre-feed static data about the product. For instance, product information, service history, number of designed lifecycle, duration of each lifecycle, disassembly and testing procedure, along with other information that might occur to be important and required by different stakeholders during the lifecycle. A typical example of this kind of information storage system is Radio-Frequency Identification (RFID) tags.

In addition to the above mentioned three design requirements the resource conservation manufacturing approach will integrate DFX tools (or a modified new tool) that may facilitate multiple lifecycle without violating the interest of the major DFX tools such as design for assembly (DFA) and design for manufacturing (DFM). Besides, careful consideration of component standardization and modularization will be carried out.

Closed loop supply chain

In product's multiple lifecycle approach, the product will return to the manufacturer at several occasions and go through disassembly, cleaning, testing. After that, depending on different component physical/functional conditions and design specifications, the product will go through upgrading or replacement and reassembly or recycling. To facilitate these processes a closed loop supply chain is required. The operational effectiveness of a supply chain mostly depends on the smooth flow of material both in forward and reverse direction without constraining the planned capacity of the manufacturing processes. It means that the manufacturing system for RCL_0 products and the manufacturing systems for RCL_1 to RCL_i (which includes disassembly, cleaning, testing, upgrading or replacement and reassembly) should not be over or under capacitated. To ensure this, the expected quantity of the product to be manufactured at RCL_0 and RCL_1 to RCL_i needs to be a known parameter. As the RCL_0 product refers to a newly manufactured product and follows a standard manufacturing forward supply chain, it is relatively easy to handle. On the other hand, RCL_1 to RCL_i manufacturing significantly depend on the availability of the products (cores) from its previous lifecycle. Availability of the return products and scrape rate of the components are the main obstacles to the success of the closed loop supply chain. In resource conservative manufacturing, the problem of product availability is solved through product design, estimation of lifecycle duration, the number of lifecycle and business model. In resource conservative manufacturing, the quantity and the timing of the product return are known and predetermined. However, the other problem with the quality of the returned product is not entirely solved but minimized to a large extent.

In the conventional approach, it is estimated that the scrap rate of returned product can be anything from 15% to 85%. The reasons for this large variation are mainly due to age, operating conditions of product and quality of service that the product receives during the lifecycle. In resource conservative manufacturing, the age of the returned product is known and service of the product is managed and controlled by the manufacturer (or authorized service provider). This means that in normal circumstance quality of the returned products is also known. For product use in extreme conditions, lifecycle monitoring devises will give information, and the product will be recalled earlier than the predetermined time. In this way currently perceived scarp rate will certainly be reduced, which eventually will ensure a well functioning closed loop supply chain with almost no uncertainty.

There are other issues, as designing the network, planning and controlling the logistics and planning and controlling of production at RCL_1 to RCL_i etcetera are related to the success of the closed loop supply chain. These issues are greatly influenced by the types of product, size and periphery of the market. As the concept is presented in a generic context and does not refer to any specific product, discussion around these issues is not within the scope of the research at this point.

Business model

The resource conservative manufacturing approach is not well fitted with ordinary sell-buy-sell business model. It requires a model that goes beyond the conventional business model and establishes a strong relationship among OEMs, consumers and 3rd parties (if the OEM decides to outsource RCL$_1$ to RCL$_i$ production). Based on the concept of RCP brand and RCL labeling the business model of resource conservative manufacturing is illustrated in Figure 2-6. In this model, the RCP production at RCL$_0$ and at RCL$_i$ are separate functions of the same enterprise. However, RCL$_i$ production can be outsourced by the OEM only if the entire process is controlled by the OEM. In this model, consumers are the part of the manufacturing system and mostly responsible for returning the product at the end of each lifecycle. As mentioned earlier, consumers are still reluctant towards 2nd hand products, therefore, at the beginning, the business model suggests a dedicated RCP reselling unit, which will act as the bridge between the consumer and OEM or 3rd party suppliers. The basis of their relationship and the interest of each stakeholder are determined mainly based on the product type, number of returns, arrangement of returns and way of

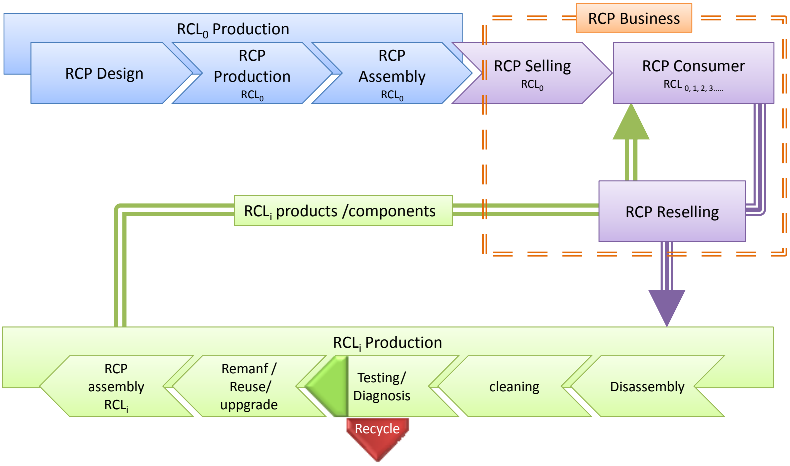


Figure 2-6 : The resource conservative manufacturing business model summarized: RCL$_0$ – new RCP product with resource conservation level zero; RCL$_i$ - RCP with resource conservation level, i= 1, 2, 3... with the subsequent lifecycle.

reselling. Besides, the RCP reselling unit will also be engaged in promoting RCL_1 to RCL_i product adoption as a social and moral responsibility.

Once the business model is established, and consumers become comfortable with the product's multiple lifecycle and consider product returning as part of their social responsibility, the RCP reselling unit will be abolished. The ordinary product distribution unit will take over both RCL_0 and RCL_i product selling.

Stakeholders

The success of resource conservative manufacturing largely depends on how the stakeholders perceive product's multiple lifecycle and what are the benefits one gets out of it. The benefits that the OEMs and society get in this approach are evident and elaborated. The direct benefits of consumers in the product's multiple lifecycle approach are not discussed because they depend on the type of business model that would be adopted. While the economic benefit is an essential factor for consumers, their higher-level responsibility for ecological sustainability is also an important requirement in the success of the concept. As the consumer is part of society, the overall social and environmental benefit can be a push for the consumer's involvement. This is particularly true in case of products that are considered an important part of lifestyle and carry an image of prestige. In order to deal with the consumer's societal aspect, resource conservative manufacturing adopts the innovative idea of product labeling with the resource conservation level by replacing the conventional concept of new, second hand or third hand products. The new products with RCP brand have been proposed to be labeled as RCL_0. The RCP at RCL_0 will carry the lowest societal prestige contrary to the highest prestige of a new product. The RCP in their second, third or fourth cycle will be labeled as RCL_i products carrying a higher societal prestige with increasing resource conservation.

Regulatory bodies are and will reinforce laws to promote resource conservation as it has been discussed in previous sections. Therefore, it is important that the OEMs become proactive to get strategic advantages be good citizens and already initiate resource conservative manufacturing.

2.3. Comparative analysis

In section 2.2 and 2.3 the state-of-the-art and the concept of resource conservative manufacturing is presented. A brief comparison among the current approach of resource conservation with the proposed concept will vividly show the existing gaps. Table 2-2 includes the main differences between the conventional and proposed way of resource conservation.

Table 2-2 : Comparison of the state-of-the-art with the proposed resource conservative manufacturing approach.

Comparison criteria		State-of-the-art	Resource conservative manufacturing
Justification of resource conservation		Mainly based on the cost; energy, environment, raw material or value added are considered individually	Based on combination of cost, energy, environment, raw material and value added
Overall approach		Efforts to conserve resource are concentrated at product's EoL, i.e., reactive	Efforts to conserve resource are concentrated both at product creation and EoL, i.e., proactive
Tool or concept		Remanufacturing, recycling is considered to be the complete solution.	Remanufacturing, recycling, upgrading is considered as few of the tools for the concept of resource conservation
		Suffers from multiple problems	Most of the problems are taken care of
Supporting areas	Supply chain	Available but not integrated and suffers from a multiple problems	Integrated and free from most of the problem
	Design	Partially available but not well supportive. It contradictsnother design tools and does not support product's multiple lifecycle	Complete, integrated and in-line with other design tools. Fully support product's multiple lifecycle
	Business model	Scope is limited and not mature for product's multiple lifecycle	Business model is specially designed for product's multiple lifecycle
	Cooperation between stakeholders	Weak	Close and firm relationship among stakeholders
	Promotion of resource conservation	Not part of the agenda and left on legislation and consumer	An essential part of the business model
Accordance with legislation		Running behind	Running ahead

Chapter III

3. Performance analysis of the closed loop supply chain

In this chapter, the hypothesis mentioned in section 1.4 is validated through a set of generic system dynamics models of the closed loop supply chain. It also includes performance analyses of the closed supply chain in both conventional and the proposed resource conservative manufacturing approaches.

3.1 Application of system dynamics in the closed loop supply chain

Before going into further detail, it is important to briefly discuss what system dynamics is. System dynamics is a method to enhance learning in the complex system which is grounded in the theory of non linear dynamics and feedback control developed in mathematics, physics and engineering [44]. System dynamics was introduced by Jay Wright Forrester and developed at MIT in the mid 1950s. Since then system dynamics has been applied to a wide range of issues in social, economic and engineering science (see Angerhofer and Angelides [45] for further references in which domains system dynamics is used).

Basically, the dynamic tendency of any complex system is the results of a system's internal structures, feedback mechanism and causal relationships among factors that are active in the system. As illustrated in Figure 3-1 [44] our decision alters our environment, leading to a new decision, but also triggering side effects, delay reactions, changes in goal and interventions by others. These feedbacks may lead to unanticipated results and ineffective policies. In general, the number of factors, their causal relations and feedbacks result in a complex system. Besides these, Sterman [44] has discussed ten characteristics of a system that causes the dynamic complexity.

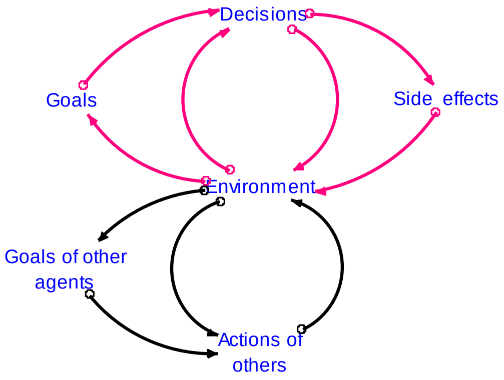


Figure 3-1 : The feedback view.

Moreover, all dynamics arises from the interaction of just two types of feedback loops; positive (reinforcing) and negative (balancing). Positive feedback denotes a self-reinforcing process which causes exponential growth, and negative feedback denotes a self-correcting one which brings the state of the system in line with a goal or desired state. Though there are only two types of feedback loops, a complex model may contains a number of loops, of both positive and negative, coupled with one another [44].

System dynamics has been applied in the management of production systems, especially in the supply chain (forward) for about five decades. An overview of the frame of the research that applied system dynamics in the supply chain is presented by Angerhofer and Angelides [45], Georgiadis and Vlachos [46] and Vlachos *et al* [47]. The trend of using system dynamics in analysis of the closed loop supply chain is relatively new but growing, and at the same time Kumar and Yamaoka [48] mentioned the lack of system dynamics research in studying the closed loop supply chain. Nevertheless, fair progress has been made in this respect. Georgiadis and Vlachos [46] studied long term behavior of reverse supply chains with product recovery under the influence of various ecological awareness. Later, Vlachos *et al* [47] examined capacity planning policies of a single product's forward and reverse supply chain transient flows due to market, technological and regulatory parameters. Qingli *et al* [49] to some extent, continued the work of Vlachos *et al* [47] and added the bullwhip effect into their studies. Similar modeling has been done by Schröter and Spengler [50], but their focus was product recovery to obtain spare parts for equipment, when the original equipment is no longer produced. Poles and Cheong [51]modeled closed loop supply chain to determine factors that influence the return of cores and concluded that customer behavior and the level of service agreement improve control over returns, thus, reducing uncertainty in remanufacturing systems. These are only few of the publications, besides these; there are a large number of publications available.

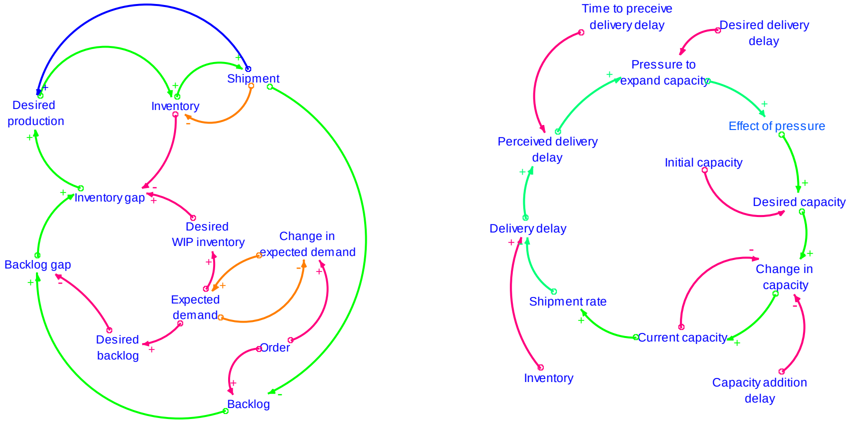
The models that have been presented in the thesis retain different objectives than the publications mentioned above. It can be said that in the modeling, I took one step backwards. As the purpose of this model is to validate the hypothesis mentioned in the section 1.4, the model does not propose any solution; instead, the model is used to capture the problem through analyzing the performance of the closed loop supply chain in conventional and in the proposed resource conservative manufacturing context. The models are used to analyze the robustness of the conventional forward supply chain in the settings of the conventional closed loop supply chain and compare it to the one proposed by resource conservative manufacturing. The aim of the modeling is to see how the key performance indicators vary with time in different settings, what are the main drivers that effects the key performance indicators and end results, and finally the behaviors of the strategic resources. With this, the model seeks to validate that in resource conservative manufacturing the closed loop supply chain is much more stable and manageable. Two models have been built, and four different analyses have been done with these models. The first model includes the forward supply chain, and the second model includes the reverse supply chain. The analyses are made as follows,

1. Performance analysis of the conventional forward supply chain.
2. Performance analysis of the conventional reverse supply chain.
3. Performance analysis of the forward supply chain when reverses supply chain is combined i.e., the conventional closed loop supply chain.
4. Performance analysis of the closed loop supply chain proposed by resource conservative manufacturing.

An obvious question may arise, ‘why system dynamics (continuous simulation)?’ ‘why not discrete event simulation?’ in performance analysis of the supply chain. The main factor in deciding which model tool to use is the level of aggregation sufficient for a particular object at hand [52]. Morecroft [53]has proven that similar results can be obtained by using both system dynamics and discrete event simulation. However, there are some clear differences in these two approaches. He also mentioned that, in system dynamics complexity is deterministic where dynamic behavior is explained by the feedback structure. This means that the unfolding future is partly and significantly pre-determined. On the other hand, in discrete event simulation complexity is stochastic where dynamics behavior is the result of multiple interactive random processes. This means that the unfolding future is partly and significantly a matter of luck. Moreover, in system dynamics, feedback is visually explicit while in discrete events feedback is inherent in equations. In certain cases (such as operational details of a factory) discrete event simulation provides a close-up view of the operational details. In a situation where operational details are not important but visual feedback loops among different entities are important, system dynamics is best applied.

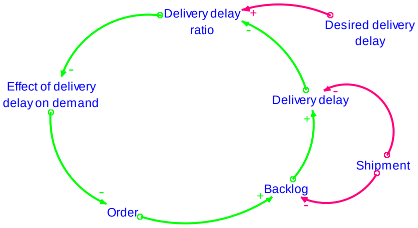
3.2 Structure of the models

The models have been built in three steps. In the first step, forward and reverse supply chains have been modeled with no dependency on each other. In the second step forward and reverse supply chains have been combined i.e., the closed loop supply chain where the forward supply chain in influenced by the reverse supply chain. In the third step, the model has been built as resource conservative manufacturing proposes. In the following sections, structure of these models is described with the mathematical formulations. The supply chain is modeled with inventory control mechanism, capacity acquisition, demand backlog and demand forecasting. The performance of the supply chain is analyzed in respect to the level of inventories, backlogs, rates (production, assembly, shipment etc.) and delays. It is important to acknowledge two main references Sterman [44] and Professor Carmine Bianchi at the University of Palermo, Italy, upon whose work the modeling has been done. The causal structures of the feedback loops used in the models are shown in Figure 3-2, and complete stock and flow diagram of the models is included in appendix I- A, B & C.



Inventory control

Capacity acquisition



Order backlog

Figure 3-2 : Causal loop diagram of inventory control, capacity acquisition and order backlog.

Regardless of which settings of the model are being discussed, in the models the performance indicators, drivers, end results and strategic resources have the same structure and relationships. In case of the demand backlog the end result, or final indicator, is the order rate that influences the strategic resource backlog directly. The end result is driven by the delivery delay ratio which is a direct effect of the key performance indicator delivery delay. This key performance indicator is affected by the shipment rate. Through the shipment rate, this part of the model is connected with other strategic resources and drivers.

Similarly, in case of the capacity, the end result is the capability of the system, i.e., at what rate the system allows the strategic resource inventory to drain (if there is no other constrains). This end result is driven by the pressure to expand capacity, which causes the strategic resource capacity to fall or rise. This is directly influenced by the key performance indicator delivery delay. Through this the model is connected with other strategic resources and drivers.

Finally, in case of inventory, the end result is the desired production rate which is driven by inventory gap and backlog gap. The gaps are influences by the strategic resources backlog, expected demand and the inventory itself which are influence by the key performance indicator delivery delay.

Forward supply chain

The forward supply chain model consists of production, assembly and distribution. These three steps in manufacturing systems have been modeled with sectors named as *'production capacity', 'assembly capacity', 'production work in progress (WIP) inventory', 'assembly WIP inventory', 'finished product inventory', 'production backlog', 'assembly backlog', 'sales backlog'* and *'demand forecasting'*[3]. The following main assumptions have been made while modeling the forward supply chain,

- The models are built for a single product.
- Production starting capacity is infinite.
- Shipment of product is only constrained by availability of product in the *'finished product inventory'*.
- Orders placed by the consumer are constant.

In the *'forward supply chain'* sector, the stock of *'production WIP inventory'* is furnished at *'desired production rate'* and the inventory moved to the next step (*'assembly WIP inventory'*) of the production system at the *'production rate'*. The production rate in the model can be determined in four ways as mentioned below,

- Available *'production WIP inventory'* starts to move to the next stage after minimum *'production delay'*.
- Available *'production WIP inventory'* start to move to the next stage as the *'current production capacity'* allows.

---

[3] Words written in *Italic* font within quotation marks from this point forward are the terms used in the models attached in the Appendix I.

- Available *'production WIP inventory'* starts to move to the next stage as a rate that can reduce the 'production backlog' to the desired level.
- Available *'production WIP inventory'* starts to move to thenext stage to fill out the *'assembly WIP inventory'* to the desired level.

'Current production capacity' is an accumulative value of the difference between the desired and current production capacity over time. If the ratio of actual and planned production delay becomes larger, that crates a pressure to expand capacity. This pressure causes the desired capacity to rise. However, the capacity does not rise suddenly but after a predefined delay. This part description corresponds to the *'production capacity'* sector.

Similarly, *'expected demand'* is an accumulative value of the difference between the *'expected demand'* and 'sales order rate' over time. It is to be noted that expected demand represents information not the physical product. If the ratio of actual and planned distribution delay becomes larger, that causes a drop in the order rate. This causes the expected demand to fall. However, the expected demand does not rise suddenly but after a predefined delay. It is important to note that in the model *'normal order'* that is placed by the consumers has been considered as the order rate in all steps in *'forward supply chain'*, i.e., shipment, assembly and production. This part of explanation corresponds to *'sales backlog'* sector.

Stock and flow structure used in the *'production backlog'* sector are as follows. As mentioned earlier the '*production order rate'* is considered equal as the *'normal order'* placed by the consumers. This rate causes the *'production backlog'* to rise, and backlog decreases with the rate of *'production order fulfillment rate'*, which is basically the *'production rate' (*it also depletes *'production WIP inventory')*. The backlog and the rate at which the order is fulfilled determine *'actual production delay'*. The ratio between planned and actual production delay causes the order to fall if the ratio becomes more than one. Similar to the 'expected demand', 'production backlog' also represents information delay not physical product.

In addition, the *'production WIP inventory sector'* is used to calculate the *'desired production WIP inventory'* and *'desired production backlog'*. Based on the expected demand and how much inventory to keep, the desired inventory is estimated. Similarly, based on expected demand and planned delay, the desired backlog is determined. *'Desired production start rate'* is estimated based on the gap between the desired and actual inventory and the gap between the desired and actual backlog.

Exactly the same stock and flow structure follows in the *'assembly WIP inventory'* and *'finished product inventory'* as in the case of *'production WIP inventory'*. The *'assembly capacity', 'assembly backlog'* and *'assembly WIP'* sectors and *'sales backlog'* and *'finished product WIP'* sectors have exactly the same flow and stock structure as the production part of the model.

Behavior of key performance indicators

At time zero the *'production WIP inventory'* is much less than desired value causing a high 'production backlog' which result in 'actual production delay' to rise. As soon as the desired backlog becomes equal to the actual level, the *'actual production delay'* becomes equal to the *'planned production delay'*. For the *'desired production backlog'* to become equal to the *'production backlog'*, the *'production WIP inventory'* level has to rise and at the same time the rate at which product is moved to the next stage (*'assembly WIP inventory'*) also has to rise. The stock of inventory and the backlog is increased with the rate at which products are piling up into the inventory and the rate at which orders are placed. The inflow and outflow of the inventory and backlog is affected by all other feedback loops that are connected with it. Similarly, with the rise of *'actual production delay'* capacity side of the model gets alarmed causing the 'desired production capacity' to rise, which eventually results the 'current production capacity' to adjusts. As soon as everything else becomes stabilized the 'current production capacity' also stabilizes. These phenomena are illustrated in the graphs in Figure 3-3, Figure 3-4, Figure 3-5, Figure 3-6, and Figure 3-7.

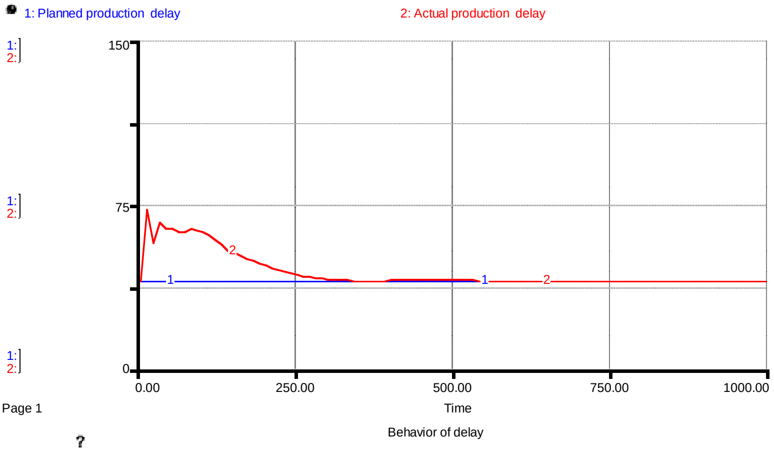


Figure 3-3: The behavior of the delay in the production.

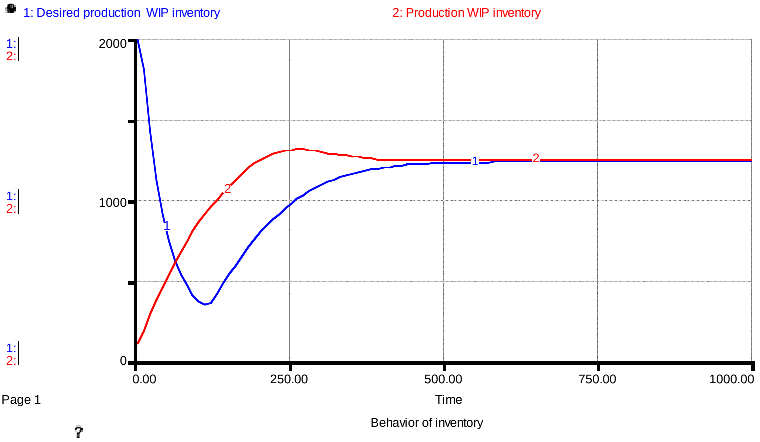


Figure 3-4: The behavior of the inventory in the production.

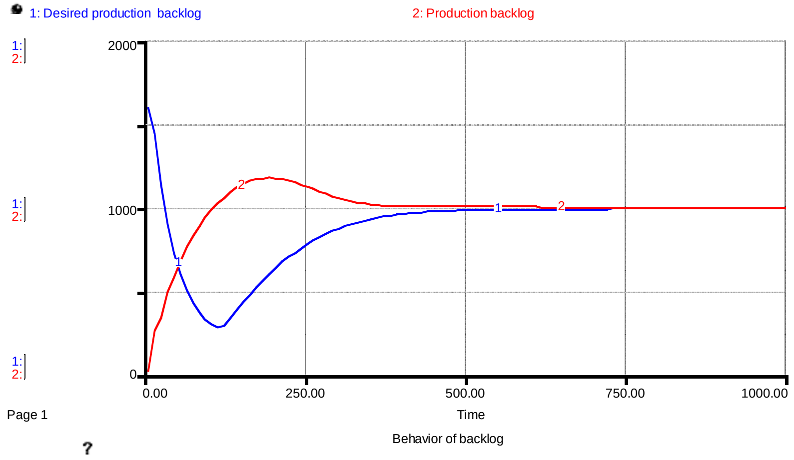


Figure 3-5: The behavior of the backlog in the production.

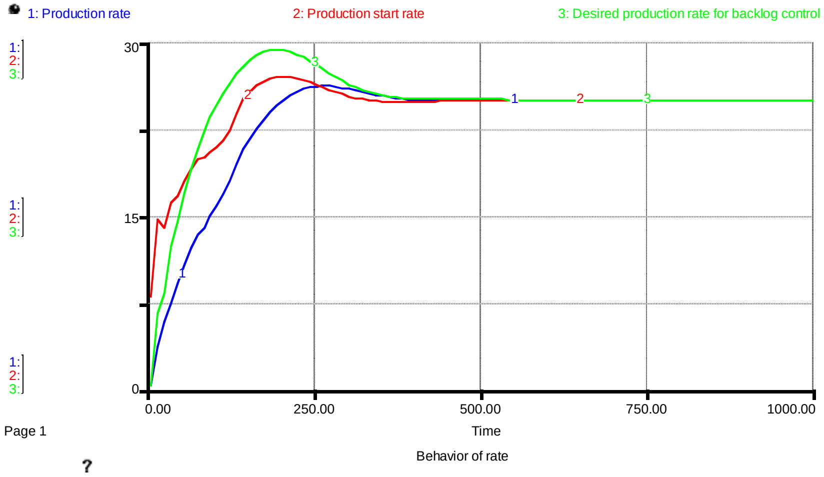


Figure 3-6: The behavior of the rate in the production.

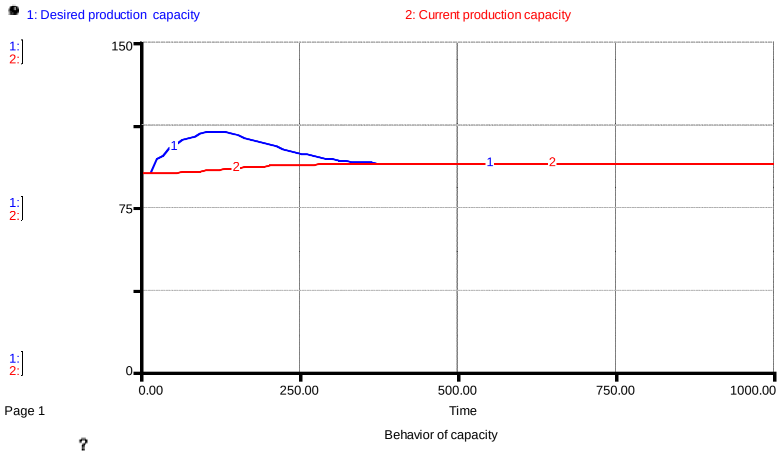


Figure 3-7: The behavior of the capacity in the production.

Exactly the same behavior and same dependency is evident in case of assembly and distribution in the forward supply chain. Therefore, detailed graphical illustration is avoided, but all the graphs that describes their behaviors are attached in appendix I-A. The above graphs are also included in the in the appendix I-A for the convenience of comparison.

Mathematical formulation

Equations for all the stocks and flows in the *'forward supply chain sector'* are as follows,

$$Production\_WIP\_inventory(t) = Production\_WIP\_inventory(t - dt) + (Production\_start\_rate - Production\_rate) * dt$$

$$Production\_start\_rate = (Desired\_production\_start\_rate + Production\_rate)$$

$$Production\_rate = (MIN((Current\_production\_capacity), (Desired\_\_production\_rate\_for\_inventory\_control + Assembly\_rate), (Desired\_production\_rate\_for\_backlog\_control), (Production\_WIP\_inventory / Min\_production\_delay)))$$

$$Assembly\_WIP\_\_inventory(t) = Assembly\_WIP\_\_inventory(t - dt) + (Production\_rate - Assembly\_rate) * dt$$

$$Assembly\_rate = MIN((Desired\_\_assembly\_rate\_for\_inventory\_contol + Shipment\_rate), (Desired\_assembly\_\_rate\_for\_backlog\_\_control), (Current\_assembly\_capacity), (Assembly\_WIP\_\_inventory / Min\_assembly\_\_delay))$$

$$Finished\_product\_\_inventory(t) = Finished\_product\_\_inventory(t - dt) + (Assembly\_rate - Shipment\_rate) * dt$$

$$Shipment\_rate = MIN((Finished\_product\_\_inventory / Shipment\_delay), (Desired\_shipment\_\_rate))$$

Equations of all the inventory sectors, i.e., *'production WIP inventory', 'assembly WIP inventory'* and *'finished product inventory'* have the same structure, and are given below.

Equations used in production WIP inventory sector

$$Desired\_production\_start\_rate = Production\_WIP\_inventory\_gap / Planned\_production\_\_start\_delay$$

$$Production\_WIP\_inventory\_gap = Desired\_production\_\_WIP\_inventory - Production\_WIP\_inventory + Production\_backlog\_gap$$

$$Desired\_production\_\_WIP\_inventory = Expected\_demand * Production\_WIP\_inventory\_coverage$$

$$Production\_backlog\_gap = Production\_backlog - Desired\_production\_\_backlog$$

$$Desired\_production\_\_backlog = Expected\_demand * Planned\_production\_\_delay$$

$$Desired\_\_production\_rate = Assembly\_WIP\_inventory\_gap/Planned\_production\_delay$$

$$Desired\ productin\ rate\ for\ backlog\ gap\ control = Production\_backlog/Planned\_production\_\_delay$$

Equations used in assembly WIP inventory sector

$$Desired\_\_production\_rate\_for\_inventory\_control = Assembly\_WIP\_inventory\_gap /Planned\_production\_\_delay$$

$$Assembly\_WIP\_inventory\_gap = Desired\_assembly\_WIP\_inventory - Assembly\_WIP\_\_inventory + Assembly\_\_backlog\_gap$$

$$Desired\_assembly\_WIP\_inventory = Expected\_demand * Assembly\_WIP\_\_invetory\_coveragre$$

$$Desired\_assembly\_backlog = Expected\_demand * Planned\_\_assembly\_delay$$

$$Assembly\_\_backlog\_gap = Assembly\_\_backlog - Desired\_assembly\_backlog$$

$$Desired\_\_assembly\_rate = Finished\_product\_inventory\_\_gap /Planned\_\_assembly\_delay$$

$$Desired\_assembly\_\_rate\_for\_backlog\_\_control = Assembly\_\_backlog/Planned\_\_assembly\_delay$$

Equations used in finished product inventory sector

$$Desired\_\_assembly\_rate\_for\_inventory\_contol = Finished\_product\_inventory\_\_gap /Planned\_\_assembly\_delay$$

$$\begin{aligned}&\mathit{Finished\_product\_inventory\_\_gap}\\&\qquad= \mathit{Desired\_finished\_\_product\_inventory}\\&\qquad- \mathit{Finished\_product\_\_inventory} + \mathit{Sales\_backlog\_\_gap}\end{aligned}$$

$$\begin{aligned}&\mathit{Desired\_finished\_\_product\_inventory}\\&\qquad= \mathit{Expected\_demand}\\&\qquad* \mathit{Finished\_product\_\_inventory\_coverage}\end{aligned}$$

$$\mathit{Desired\_sales\_backlog} = \mathit{Expected\_demand} * \mathit{Planned\_distribution\_\_delay}$$

$$\mathit{Sales\_backlog\_\_gap} = \mathit{Sale\_backlog} - \mathit{Desired\_sales\_backlog}$$

$$\mathit{Desired\_shipment\_\_rate} = \mathit{Sale\_backlog}/\mathit{Planned\_distribution\_\_delay}$$

Equation used in the sector *'demand forecasting'* has been the same for the entire forward supply chain,

Equations used in demand forecasting sector

$$\begin{aligned}&\mathit{Expected\_demand}(t)\\&\qquad= \mathit{Expected\_demand}(t - dt)\\&\qquad+ (\mathit{Change\_in\_expected\_\_demand\_}1) * dt\end{aligned}$$

$$\begin{aligned}&\mathit{Change\_in\_expected\_\_demand\_}1\\&\qquad= (\mathit{Sales\_order\_rate}\\&\qquad- \mathit{Expected\_demand})/\mathit{Time\_to\_adjust\_\_expected\_demand\_}1\end{aligned}$$

Equations of all the backlog sectors, i.e., '*production backlog', 'assembly backlog'* and '*sales backlog*' have the same structure, and are given below.

Equations used in production backlog sector

$$\begin{aligned}&\mathit{Production\_backlog}(t)\\&\qquad= \mathit{Production\_backlog}(t - dt) + (\mathit{Production\_order\_rate}\\&\qquad- \mathit{Production\_order\_\_fulfillment\_rate}) * dt\end{aligned}$$

$$\mathit{Production\_order\_\_fulfillment\_rate} = \mathit{Prodution\_rate}$$

$$Actual\_production\_\_delay = Production\_backlog/Production\_order\_\_fulfillment\_rate$$

$$Production\_delivery\_\_delay\_ratio = Actual\_production\_\_delay/Planned\_production\_\_delay$$

$$Effect\_of\_production\_\_DD\_on\_order = GRAPH(Production\_delivery\_\_delay\_ratio)$$

$(1.00, 1.00), (1.15, 0.986), (1.30, 0.944), (1.45, 0.867), (1.60, 0.751),$

$(1.75, 0.509), (1.90, 0.344), (2.05, 0.27), (2.20, 0.228), (2.35, 0.214), (2.50, 0.2)$

$$Production\_rder\_rate = (Normal\_order * Effect\_of\_production\_\_DD\_on\_order)$$

<u>Equations used in assembly backlog sector</u>

$$Assembly\_\_backlog(t) = Assembly\_\_backlog(t - dt) + (Assembly\_order\_rate - Assembly\_order\_\_fulfillment\_rate) * dt$$

$$Assembly\_order\_\_fulfillment\_rate = Assembly\_rate$$

$$Actual\_assembly\_\_delay = Assembly\_\_backlog/Assembly\_order\_\_fulfillment\_rate$$

$$Assembly\_delivery\_\_delay\_ratio = Actual\_assembly\_\_delay/Planned\_\_assembly\_delay$$

$$Effect\_of\_assembly\_\_DD\_on\_order = GRAPH(Assembly\_delivery\_\_delay\_ratio)$$

$(1.00, 1.00), (1.15, 0.986), (1.30, 0.944), (1.45, 0.867), (1.60, 0.751), (1.75, 0.509),$

$(1.90, 0.344), (2.05, 0.27), (2.20, 0.228), (2.35, 0.214), (2.50, 0.2)$

$$Assembly\ order\_rate = (Normal\_order * Effect\_of\_assembly\_\_DD\_on\_order)$$

Equations used in sales backlog sector

$$Sales\_backlog(t) = Sales\_backlog(t - dt) + (Sales\_order\_rate - Order\_\_fulfillment\_rate) * dt$$

$$Order\_\_fulfillment\_rate = Shipment\_rate$$

$$Actual\_distribution\_\_delay = Sales\_backlog / Order\_\_fulfillment\_rate$$

$$Delivery\_delay\_ratio\_1 = Actual\_distribution\_\_delay / Planned\_distribution\_\_delay$$

$$Effect\_of\_distribution\_\_\_DD\_on\_\_order = GRAPH(Delivery\_delay\_ratio\_1)$$

$$(1.00, 1.00), (1.15, 0.986), (1.30, 0.944), (1.45, 0.867), (1.60, 0.751), (1.75, 0.509),$$

$$(1.90, 0.344), (2.05, 0.27), (2.20, 0.228), (2.35, 0.214), (2.50, 0.2)$$

$$Sales\_order\_rate = (Normal\_order) * (Effect\_of\_distribution\_\_\_DD\_on\_\_order)$$

Equations of all the capacity sectors, i.e., '*production capacity*' and '*assembly capacity*' have the same structure, and are given below.

Equations used in production capacity sector

$$Production\_delivery\_\_delay\_\_perceived\_by\_company = SMTH1(Actual\_production\_\_delay,$$

$$Time\_to\_perceive\_production\_delivery\_delay)$$

$$Pressure\_to\_expand\_\_production\_capacity = Production\_delivery\_\_delay\_\_perceived\_by\_company / Planned\_production\_\_delay$$

$$Effect\_of\_expansion\_pressure\_\_on\_desired\_production\_capacity = GRAPH(Pressure\_to\_expand\_\_production\_capacity)$$

$$(0.00, 0.25), (0.5, 0.8), (1.00, 1.00), (1.50, 1.18), (2.00, 1.36), (2.50, 1.56)$$

, (3.00, 1.75), (3.50, 2.00), (4.00, 2.10), (4.50, 2.19), (5.00, 2.20)

$$\begin{aligned}&Desired\_production\_\_capacity\\&= (Initial\_production\_capacity\\&* Effect\_of\_expansion\_pressure\_\_on\_desired\_production\_capacity)\end{aligned}$$

$$\begin{aligned}Current\_production\_capacity(t)&\\&= Current\_production\_capacity(t - dt)\\&+ (Change\_in\_\_production\_capacity) * dt\end{aligned}$$

$$\begin{aligned}Change\_in\_\_production\_capacity&\\&= (Desired\_production\_\_capacity\\&- Current\_production\_capacity)\\&/Production\_capacity\_\_acquisition\_delay\end{aligned}$$

Equations used in production capacity sector

$$\begin{aligned}Assembly\_delivery\_\_delay\_\_perceived\_by\_company&\\&= SMTH1(Actual\_assembly\_\_delay,\end{aligned}$$

$$Time\_to\_perceive\_assembly\_\_delivery\_delay)$$

$$\begin{aligned}Pressure\_to\_expand\_\_assembly\_capacity&\\&= Assembly\_delivery\_\_delay\_\_perceived\_by\_company\\&/Planned\_\_assembly\_delay\end{aligned}$$

$$\begin{aligned}Effect\_of\_expansion\_pressure\_\_on\_desired\_assembly\_capacity&\\&= GRAPH(Pressure\_to\_expand\_\_assembly\_capacity)\end{aligned}$$

(0.00, 0.25), (0.5, 0.8), (1.00, 1.00), (1.50, 1.18), (2.00, 1.36), (2.50, 1.56),

(3.00, 1.75), (3.50, 2.00), (4.00, 2.10), (4.50, 2.19), (5.00, 2.20)

$$\begin{aligned}&Desired\_assembly\_\_capacity\\&= Initial\_assembly\_\_capacity\\&* Effect\_of\_expansion\_pressure\_\_on\_desired\_assembly\_capacity\end{aligned}$$

$$\begin{aligned}Current\_assembly\_capacity(t)&\\&= Current\_assembly\_capacity(t - dt)\\&+ (Change\_in\_\_assembly\_capacity) * dt\end{aligned}$$

$$\begin{aligned}Change\_in\_\_assembly\_capacity \\ &= (Desired\_assembly\_\_capacity \\ &- Current\_assembly\_capacity) \\ &/Assembly\_capacity\_acquisition\_delay\end{aligned}$$

Reverse supply chain

The reverse supply chain in the model includes the sectors *'reverse supply chain', 'remanufactureable product inventory', 'remanufactured product demand forecasting'* and *'remanufactured product backlog'*. The '*reverse supply chain'* sector consists of *'EoL product inventory'* where products accumulate at their end-of-life through three ageing chains named *'product in use 1,2,3'*. The ageing is deterministic; however, the rate at which product will reach EoL or the succeeding stages of *'product in use'* are probabilistic. It is assumed that at the earlier age of the product, the probability of failure is low and increases with the age. Products then move from '*EoL product inventory'* to *'collected EoL product inventory'* after some predefined delay. Products in '*collected EoL product inventory'* are then inspected, (*'inspection rate 1, 2'*) and depending on their physical and functional condition products are stored either in *'Remanufactureable product inventory'* or in *'non remanufactureable product inventory'*. The physical and functional condition is denoted by *'functionality factor'* which is probabilistic and generates any random values between 0.1 and 1. The main assumptions that are made in this section are,

- There is no capacity constrain in the reverse supply chain.
- The rate, i.e., *'shipment rate of manufactured products'* at which product will be supplied in the next stage is only constrained by availability of *'collected EoL product inventory'* and 're*manufactureable product inventory'* or the '*desired shipment of remanufactured product'.*
- Each product reaching EoL creates a demand and order is placed immediately.

The stock and flow structure used in the sector *'remanufactured product backlog', 'remanufactured product demand forecasting'* and *'remanufactured product inventory'* has the same structure as the backlogs, demand forecasting and inventory sectors described in the forward supply chain in the previous section.

Behavior of the key performance indicators

Behavior of the key performance indicators in reverse supply chain is not the same as the key performance indicators in the forward supply chain. The main reason for inconsistency in the behavior is the randomly varying variables that determine different rates in the model. Besides, in the reverse supply chain model the demand is always more than the supply (this consideration is quite known characteristic of reverse supply chain as is elaborately discussed in section2.1 and 2.2.). This causes the planned and actual distribution delay, inventory, backlog and shipment rate never to balance. This hypothesis is well known and an accepted fact of reverse supply chain. These phenomena are illustrated in the graphs in Figure 3-8, Figure 3-9, Figure 3-10 and Figure 3-11.

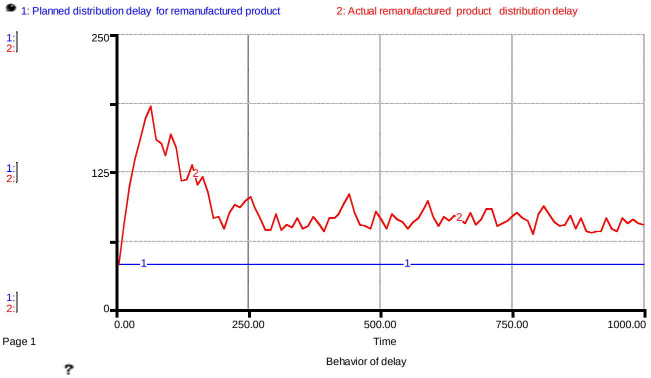


Figure 3-8: The behavior of the delay in the reverse supply chain.

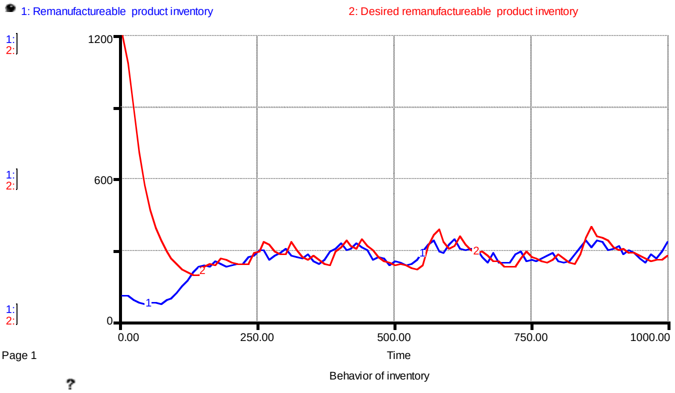


Figure 3-9: The behavior of the inventory in the reverse supply chain.

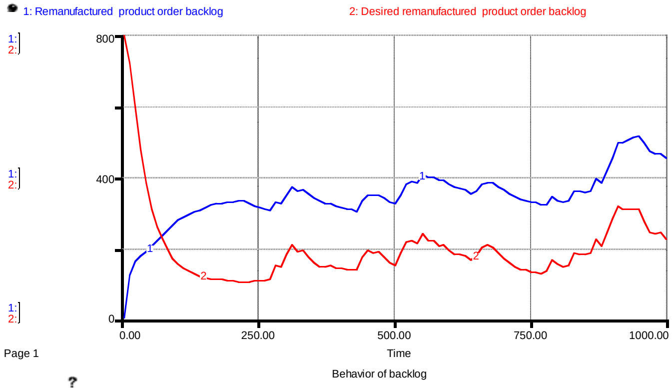


Figure 3-10: The behavior of the backlog in the reverse supply chain.

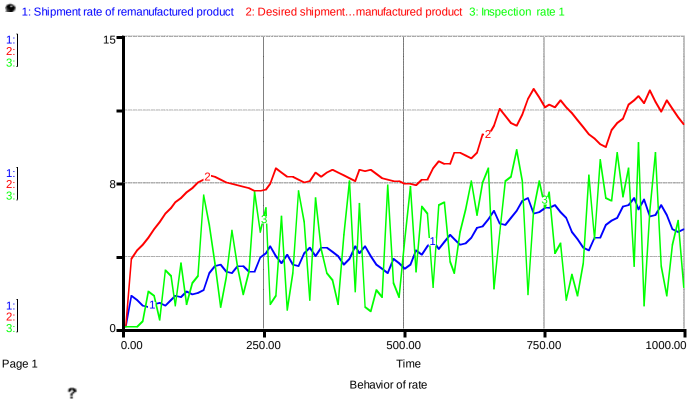


Figure 3-11: The behavior of the rate in the reverse supply chain.

From the above graphs it can be concluded that the reverse supply chain is unstable in nature. The uncertainty of core arriving time, quantity and quality, causes the feedback loops to suffer. This type of behavior hinders the creation of a robust policy. The decision makers usually cannot identify key drivers within the system that can improve the system's performance in such situations. The graphs shown above are also included in the appendix I-A for the convenience of comparison with the forward supply chain.

Mathematical formulation

The equations used in the sector ‘reverse supply chain’ are as follows,

$$Product\_in\_\_use\_1(t) = Product\_in\_\_use\_1(t - dt) + (Delivery\_rate\_1 - EoL\_1 - Delivery\_rate\_1\_to\_2) * dt$$

$$Delivery\_rate\_1 = Shipment\_rate$$

$$EoL\_1 = (Product\_in\_\_use\_1 * EoL\_ratio\_1)/EoL\_delay\_1EoL\_1 = (Product\_in\_\_use\_1 * EoL\_ratio\_1)/EoL\_delay\_1$$

$$Delivery\_rate\_1\_to\_2 = ((1 - EoL\_ratio\_1) * Product\_in\_\_use\_1)/EoL\_delay\_1$$

$$Product\_in\_\_use\_2(t) = Product\_in\_\_use\_2(t - dt) + (Delivery\_rate\_1\_to\_2 - EoL\_2 - Delivery\_rate\_2\_to\_3) * dt$$

$$EoL\_2 = (Product\_in\_\_use\_2 * EoL\_ratio\_2)/EoL\_\_delay\_2$$

$$Delivery\_rate\_2\_to\_3 = ((1 - EoL\_ratio\_2) * Product\_in\_\_use\_2)/EoL\_\_delay\_2$$

$$Product\_in\_\_use\_3(t) = Product\_in\_\_use\_3(t - dt) + (Delivery\_rate\_2\_to\_3 - EoL\_3) * dt$$

$$EoL\_3 = (Product\_in\_\_use\_3 * EoL\_ratio\_3)/EoL\_\_delay\_3$$

$$EoL\_product\_inventory(t) = EoL\_product\_inventory(t - dt) + (EoL\_1 + EoL\_2 + EoL\_3 - Collection\_rate) * dt$$

$$Collection\_rate = EoL\_product\_inventory/Collection\_delay$$

$$
\begin{aligned}
&Collected\_EOL\_product\_inventory(t)\\
&\qquad = Collected\_EOL\_product\_inventory(t - dt)\\
&\qquad + (Collection\_rate - Inspection\_\_rate\_1\\
&\qquad - Inspection\_\_rate\_2) * dt
\end{aligned}
$$

$$
\begin{aligned}
&Inspection\_\_rate\_2\\
&\qquad = (1 - Functionality\_factor)\\
&\qquad * Collected\_EOL\_product\_inventory/Inspection\_delay
\end{aligned}
$$

$$
\begin{aligned}
&Non\_remanufactureable\_product\_inventory(t)\\
&\qquad = Non\_remanufactureable\_product\_inventory(t - dt)\\
&\qquad + (Inspection\_\_rate\_2) * dt
\end{aligned}
$$

$$
\begin{aligned}
&Remanufactureable\_\_product\_inventory(t)\\
&\qquad = Remanufactureable\_\_product\_inventory(t - dt)\\
&\qquad + (Inspection\_\_rate\_1\\
&\qquad - Shipment\_rate\_of\_remanufactured\_product) * dt
\end{aligned}
$$

$$
\begin{aligned}
&Inspection\_\_rate\_1\\
&\qquad = MIN((((Collected\_EOL\_product\_inventory\\
&\qquad * Functionality\_factor)\\
&\qquad /Min\_inspection\_\_delay)), (Desired\_\_inspection\_rate\_1\\
&\qquad + Shipment\_rate\_of\_remanufactured\_product))
\end{aligned}
$$

$$
\begin{aligned}
&Shipment\_rate\_of\_remanufactured\_product\\
&\qquad = MIN((Remanufactureable\_\_product\_inventory\\
&\qquad /Shipment\_delay\_for\_\_remanufactured\_\_product),
\end{aligned}
$$

$$(Desired\_shipment\_rate\_of\_\_remanufactured\_product))$$

The equations used in the sectors *'remanufactured product backlog'*, *'remanufactured product demand forecasting'* and *'remanufactured product inventory'* are the same used in the *'backlog'*, *'demand forecasting'* and *'inventory'* sectors in the forward supply chain. Of course, the notations are different. The equations are listed below.

Equations used in remanufactured product backlog sector

$$Remanufactured\_\_product\_order\_backlog(t) = Remanufactured\_\_product\_order\_backlog(t - dt) + (Order\_rate\_of\_\_remanufactured\_\_product - EoL\_product\_\_order\_\_fulfillment\_rate) * dt$$

$$EoL\_product\_\_order\_\_fulfillment\_rate = Shipment\_rate\_of\_remanufactured\_product$$

$$Order\_rate\_of\_\_remanufactured\_\_product = (EoL\_1 + EoL\_2 + EoL\_3 + Normal\_order\_rate\_of\_remanufactured\_product) * Effect\_of\_DD\_on\_\_order\_2$$

$$Effect\_of\_remanufactured\_\_product\_DD\_on\_\_order = GRAPH(Remanufactured\_product\_delivery\_delay\_ratio)$$

$$(1.00, 1.00), (1.15, 0.986), (1.30, 0.944), (1.45, 0.867), (1.60, 0.751), (1.75, 0.59),$$

$$(1.90, 0.344), (2.05, 0.27), (2.20, 0.228), (2.35, 0.214), (2.50, 0.2)$$

$$Remanufactured\_product\_delivery\_delay\_ratio = Actual\_remanufactured\_\_product\_\_\_distribution\_delay / Planned\_distribution\_delay\_\_for\_remanufactured\_product$$

$$Actual\_remanufactured\_\_product\_\_\_distribution\_delay = Remanufactured\_\_product\_order\_backlog / EoL\_product\_\_order\_\_fulfillment\_rate$$

Equations used in remanufactured product demand forecasting sector

$$Expected\_demand\_\_of\_remanufactured\_product(t) = Expected\_demand\_\_of\_remanufactured\_product(t - dt) + (Change\_in\_expected\_\_demand\_2) * dt$$

$$Change\_in\_expected\_\_demand\_2 = (Order\_rate\_of\_\_remanufactured\_\_product - Expected\_demand\_\_of\_remanufactured\_product) / Time\_to\_adjust\_\_expected\_demand\_2$$

Equations used in remanufactured product inventory sector

$$\begin{aligned}&\mathit{Desired\_\_inspection\_rate\_}1\\&\qquad= \mathit{Remanufactureable\_product\_inventory\_\_gap}\\&\qquad\ \mathit{/Planned\_\_inspection\_delay}\end{aligned}$$

$$\begin{aligned}&\mathit{Remanufactureable\_\_product\_inventory\_\_gap}\\&\qquad= \mathit{Desired\_remanufactureable\_\_product\_inventory}\\&\qquad- \mathit{Remanufactureable\_\_product\_inventory}\\&\qquad+ \mathit{Remanufactured\_product\_order\_\_backlog\_gap}\end{aligned}$$

$$\begin{aligned}&\mathit{Desired\_remanufactureable\_\_product\_inventory}\\&\qquad= \mathit{Expected\_demand\_\_of\_remanufactured\_product}\\&\qquad* \mathit{Remanufactureable\_product\_\_inventory\_coverage}\end{aligned}$$

$$\begin{aligned}&\mathit{Remanufactured\_product\_order\_\_backlog\_gap}\\&\qquad= \mathit{Remanufactured\_\_product\_order\_backlog}\\&\qquad- \mathit{Desired\_remanufactured\_\_product\_order\_backlog}\end{aligned}$$

$$\begin{aligned}&\mathit{Desired\_remanufactured\_\_product\_order\_backlog}\\&\qquad= \mathit{Expected\_demand\_\_of\_remanufactured\_product}\\&\qquad* \mathit{Planned\_remanufactured\_\_product\_distribution\_delay}\end{aligned}$$

$$\begin{aligned}&\mathit{Desired\_shipment\_rate\_of\_\_remanufactured\_product}\\&\qquad= \mathit{Remanufactured\_\_product\_order\_backlog}\\&\qquad\ \mathit{/Planned\_distribution\_delay\_\_for\_remanufactured\_product}\end{aligned}$$

Conventional closed loop supply chain

In the conventional closed loop supply chain the above mentioned two models have been kept the same but with two distinct differences. Firstly, ‘*remanufactureable product inventory’* has been connected to the *‘assembly WIP inventory’.* Products accumulated in the ‘re*manufactureable product inventory’* move to the *‘assembly WIP inventory’* at the *‘shipment rate of manufactured product’.* Secondly, the *‘Order rate of remanufactured product’* has been added in the sector *‘production backlog’, ‘assembly backlog’* and ‘*sales backlog’* in the forward supply chain. These changes are shown in the model with ‘green’ colored flows and connections. The main assumptions of the conventional closed loop supply chain are,

- Both remanufactured and newly manufactured products are sold through the same channel.
- All remanufactured products are as good as the newly manufactured products and can substitute the need for production.
- The market becomes larger as soon as the firm decides to remanufacture products.
- All remanufactureable products are remanufactured without any delay.

Behavior of the key performance indicators

The behavior of key performance indicators in the conventional closed loop supply is included in the appendix I-B.

Mathematical formulation

In conventional closed loops supply chain almost all the equations are the same, except two. Connecting the forward and reverse supply chain directly affects equations previously used in *'assembly WIP inventory' 'production rate'* and all backlog sectors in *'order rate'* in the forward supply chain. These equations are listed below, and the changes are indicated in bold.

$$Assembly\_WIP\_\_inventory(t) = Assembly\_WIP\_\_inventory(t - dt) + (Production\_rate + \boldsymbol{Recovered\_product\_rate} - Assembly\_rate) * dt$$

$$Production\_rate = (MIN((Current\_production\_capacity), (Desired\_\_production\_rate\_for\_inventory\_control + Assembly\_rate - \boldsymbol{Recovered\_product\_rate}), (Desired\_production\_rate\_for\_backlog\_control - \boldsymbol{Recovered\_product\_rate}), (Production\_WIP\_inventory / Min\_production\_delay)))$$

$$Recovered\_product\_rate = Shipment\_rate\_of\_remanufactureable\_\_product$$

$$Sales\_rder\_\_rate = (Normal\_order + \boldsymbol{Order\_rate\_of\_\_remanufactured\_\_product}) * (Effect\_of\_distribution\_\_\_DD\_on\_\_order)$$

$$
\begin{aligned}
&Assembly\_order\_rate \\
&\qquad\qquad = (Normal\_order \\
&\qquad\qquad + \boldsymbol{Order\_rate\_of\_\_remanufactured\_\_product}) \\
&\qquad\qquad * (Effect\_of\_assembly\_\_DD\_on\_order)
\end{aligned}
$$

$$
\begin{aligned}
&Production\_order\_\_rate \\
&\qquad\qquad = (Normal\_order \\
&\qquad\qquad + \boldsymbol{Order\_rate\_of\_\_remanufactured\_\_product}) \\
&\qquad\qquad * (Effect\_of\_production\_\_DD\_on\_order)
\end{aligned}
$$

Closed loop supply chain in resource conservative manufacturing

The closed loop supply chain in resource conservative manufacturing has a slightly different structure than the conventional closed loop supply chain. As in resource conservative manufacturing the time of product return is predetermined, the ageing chain does not exist in setting of the models. The only delay to accumulate products from *'product in use 1'* to *'EoL product inventory'* is at a predetermined interval. Addition to this, all products are assumed to be returned; therefore, there is no random variation in *'EoL ratio'*. Moreover, the *'functionality factor'* that determines *'inspection rate 1,2 '* is assumed to be quite high (90% of the products are remanaufactureable) and constant. This assumption is in-line with the argument made in section 2.2, i.e., in the proposed resource conservative manufacturing approach the quality of the returned products is known (high) to some extents and almost all of them can be used further (if designed for multiple lifecycle). The assumptions made in the models discussed above are valid, and no new assumptions are made.

Behavior of the key performance indicators

The behavior of key performance indicators in the closed loop supply chain in resource conservative manufacturing is included in the appendix I-C.

Mathematical formulation

There is almost no change in the equations in this part compared to the conventional closed loop supply chain discussed above, except simplification of some of the equations.

$$Product\_in\_\_use\_1(t) = Product\_in\_\_use\_1(t - dt) + (Delivery\_rate\_1 - EoL\_1) * dt$$

$$EoL\_1 = Product\_in\_\_use\_1/EoL\_delay\_1$$

$$EoL\_product\_inventory(t) = EoL\_product\_inventory(t - dt) + (EoL\_1 - Collection\_rate) * dt$$

$$Collection\_rate = EoL\_product\_inventory/Collection\_delay$$

3.3 Simulation results

The simulation results have been presented in terms of performance of the supply chain in three different settings. The trend (graphs) of the key performance indicators such as level of inventories, backlogs, rates and delays are shown in this section as well as in appendix- I [A, B & C]. The trends clearly depict that the reserve supply chain is faces uncertainty due to the availability of cores and the quality of returned cores. The forward supply chain becomes unstable when the reverse supply chain is combined i.e., the conventional closed loop supply chain. The forward supply chain becomes stable again if the resource conservative manufacturing approach is adopted.

The feedback loop that exists within the dynamics of the supply chain helps decision makers to take actions that are sustainable over time. The simulation helps to understand to what extent the policy is robust and what are the drivers that affect robustness of the policy. In case of the forward supply chain, this is particularly true, and validated through the model once again. However, the models presented in this report aims to demonstrate completely opposite characteristics of the supply chain, that is to what extent the policies are not robust and there is no way that decision makers can take actions to create a robust policy in such situations. Industries that use the reverse supply chain or closed loops supply chain cannot manage their supply chain with traditional thinking and well-established policies. Industries that are planning to incorporate the reverse supply chain with their forward supply chain should, from these models, gain insight that as soon as two supply chains are combined their policies (that have been in place and working well) will be disturbed, and the robustness will not be within manageable limits. Nevertheless, if the concept of resource conservative manufacturing is adopted the closed loop supply chain will behave more or less similar as the forward supply chain usually behaves.

By analyzing the behavior of the key performance indicators it can certainly be said that the hypothesis 'by adopting the resource conservative manufacturing approach a well functioning closed loop supply chain can be designed' is validated.

3.4 Model testing

The models were tested through the initialization of the model in a balanced equilibrium. It means that all stocks in the system remain unchanged despite the variation of time, requiring their inflow and outflow to be equal. The part of the model with random variables could not be initialized as it is; in this case, random variables were replaced with constant values. Initialization confirms that there is no discrepancy in the equations or in the feedback loops.

The models were tested using extreme condition test [44], where extreme input values such were assigned concurrently. A robust model should behave rationally in extreme conditions. The models passed the extreme condition tests. This was the case for the forward supply chain, but the reverse part did not fulfill the condition of extreme test. This is mainly due to the random variables used in the reverse supply chain.

The simulation time has been extended to test if the model causes any reaction. In this case the trends (graphs) of key performance indicators remain more or less steady despite the largely varied simulation duration.

3.5 Summary and discussions

The models that have been presented are generic models, which do not depict any specific type of product or industry. The boundaries of the models are quite broad; therefore, lack details in many cases. The input data of the models are factious but correspond to the reality. In the models some random variables are used, which do not comply with system dynamics principles as Sterman [44]describes randomness as *'a measure of our ignorance, not intrinsic to the system'*. However, in this particular case randomness could not been avoided, as no research has been found that describes this phenomena otherwise, and the span of the analysis is relatively shorter than what system dynamics usually suggest and finally there is a lack of empirical data.

The model raises at least two questions related to dynamics of policy and performance of supply chain. One is, when remanufactured products enter (in rate of nondeterministic number) the forward supply chain and the production rate adjusts itself, what are the dynamics and the feedback loops acting on it? The other question is, when a firm decides to enter the remanufacturing (new) market, how do the dynamics of the supply-demand and market share become balanced and what are the feedback loops that cause the balance? At the same time, it has been realized that to make the model complete the incorporation of societal perception, environmental benefits and level of natural resource conservation is needed.

The purpose of the modeling has been different from what people usually expect from system dynamics modeling. Through modeling it has been shown how the policy and its leverage get affected when there is large uncertainty in any part of the supply chain. Therefore, the descriptions and arguments that are built around the models may not be as they would have been in the case of a conventional system dynamics model.

Referring to the argument presented at the beginning of this chapter concerning continuous simulation and discrete event simulation, system dynamics is particularly useful in demonstrating the complex dynamics relations of factors that are essential to manage a supply chain. It also helps to visualize the feedback loops and how they influence each other in a supply chain. Moreover, it gives management a base for decision making i.e., in a supply chain, what degree of freedom one has to change different variables. As the objective of modeling has been to demonstrate performance of the supply chain in different settings and how they influence each other in terms of behavior, no other tool can fulfill the purpose as explicitly as system dynamics did.

Chapter IV

4. Conclusions and future research

This chapter includes conclusions and discussions. Directions for future research have also been included in this chapter.

4.1 Conclusions

The manufacturing industry is facing a major dilemma; on the one hand, it is forced to grow with the development of society to harmonize the living standards and crate new job opportunities, and on the other hand it is held responsible for worsening living standards by pollution and environmental impact. At the same time, growth of the manufacturing industry is threatened by resource scarcity. This cause and effect relationship clearly indicates two reinforcing loops, which are shown in the Figure 4-1. To balance these two reinforcing loops either manufacturing growth has to stop or living standards have to be compromised. However, choosing one alternative will not solve the problem as limiting the growth of one will limit the other. Resource conservative manufacturing proposes solutions that would balance (to a large extent) these two reinforcing loops by introducing the concept of the product's multiple lifecycle.

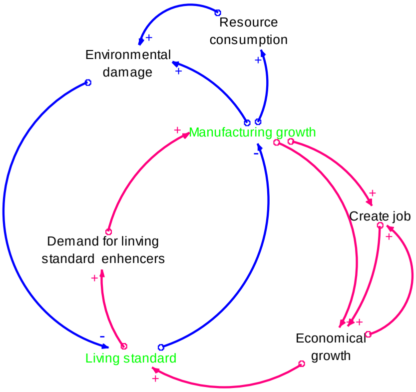


Figure 4-1 : Two reinforcing loops in manufacturing.

The conventional ways of resource conservation suggest remanufacturing and recycling to tackle the problem. However, the approach does not properly evaluate product's lifecycle analysis at systems level considering and combining energy, resource, environment, recoverable values and economy. Even if it does, in some cases the analysis is short- sighted and does not consider the dynamics of the system in respect to time or space.

In the conventional approach resource conservation is reactive i.e., remanufacturing and recycling are actions to be taken at the product's EoL/EoU. This reactive approach is proven to be inefficient, as at that point nothing can be influenced except following the instincts. Due to limited scope, benefits and feasibility, OEMs are staying away from remanufacturing. Small and medium-size remanufacturing industries are struggling to cope with the reality with limited success and slow growth.

As the root of the problem lies within identifying and integrating enabling factors and stakeholders for resources conservation, the contributions of the state-of-the-art research have limited applicability. Moreover, not having a holistic and integrated approach for resource conservation, independent research suffers from a number of pitfalls and gaps. By reviewing the state-of-the-art it has been concluded that the overall research efforts tries to solve the problem with the conventional business thinking. The researchers in remanufacturing are still trying to convince that it is worth doing through the example of some certain specific products and success stories of a few known manufactures. Highlighting problems that are faced by a large number of independent remanufacturers is not that common in the literature. However, valuable insight of different researchers concerning the drawbacks in remanufacturing has been merged to highlight point that the ultimate success of the remanufacturing lies with the involvement of the OEMs and consumers. Problems related to operations and processes of remanufacturing can to a large extent be solved by careful product design. Nevertheless, the design itself has multiple problems that need to be solved and take beyond the conventional design approaches.

The closed loop supply chain is an inseparable part of the business if the resources to be conserved efficiently by remanufacturing and recycling. The very basic function of core acquisition in the closed loop supply chain is suffering due to unpredictable time, quality and quantity of the returned core. Due to this uncertainty, there is always the mismatch between supply and demand of core, which is fundamental for a business to survive. Liaison with consumers is a common way to ensure core return, but this is a luxury which can only be exploited by OEMs. The success of these liaisons or business models is limited if the OEMs, consumers or society is reluctant to remanufacturing or recycling. The importance of the societal perceptions is not considered within the frame of the conventional resource conservation thinking.

The legislative directives can be seen of as a wakeup call for strategic decision makers in regards of which directions the future manufacturing business may go. Unfortunately, this wakeup call is often disregarded due to the lack of long-term thinking. If nothing else is considered except profitability, even then, at this point the manufacturing industry needs to be more proactive with the upcoming regulations.

By reviewing the state-of-the–art, it is clear that despite many problems, the most essential step in resource conservation is to integrate product design, closed loop supply chain and suitable business model. The integration should be supported mainly by the OEMs and consumers, but other stakeholders such as 3rd party remanufacturers, regulatory bodies and municipalities should be part of it where relevant. For instance, product's/component's number of lifecycle, its duration and EoL/EoU strategies should be determined at the design phase, and design should be done accordingly. Here, it is extremely important that OEMs take the initiatives as they have good knowledge of the product. As the products are expected to be returned the closed loop supply chain should be designed based on the number of lifecycle(s) and its duration, which requires involvement of the OEMs (product provider), consumers (core provider) and 3rd party (EoL/EoU facilitator). A viable business model is fundamental to the success of the closed loop supply chain as different stakeholders have to cooperate. To strengthen stakeholder's motivation, relation and involvement, promotion of the resource conservation is vital. Moreover, relevant stakeholders' perception of resource conservation needs to be changed. To summarize the integration requires mainly,

- Change in consumers' behavior to accept to return the product after each lifecycle and accept resource conserved products.

- Change in view of OEMs concerning resource conservation.
- All stakeholders see the value of resource conservative manufacturing in both local and global perspectives.

The research material in this thesis introduced the novel concept of,

- Resource conservation named as resource conservative manufacturing.
- Product's multiple lifecycle.
- Lifecycle analysis that take both space and time into consideration.

In addition, it presented and discussed different enablers to establish and implement the concepts. It discussed misconception concerning the closed loop supply chain and presented a revised concept which is more certain in terms of its functionality. It proposed essential cooperation between the OEMs, consumers, 3rd party and regulatory bodies and proposed viable business model to tie them up. It also proposed a new concept of product labeling tied with social prestige of owning the most resource conserved product/component. It also proposed to initiate promotion in the society for the realization of resource conservation and to improve stakeholder's perception about resource conservative product.

The unique features of resource conservative manufacturing can be summarized as,

1. Extensive multidimensional (cost, energy, resource, environment and value added) lifecycle analysis of the product in combination with different EoL/EoU strategies (reuse, remanufacturing recycling and landfilling), number of lifecycles and their duration.
2. Design product for extended and multiple lifecycles including lifecycle monitoring and information storage devices.
3. Integrate forward and reverse manufacturing in a single enterprise.
4. Integration of different stakeholder as part of the business model.
5. Promotion for realization of resource conservation and improvement in stakeholders' social perception about the level of resource conservation.

It is equally important that the concepts and ideas are somehow validated for the acceptance of the scientific society. In this thesis, one of the key concepts i.e., resource conservative manufacturing ensures a well functioning closed loop supply chain, has been validated by a set of system dynamics models and simulations.

The research findings that are documented in this thesis are the results of active research started in 2009 with a set of evolving ideas originating even a few years earlier. With the progress of the research, the problem and gap with the state-of-the-art research became visible, and the idea became mature. At this point, those initial ideas became concrete and presented as set of concepts. The next step would be to implement these ideas in small or medium scale for validation. Of course, alternative approaches may become necessary during the implementation.

The author believes that every research work is important but the excellence comes across the implementation, and true benefits are achieved through successful implementation and complete use of the research findings.

4.2 Future research

The research presented in this thesis report contains a large body of knowledge, which requires further research. Based on these, future work to this research has been identified as follows.

- Develop a methodology for product's lifecycle analysis in the contexts of multiple lifecycles both in unforeseen temporal and spatial conditions.
- Develop a design methodology for product's multiple lifecycle.
- Identify ways to promote resource conservative manufacturing and construct a viable business model.
- Develop a platform to integrate all the above mentioned future research efforts
- Validate all hypothesizes through case studies.
- Develop an easy-to-use analysis method and standard for Small and Medium size Enterprises (SME:s)

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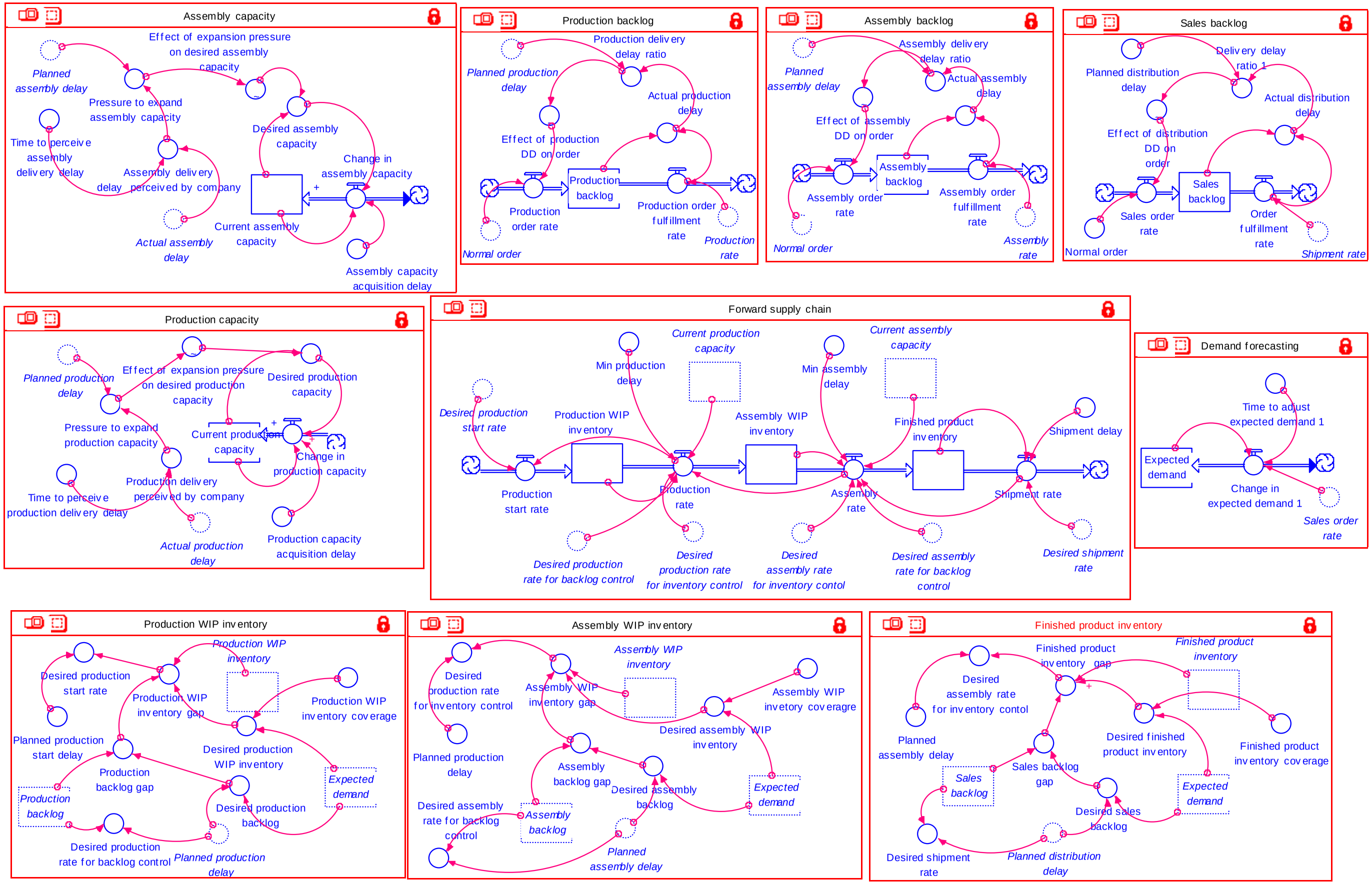
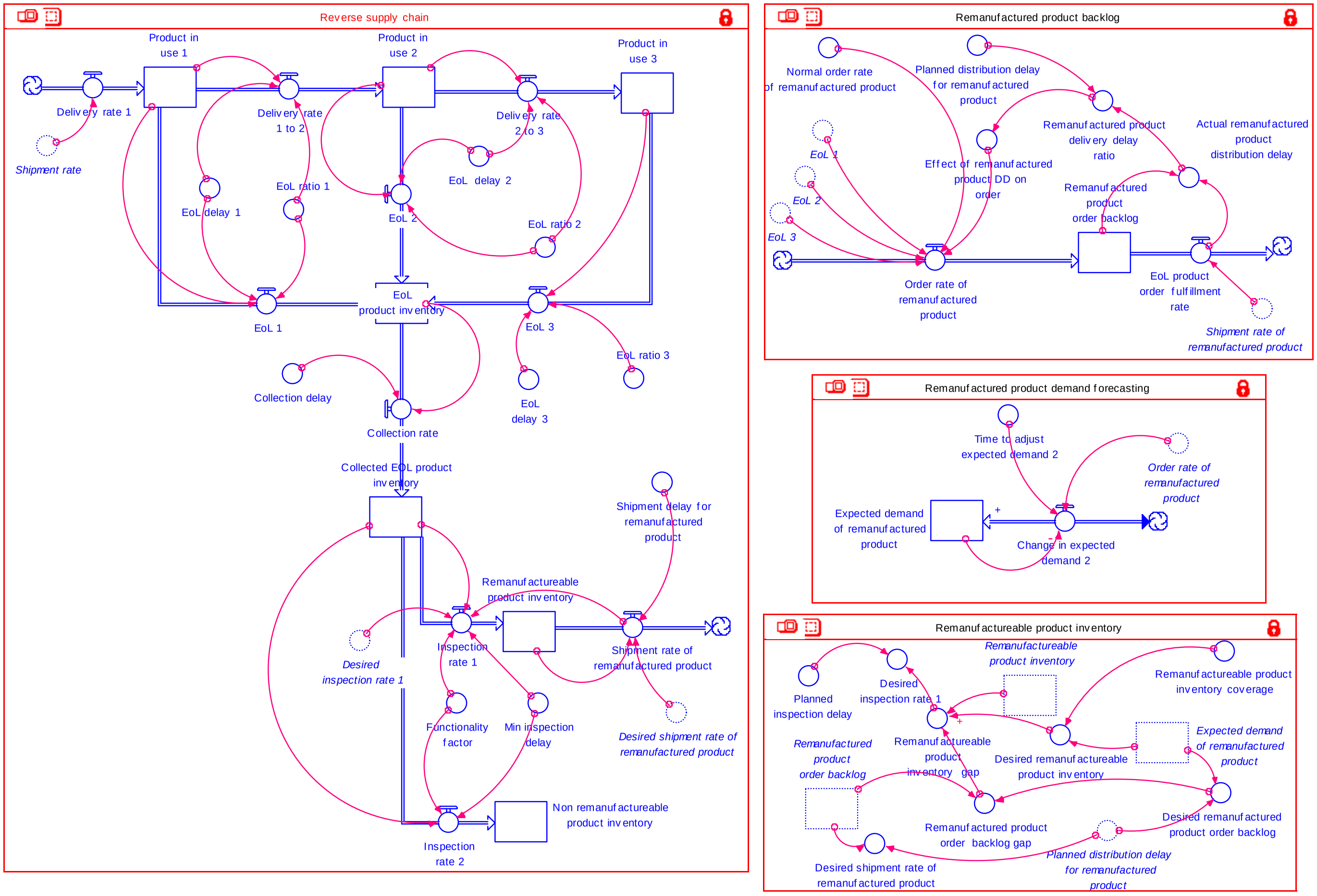
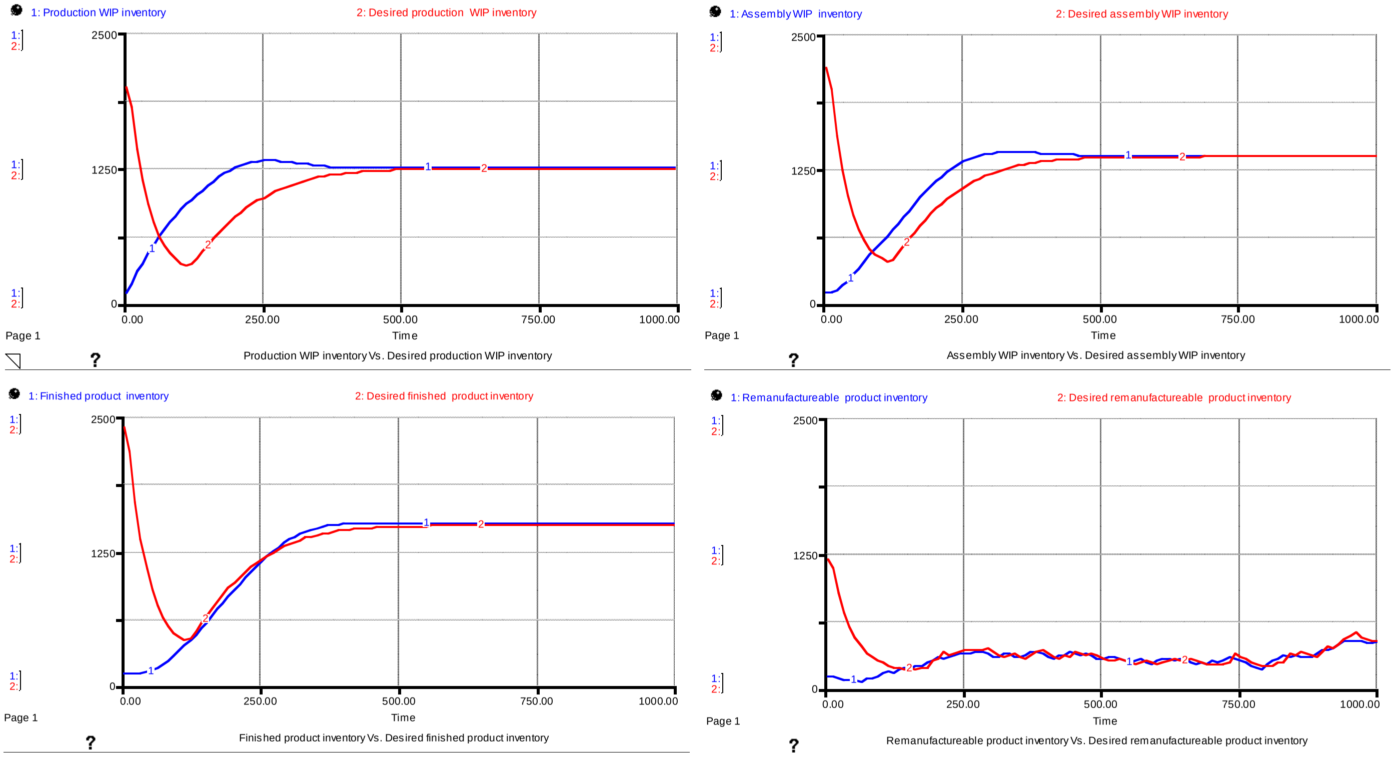
Appendix I- A - Stock and flow diagram of conventional forward and reverse supply chain with analysis of key performance indicators



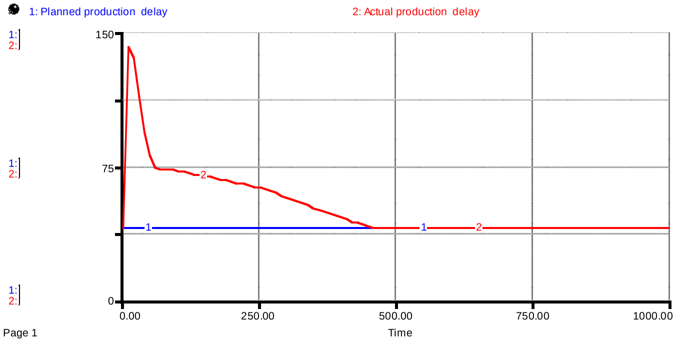
Forward supply chain



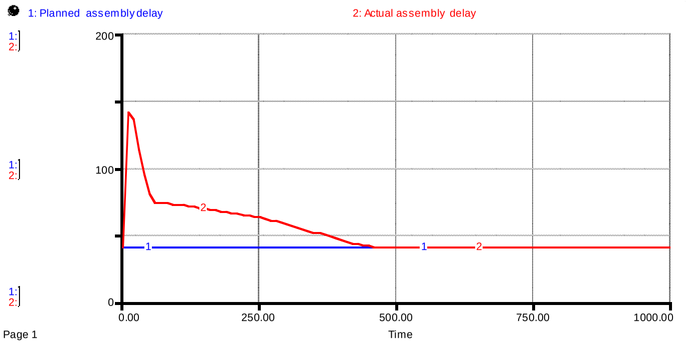
Reverse supply chain



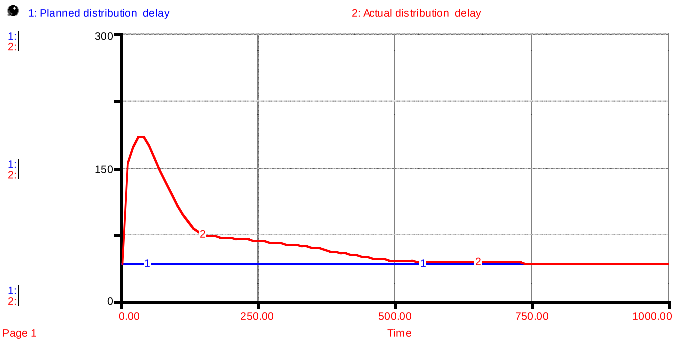
Performance analysis of conventional forward and reverse supply chain (inventory level)



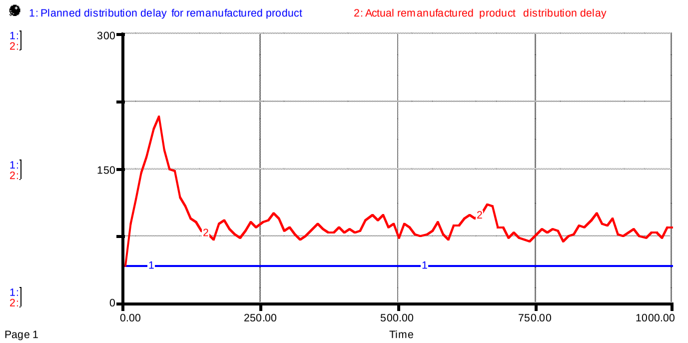
Actual production delay Vs. Planned production delay



Actual assembly delay Vs. Planned assembly delay

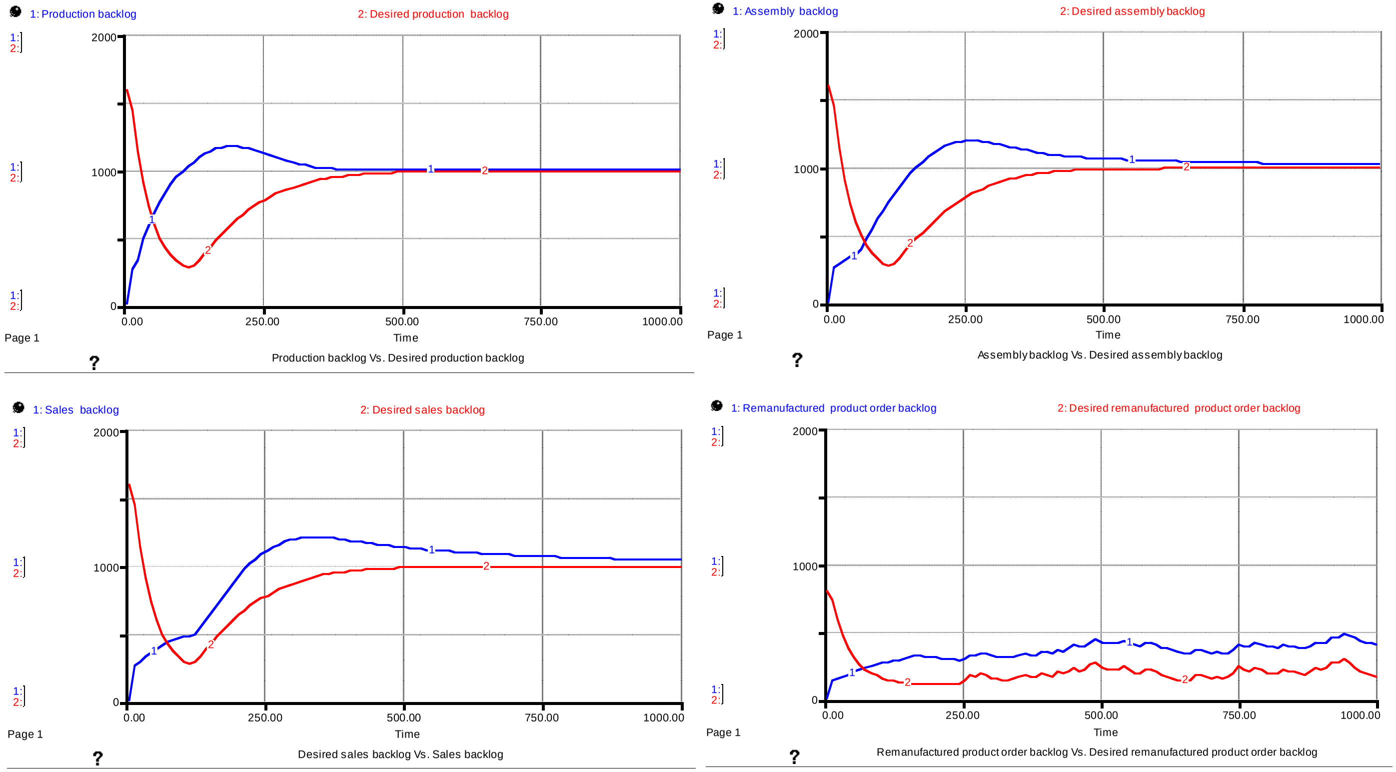


Actual distribution delay Vs. Planned distribution delay

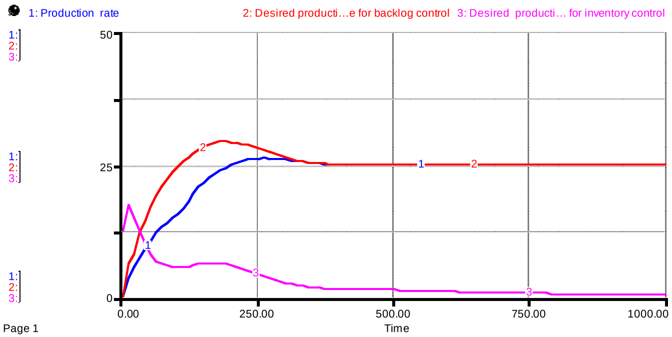


Actual EoL product distribution delay Vs. Planned EoL product distribution delay

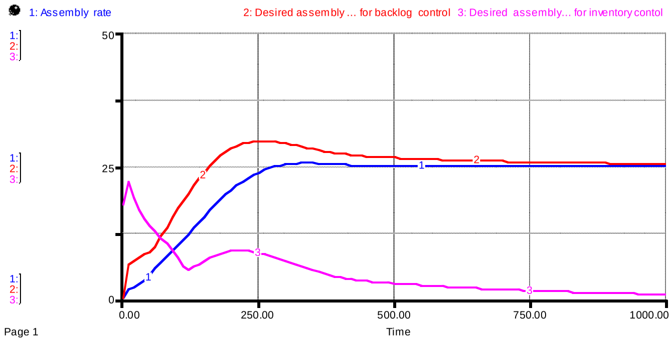
Performance analysis of conventional forward and reverse supply chain (delay)



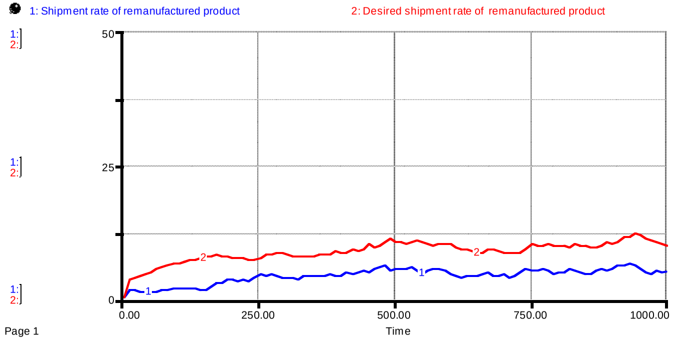
Performance analysis of conventional forward and reverse supply chain (backlog)



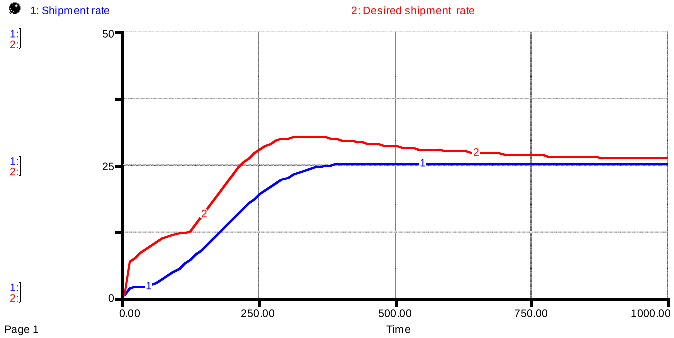
Production rate Vs. Desired production rate for backlog and inventory control



Assembly rate Vs. Desired assembly rate for backlog and inventory control



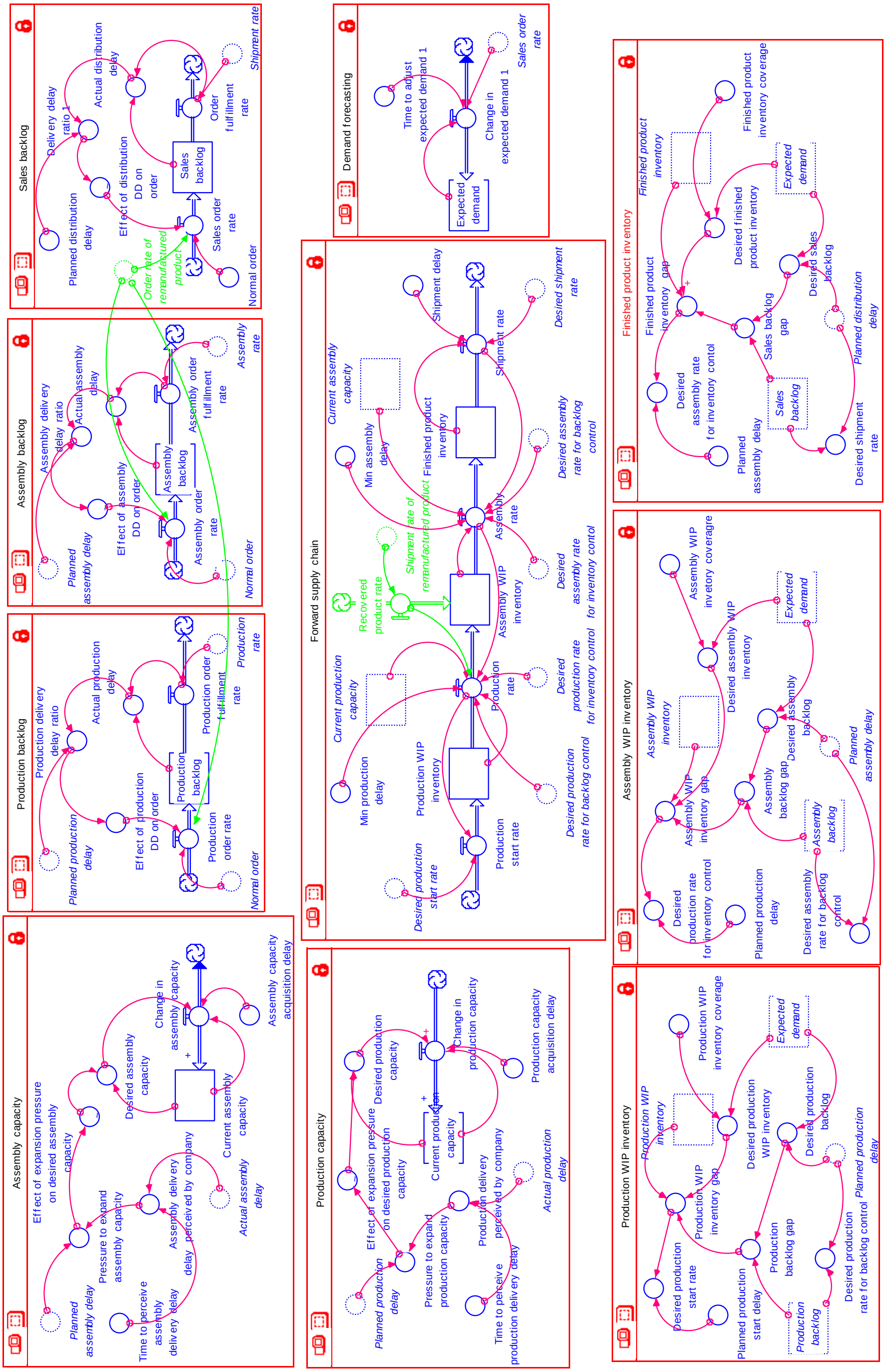
Shipment rate of remanufactured product Vs. Desired shipment rate of remanufactured product



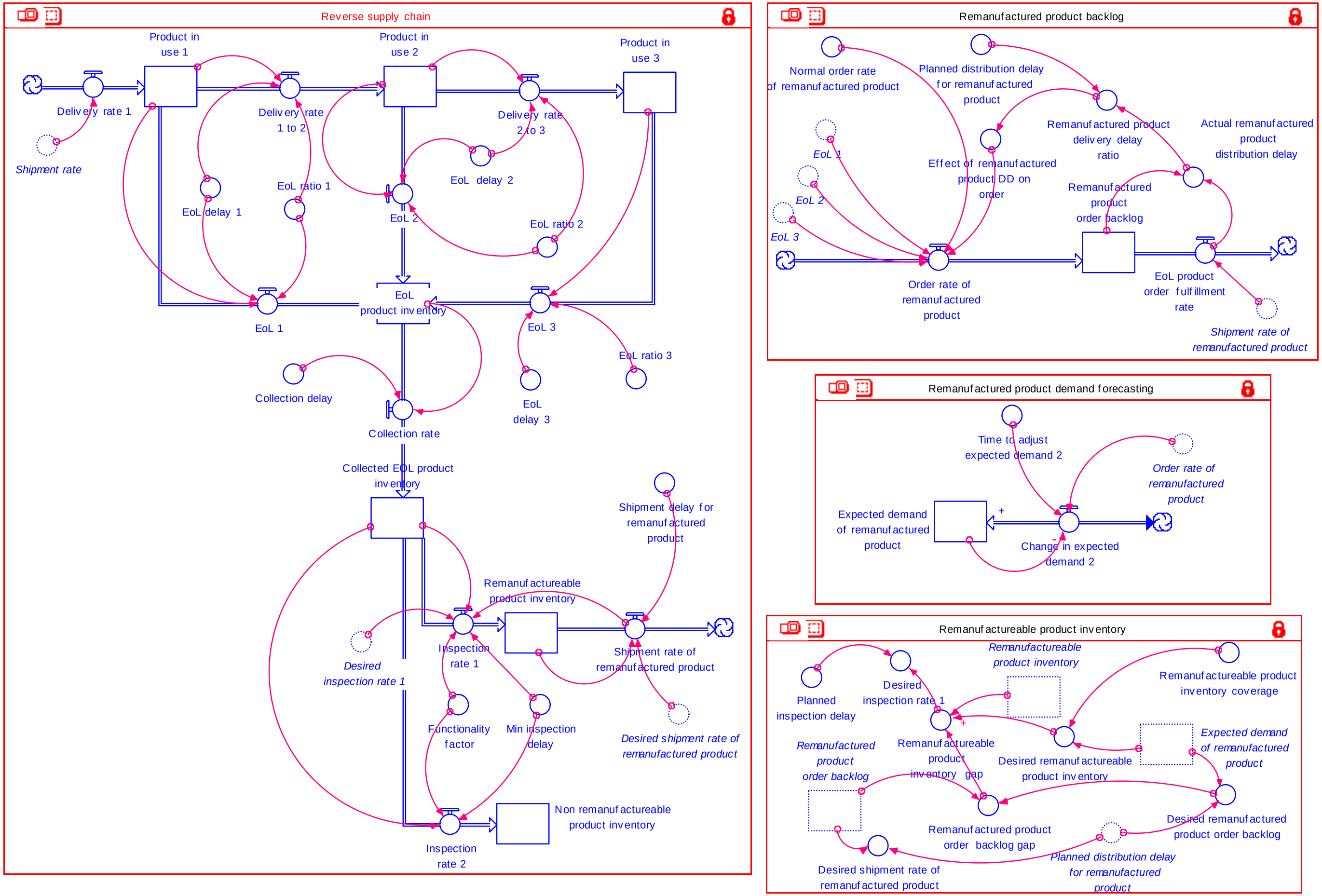
Shipment rate Vs. Desired shipment rate

Performance analysis of conventional forward and reverse supply chain (rate)

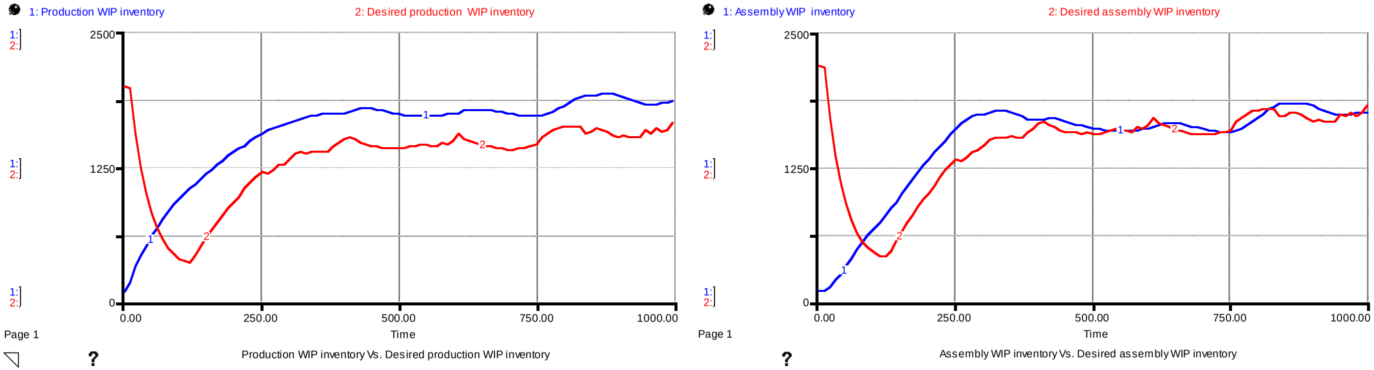
Appendix I- B -Stock and flow diagram of conventional closed loop supply chain with analysis of key performance indicators



Forward supply chain

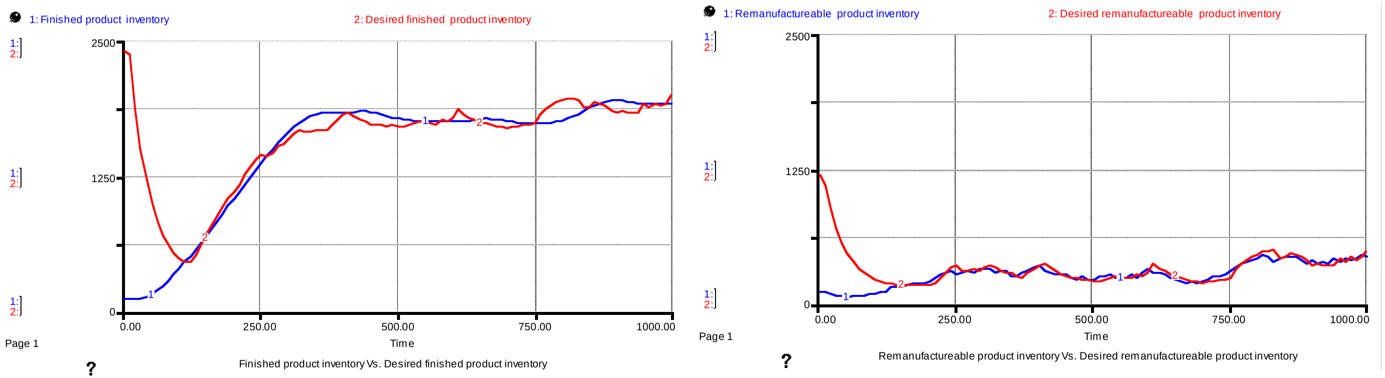


Reverse supply chain



Production WIP inventory Vs. Desired production WIP inventory

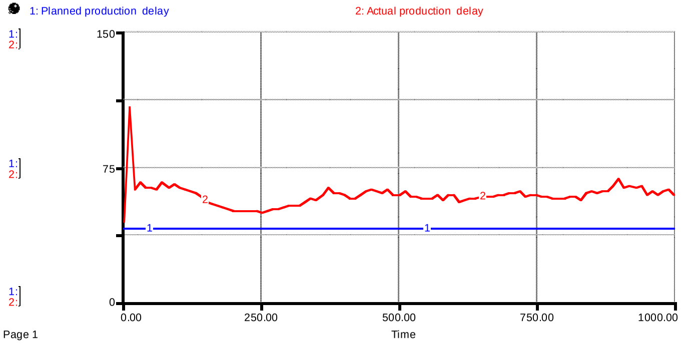
Assembly WIP inventory Vs. Desired assembly WIP inventory



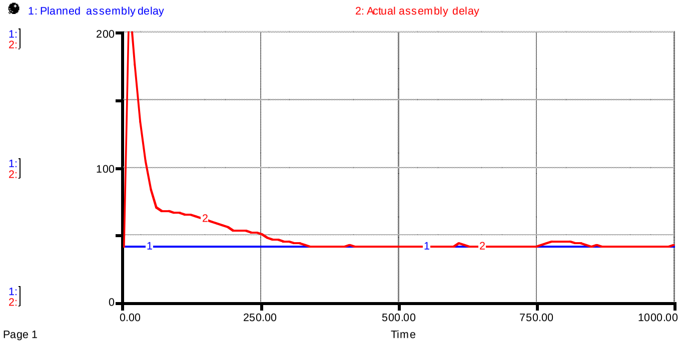
Finished product inventory Vs. Desired finished product inventory

Remanufactureable product inventory Vs. Desired remanufactureable product inventory

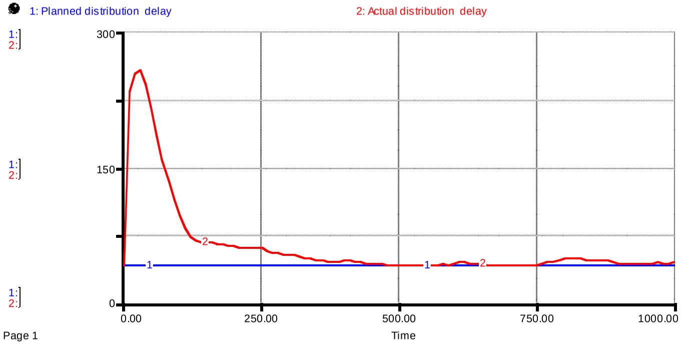
Performance analysis of conventional closed loop supply chain (inventory level)



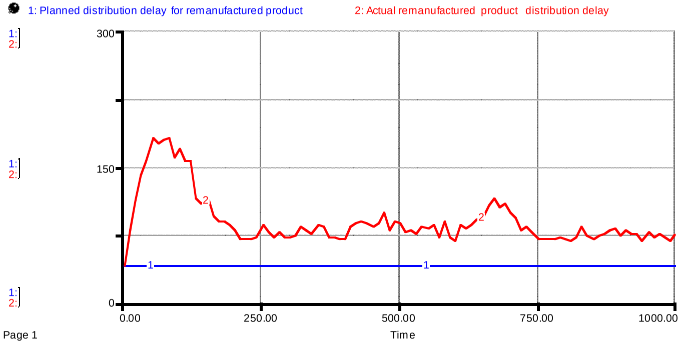
Actual production delay Vs. Planned production delay



Actual assembly delay Vs. Planned assembly delay

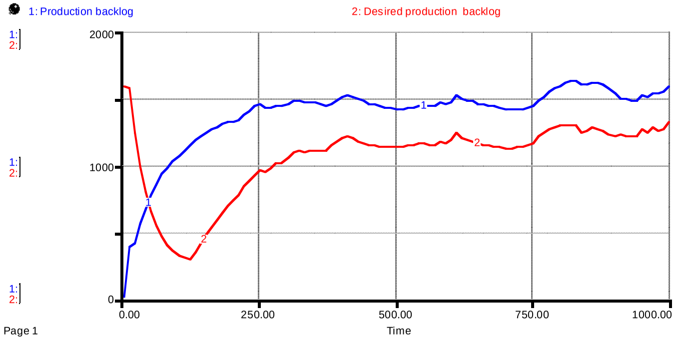


Actual distribution delay Vs. Planned distribution delay

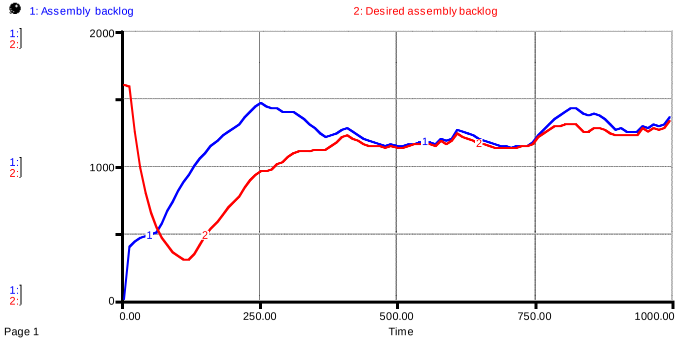


Actual EoL product distribution delay Vs. Planned EoL product distribution delay

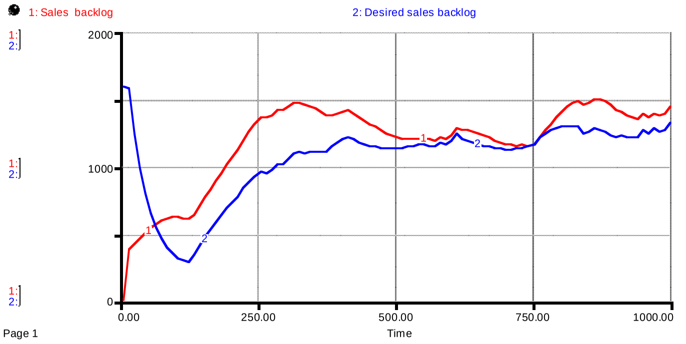
Performance analysis of conventional closed loop supply chain (delay)



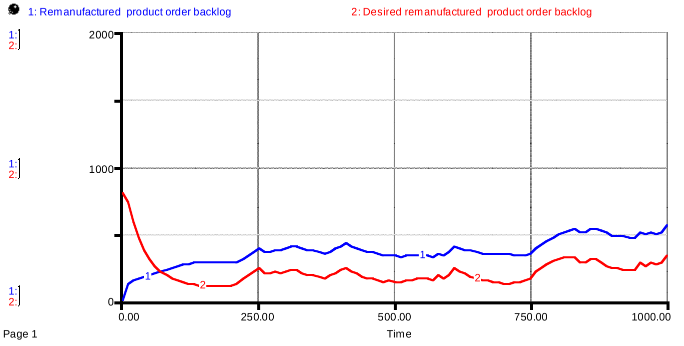
Production backlog Vs. Desired production backlog



Assembly backlog Vs. Desired assembly backlog

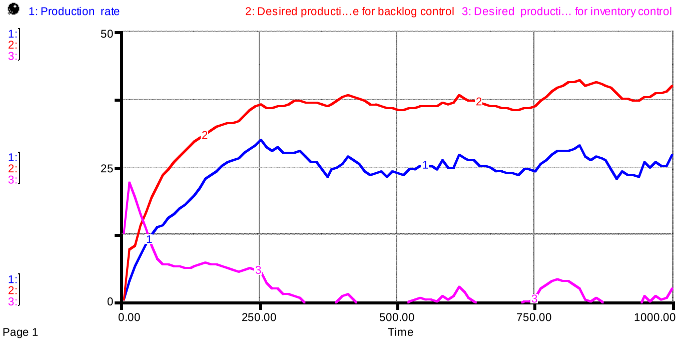


Desired sales backlog Vs. Sales backlog

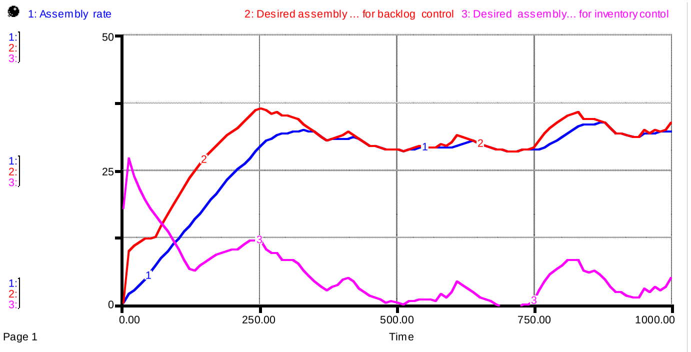


Remanufactured product order backlog Vs. Desired remanufactured product order backlog

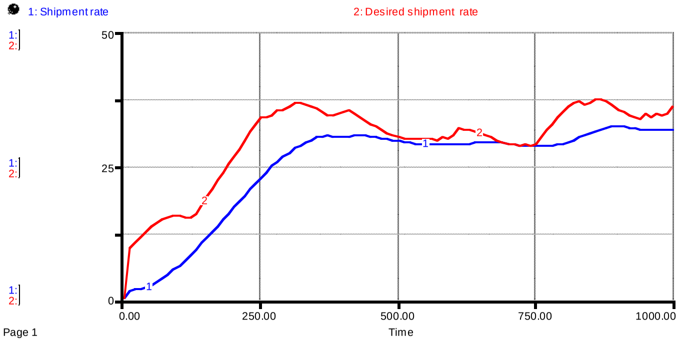
Performance analysis of conventional closed loop supply chain (backlog)



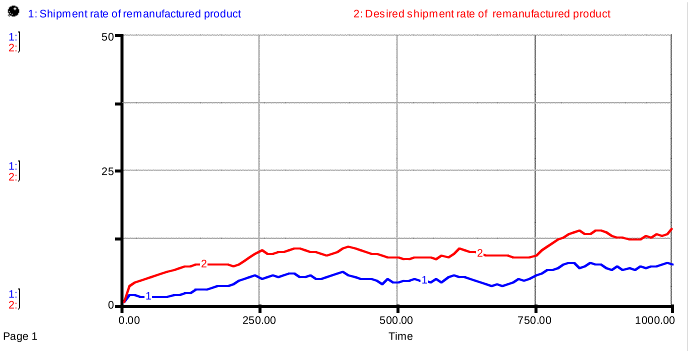
Production rate Vs. Desired production rate for backlog and inventory control



Assembly rate Vs. Desired assembly rate for backlog and inventory control



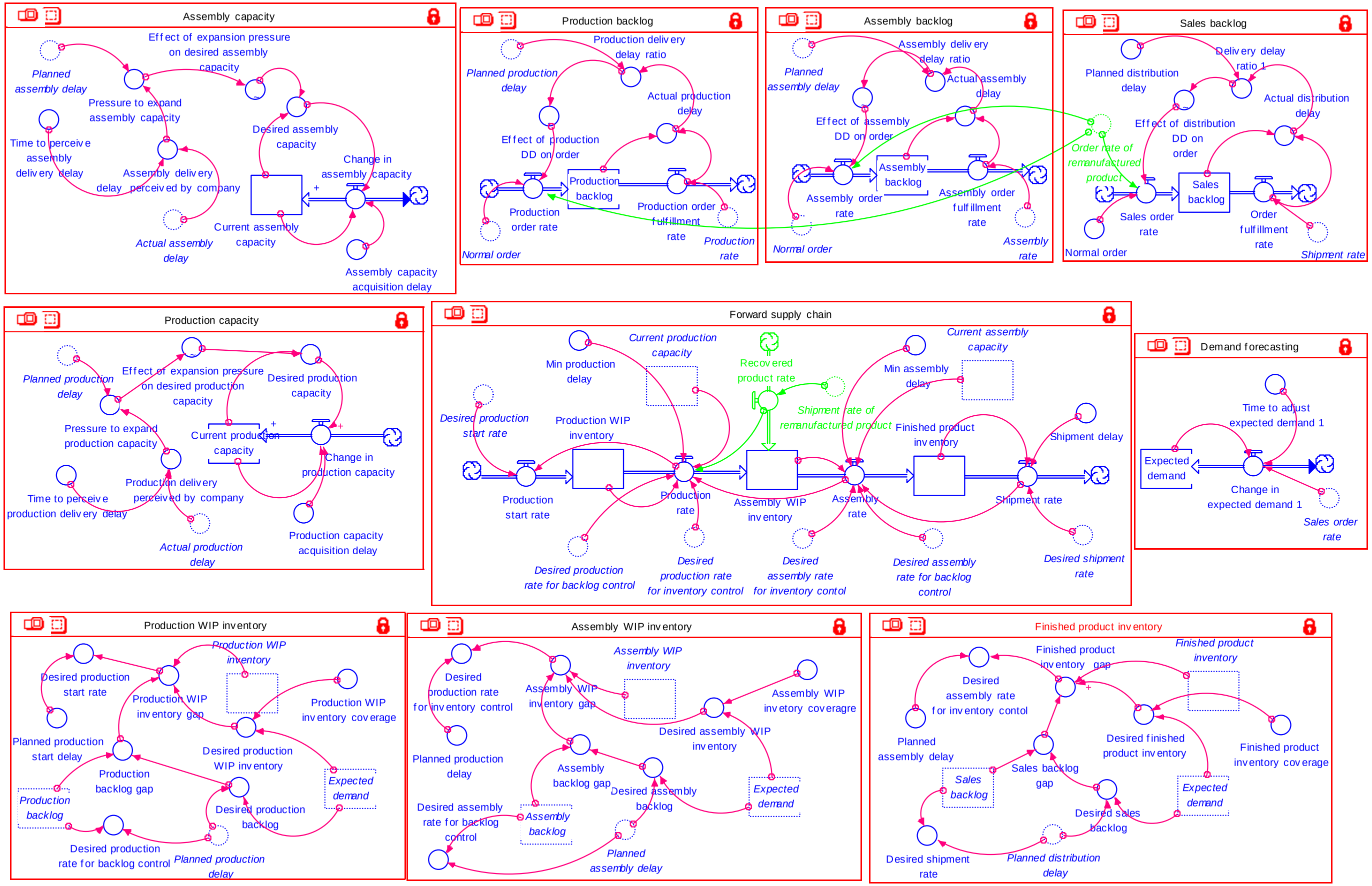
Shipment rate Vs. Desired shipment rate



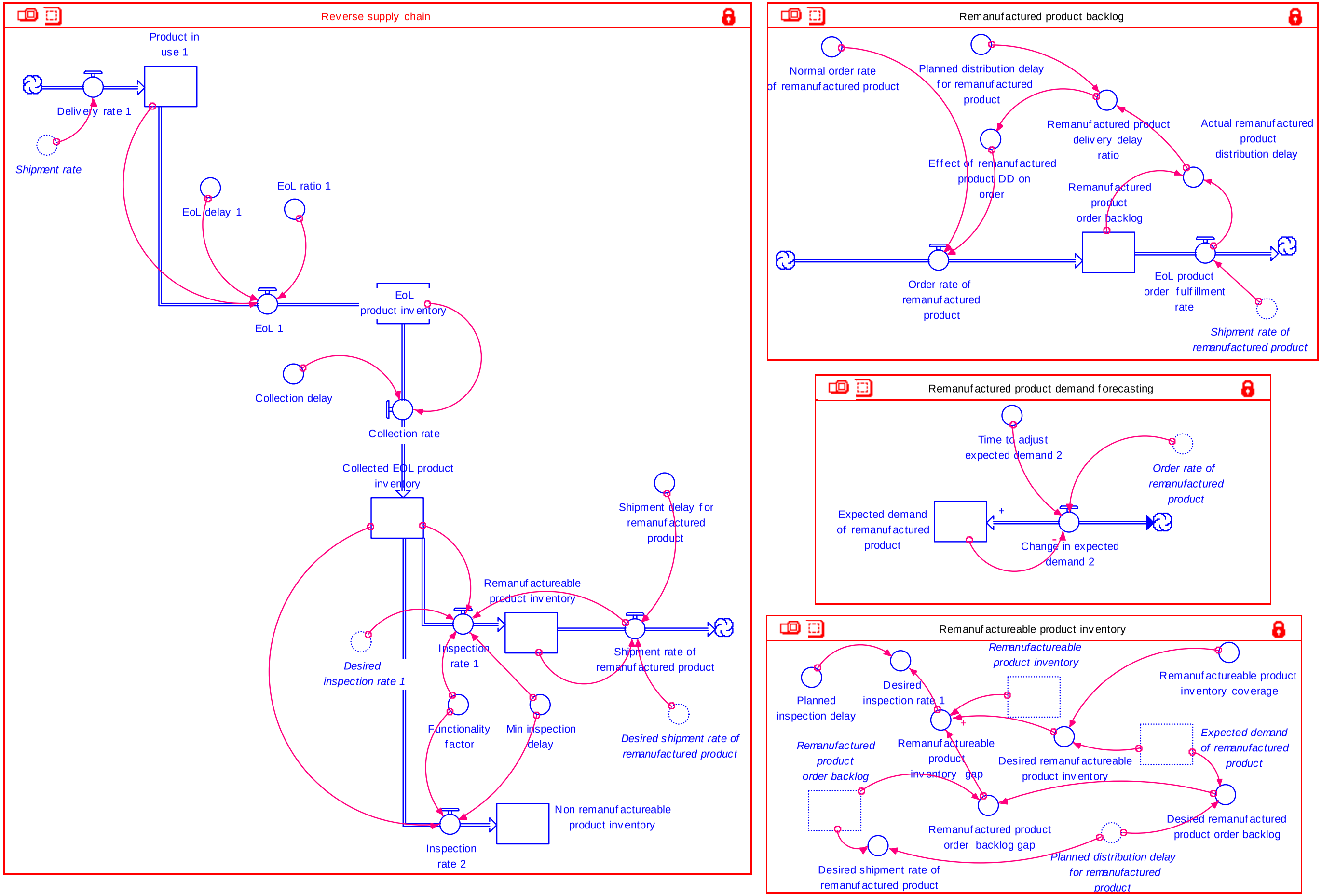
Shipment rate of remanufactured product Vs. Desired shipment rate of remanufactured product

Performance analysis of conventional closed loop supply chain (rate)

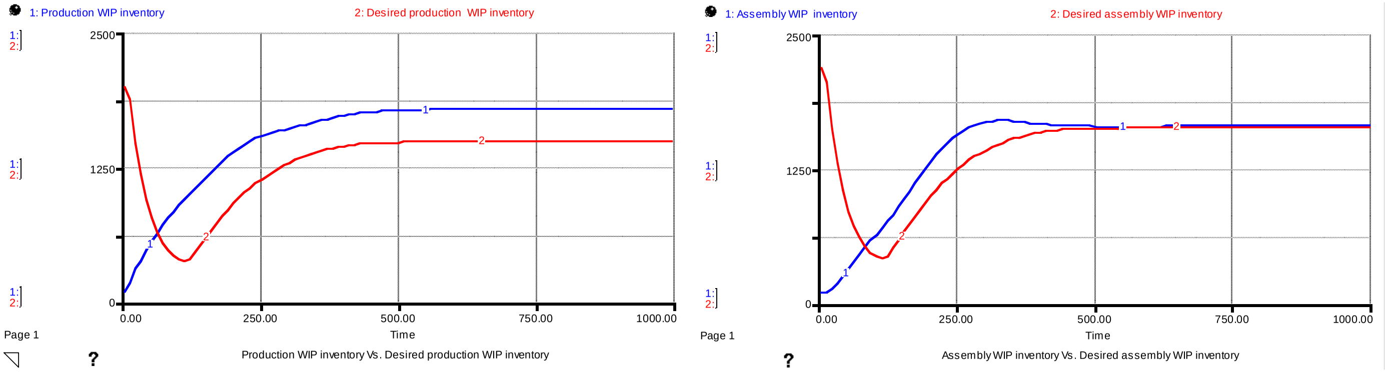
Appendix I- C –Stock and flow diagram of closed loop supply chain proposed by resource conservative manufacturing with analysis of key performance indicators



Forward supply chain

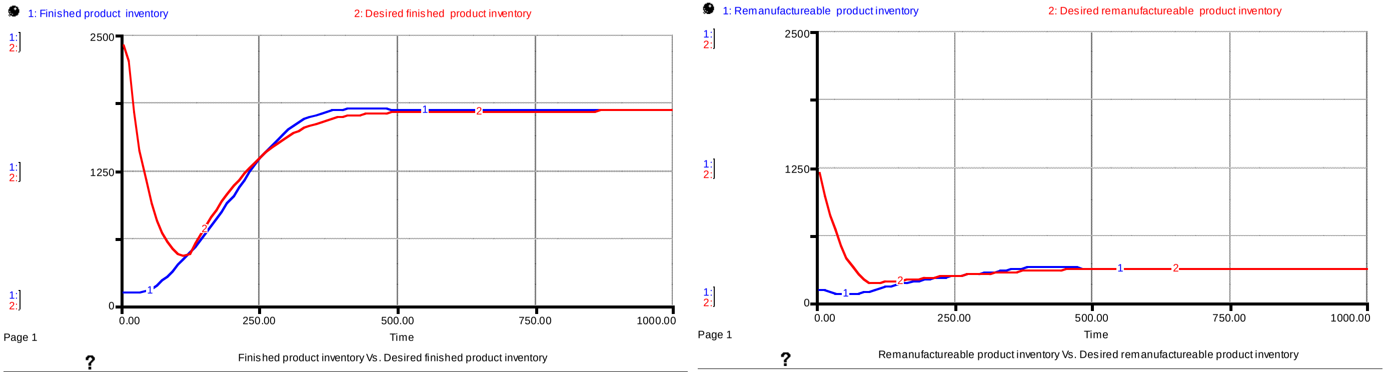


Reverse supply chain



Production WIP inventory Vs. Desired production WIP inventory

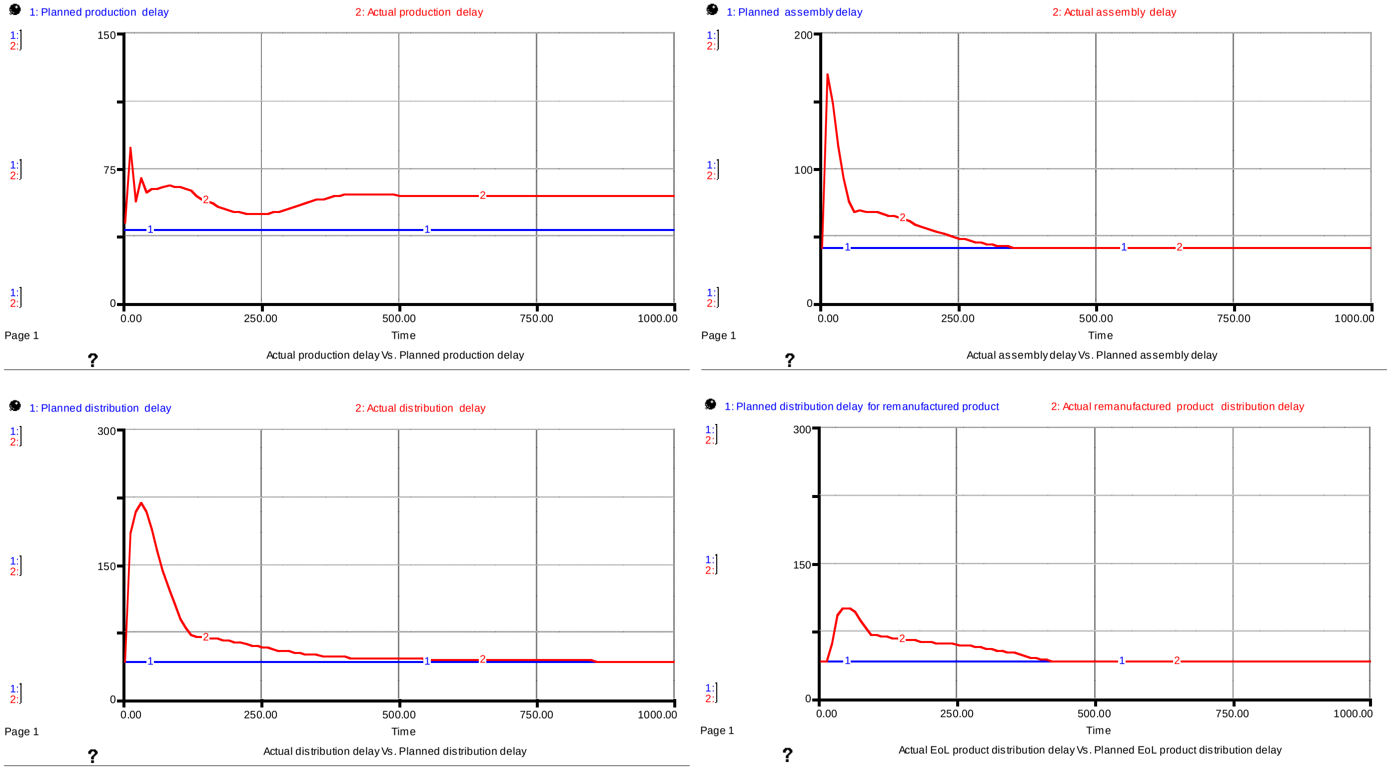
Assembly WIP inventory Vs. Desired assembly WIP inventory



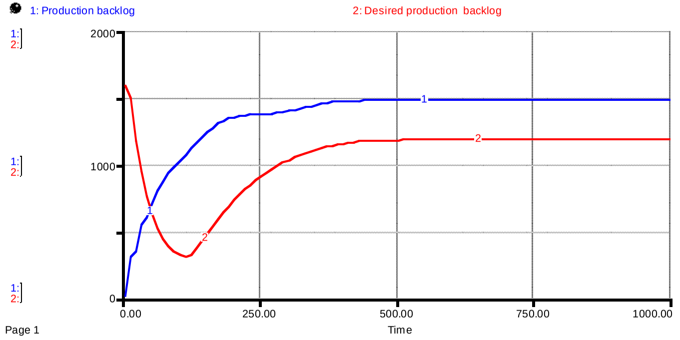
Finished product inventory Vs. Desired finished product inventory

Remanufactureable product inventory Vs. Desired remanufactureable product inventory

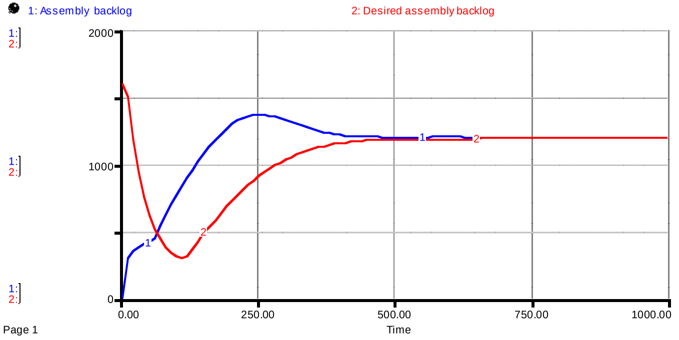
Performance analysis of closed loop supply chain proposed by resource conservative manufacturing (inventory level)



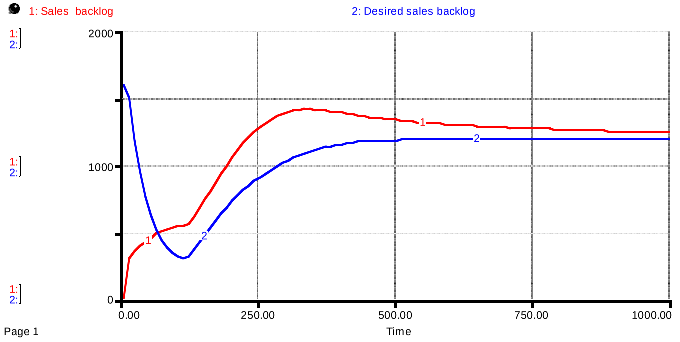
Performance analysis of closed loop supply chain proposed by resource conservative manufacturing (delay)



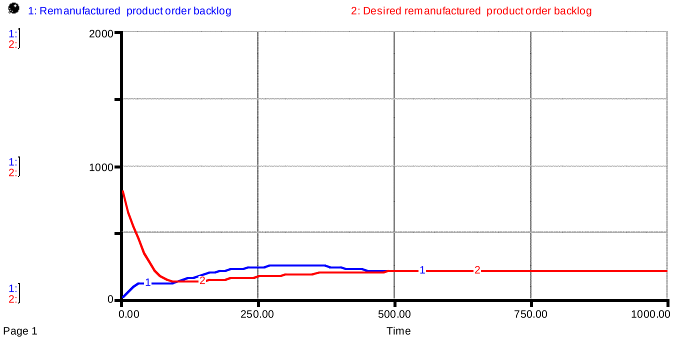
Production backlog Vs. Desired production backlog



Assembly backlog Vs. Desired assembly backlog

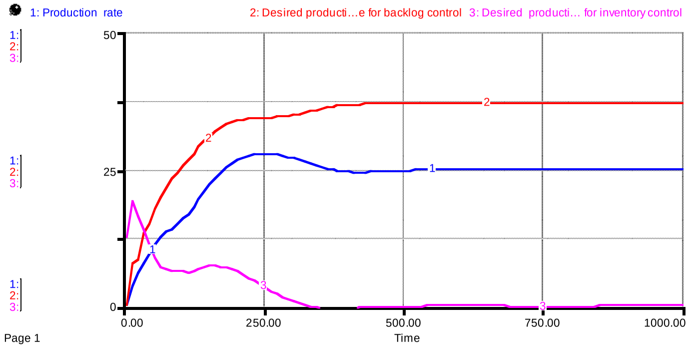


Desired sales backlog Vs. Sales backlog

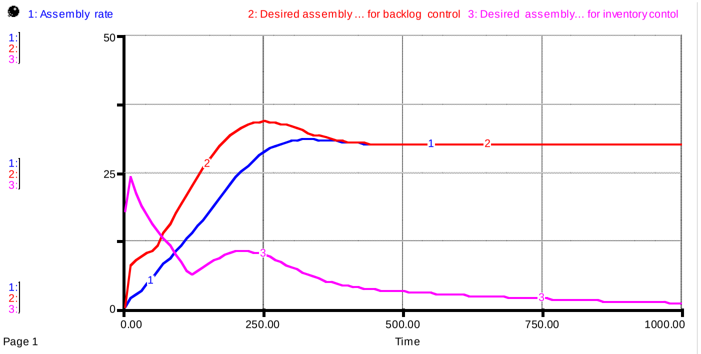


Remanufactured product order backlog Vs. Desired remanufactured product order backlog

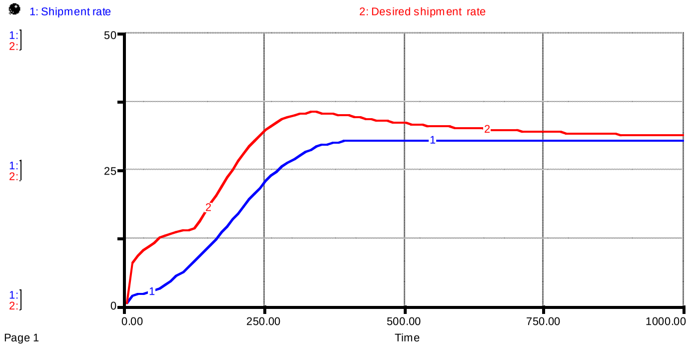
Performance analysis of closed loop supply chain proposed by resource conservative manufacturing (backlog)



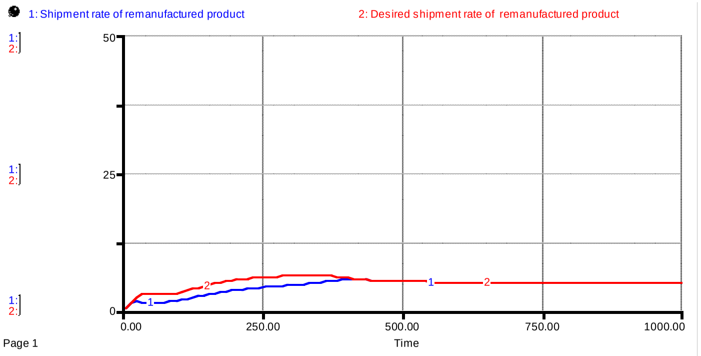
Production rate Vs. Desired production rate for backlog and inventory control



Assembly rate Vs. Desired assembly rate for backlog and inventory control



Shipment rate Vs. Desired shipment rate



Shipment rate of remanufactured product Vs. Desired shipment rate of remanufactured product

Performance analysis of closed loop supply chain proposed by resource conservative manufacturing (rate)

Appendix II-PAPER-A

A Novel Concept for End-of-life Vehicles (ELV). *Proceeding of the International 3rd Swedish Production Symposium*, *pp* 325-331, ISBN-978-91-633-6006-0, 2-3 December 2009, Göteborg, Sweden.

Appendix II-PAPER-B

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