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Changeable Manufacturing Systems Supporting Circular Supply Chains

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Abstract

Sustainability is gaining more attention as a result of climate change and depleting resources. In manufacturing industry one way of becoming more sustainable is by introducing circular supply chains, by taking back used products from the market and in various ways turning them into new products. This however presents a number of challenges since current practices and research on manufacturing system design have primarily been concerned with open loop supply chains, where new products are manufactured from virgin materials. This research investigates how different types of circular supply chains can be supported by the concepts from changeable manufacturing systems. This is done by analyzing how the end-of-life strategies repair, refurbish, and remanufacturing can be enabled by applying the different changeability levels flexibility, changeover ability, and reconfigurability. It is concluded that due to the changing volumes in new products, and returned, used products over time, reconfigurability seems promising, while changeover ability and flexibility will be able to address the variation in the state of incoming products from the market.

Keywords: changeable manufacturing; reconfigurable manufacturing; changeability; circular supply chains; sustainable manufacturing.

1. Introduction

Changeable and reconfigurable manufacturing systems have for almost 20 years been an important research topic that continues to increase attention in industry due to the attractiveness of being able to respond to changes rapidly and efficiently [1, 2]. In this regard, a changeable manufacturing system is defined as a manufacturing system that can accomplish early and foresighted adjustments of its structures and processes on all levels in an economically feasible way [3]. Multiple classes of changeability exist, e.g. changeoverability, flexibility, reconfigurability, transformability, and agility, which on different structuring levels and in different ways enables manufacturing changeability [3]. Changeability can for instance be accomplished through reconfigurability, where a modular system architecture, standard interfaces and platform principles enables the manufacturing system to be dynamically and efficiently reconfigured to provide capacity and functionality on demand [4].

When the concept of the Reconfigurable Manufacturing System (RMS) was introduced in the 90's by Koren [5] as an alternative to traditionally and widely used dedicated and flexible manufacturing systems, the primary goal was to enable both high productivity and variety, as well as mass customization and personalization [5, 6]. Likewise, research on changeable manufacturing has predominately focused on enabling efficient production of product variety and customization. However, manufacturing requirements has continuously evolved and now go far beyond requirements solely of low cost, high quality, high variety, and responsiveness, as manufacturing sustainability is becoming an ever increasing priority [1, 7] . Driven by consciousness about the deterioration of the global environment, pollution, and shortage of natural resources, sustainability has become a key concern in manufacturing, e.g. in terms of

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environmentally conscious manufacturing, green manufacturing, reverse manufacturing, circular manufacturing, de-manufacturing, and re-manufacturing [7, 8]. These recent trends and requirements of manufacturing sustainability increase the importance of manufacturing systems that are changeable and reconfigurable [8, 9]. For instance, capitalizing on recycling, reuse, de-manufacturing and re-manufacturing requires manufacturing systems that can match the dynamics of the product life-cycles and different end-to-life product strategies in a very changeable and unpredictable market and context [8]. This may involve even higher product variety, higher unpredictability in processing requirements, multiple product generations, higher variability of the post-use product conditions, and fluctuating capacity requirements [8]. Consequently, the need for new forms of changeable and reconfigurable manufacturing systems that can support sustainable and circular business models and supply chains are needed. However, this topic has only been addressed to limited extent in previous research. Nielsen and Brunoe [10] investigated the relations between different closed loop supply chain modes and the mechanism of mass customization, however only briefly touched upon the impact on the manufacturing system. Dubey et al. [11] investigated the link between reconfigurable manufacturing and environmental performance, focusing on the role of top management and organizational culture in the adoption of reconfigurability. Tolio et al [8] explored the requirements and challenges in de-manufacturing and re-manufacturing, emphasizing the need for various types of system and value chain reconfigurability. Garbie [12] addressed the design of sustainable manufacturing enterprises, and identified reconfigurability as an important component of the sustainable manufacturing emprise, as well as included reconfigurability in the proposed assessment procedure for determining the sustainability of an emprise. Huang et al. [13] examined sustainability performance of the reconfigurable manufacturing system, using different sustainability metrics and the reconfigurability characteristics. Bi [7] investigated the contribution of the reconfigurable manufacturing system to sustainability in terms of reducing waste through reuse of manufacturing resources and in term of reducing energy cost through optimization of processes and reconfigurability. He concludes that the reconfigurable manufacturing system should be further evolved to fully accommodate manufacturing sustainability. Thus, previous research largely acknowledges changeability and reconfigurability as means to achieving manufacturing sustainability, however, only to limited extent addresses how these types of systems can support requirement in circular and sustainable business models and supply chains, considering important system design decisions e.g. the classes and the extent of changeability. Therefore, this paper addresses the following research question:

which changeability classes can support circular supply chains in terms of different end-of-life product strategies?

The contribution of this paper is mainly to conceptualize the mechanisms of changeable manufacturing on different levels that could potentially contribute to implementing circular economy. A conceptualization of these relations provides a staring point for future research, supporting e.g. experiments and case studies into this topic.

The remainder of the paper is structured as follows: Section 2 describes the methodology for addressing the research question, while Section 3 presents the different end-of-life strategies addressed in the research. Section 4 present three different scenarios of how changeability classes, i.e. changeability on different manufacturing system levels, can support the end-of-life product strategies. Finally, the scenarios are discussed in Section 6, including directions for further research.

2. Methodology

Based on literature, a number of different end-of-life strategies are outlined. These are consolidated into three different scenarios, which are deemed the most relevant in relation to changeable manufacturing, since the remaining strategies involve only recycling, where the materials can usually substitute virgin materials, and as such does not affect the manufacturing systems for products.

For each of these three scenarios, generic process chains are described, in order to determine the overall structure of the manufacturing systems. Furthermore, generic demand profiles are outlined for the three scenarios. Based on this, it is analyzed what the requirements in terms of changeability are for each of the scenarios. This is framed by the changeability classes outlined by Wiendahl et al [14] adapted by Brunoe et al. [15]:

- Changeoverability: The manufacturing systems' ability on process and cell level to changeover and instantly manufacture different variants.
- Flexibility: The manufacturing systems' ability to manufacture different products by reprogramming or rerouting products.
- Reconfigurability: The manufacturing systems' ability to accommodate new product variety, similar to but different from what is currently manufactured, by adding, removing or changing modules in the system
- Transformability and agility: The manufacturing system's ability to change significantly from producing one product type to an entirely different product type.

In this research we have only evaluated the lower levels, i.e. changeover ability, flexibility and reconfigurability, since transformability and agility, implies entirely new products, and is more concerned with factory level and manufacturing network levels, which is incompatible with the End of life strategies in question.

3. End-of-life Strategies

In closed loop supply chains, when a product reaches its end of useful life, the value of the product is in various ways reclaimed, by e.g. reusing the product itself or recycling the materials. Inspired by the “Ricoh Comet” introduced by the Japanese company Ricoh [16], the different end-of-life strategies are illustrated in Fig. 1. An open loop supply chain implies that after a product is discarded, it is not transformed into something that can be utilized for manufacturing new products, but rather incinerated or dumped in a landfill. In a closed loop supply chain, less virgin material is needed for manufacturing products, and the energy required for extracting materials, and processing those is saved, typically leading to significantly lower environmental impacts. Generally speaking, the shorter loops, the greater environmental benefits, since more value is sustained in the products, and less energy an material is needed for manufacturing new components and products.

In many cases, companies who attempt to create more environmentally sustainable products, will seek to “close the material loop”, thus establishing closed loop supply chains. This can be done various ways, using different strategies. Outlined below based on Rose [16]:

1. Reuse: After a product ends its life with one customers, if it is still functional it is reused by another user directly without involvement by the manufacturer.
2. Service / repair: After a product ends its life due to defect, it is repaired either by the vendor or a third party. This will usually require spare parts
3. Refurbish: After a product is ends it’s life either due to a user no longer needs the product or defect, it is returned to the vendor, manufacturer or 3rd party, which systematically processes the product by restoring it to near new condition, possibly using spare parts. The product itself however is the same.
4. Remanufacturing: After a product is ends it’s life either due to a user no longer needs the product or defect, it is returned to the manufacturer. Here it is demanufactured, i.e. disassembled, and the useful components are reclaimed and stocked and defect components are recycled. The reclaimed components are then used in combination with virgin components for assembling products, possibly in new configurations, according to customer demand.
5. Recycling: Products are disassembled or shredded for recycling the materials for manufacturing new components. Typically handled by a 3rd party.
6. Incineration or landfilling: These are open loop supply chains as the materials in the products are lost and energy will need to be spent on extracting new materials for new products.

The reuse strategy is said to have the “shortest loop”, i.e. least energy consuming activities happen after the product ends it use until a new user uses it. In terms of environmental impact, this is usually the most desirable option, and incineration or landfilling have the most negative impact and are the least desirable. In the strategies above, they go from shorter loops to longer loops, ending with open loops.

As this research focuses on manufacturing systems, we will disregard the first EOL strategy, since this does not at all involve the manufacturer. Furthermore, we will disregard recycling, incineration and landfilling, since theses EOL strategies also do not involve the manufacturer. This leaves the three strategies Service/repair, refurbish, and remanufacturing. Service/repair and refurbish are combined into one scenario for simplicity, as they would be similar in structure and demand profiles. Hence, we will address two closed loop scenarios, one for repair & Refurbish, one for remanufacturing and finally an “as-is” scenario representing a manufacturing system, not yet having an operational closed material loop. In the following section, the generic structure and production volume profiles are presented for each scenario.

4. Description of Scenarios

4.1 Scenario A – No EOL strategy / open loop supply chain

This scenario represents the traditional setup in most manufacturing companies; product are produced using virgin components, and products are not repaired or refurbished, and there is thus no circular system in place. The structure of the internal value chain is illustrated in Fig 1.A. one, or more likely, several processes manufacture new (virgin) components, which are supplied to an assembly process, supplying new products to the market. Figure 2.A illustrates a generic profile of a production volume as a function of time, consisting of a market introduction, growth, maturity, decline, and phase-out.

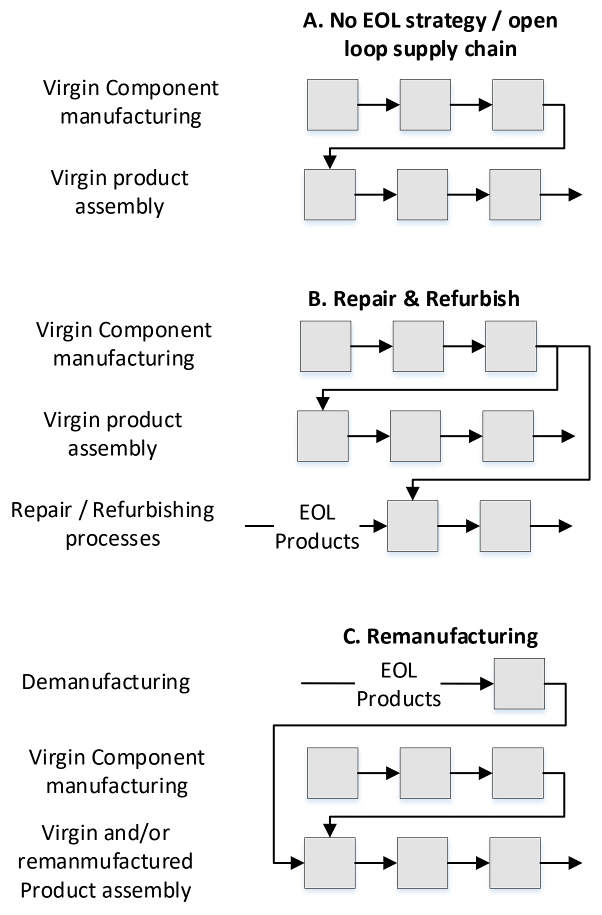

Fig. 1. Manufacturing system structures for diffent EOL scenarios.

4.2 Scenario B – Repair and Refurbish

This scenario represents a company which introduces repairs and refurbishing as a means to establish closed loop supply chains. As illustrated in figure 1.B., compared to scenario A, this will require an additional type of processes, i.e. the repair and refurbishing processes. The assembly of new products and manufacturing of virgin components are similar to scenario A, except, the manufacturing processes for components will also feed the repair and refurbishing processes. As illustrated in figure 2.B., the production volume is different compared to that of scenario A. This is due to two factors: 1) as the total demand for the product is assumed the same, refurbished products substitute virgin products, and the production volume of virgin products wear off earlier. 2) A new demand for replacement components needs to be met from the time where the first products are taken back from the market, implying that certain types of components may need to be manufactured in a larger scale than previously, as it would be expected that some components are more likely to need replacement than others. This implies that over time, the mix of components being manufactured will change, from initially reflecting the mix of components that go into a new product, to eventually reflecting the mix of components needing replacement when repairing or refurbishing.

4.3 Scenario C - Remanufacturing

This scenario represents a company that takes back their own products, disassemble them and use the reclaimed components to manufacture new products, possibly unlike old products, as they may be assembled in new configurations or in combination with newly introduced component types. This also involves new processes compared to scenario A as illustrated in figure 1.C. A takeback process must be introduced which disassembles the old products, evaluates the state of each component, and based on that either discards the component to recycling, or placing it in stock ready to be used for assembling a new product, possibly involving reconditioning the components if necessary. Figure 2.C illustrates the production volume profile of this scenario. As with scenario B, we assume that remanufactured products substitute virgin products. For this reason, once the first products are taken back and remanufactured, the production of virgin products wears off. Once this happens, remanufactured products are assembled. However as it must be expected that there are differences in the wear of different component types, some components are more likely to be reconditioned, reclaimed components, while other are more likely to be virgin components, even in remanufactured products, if the wear more quickly. Hence, just like in scenario B, the component mix will change over time, reflecting a transition from products based on virgin components to remanufactured products.

Although remanufacturing may at first seem unattractive to companies, while it is a greater loop and thus requires more energy, and also requires a more complex setup internally, it does provide other opportunities for companies. If the products in question are manufactured in high variety, it is somewhat unlikely that a customer would want exactly the same configuration as a customer did when the product was previously sold. When products are remanufactured, the can be assembled in new configurations. Furthermore, products can be upgraded, so that reclaimed components can be included in the assembly process in combination with newly developed virgin components, for new generations of the product.

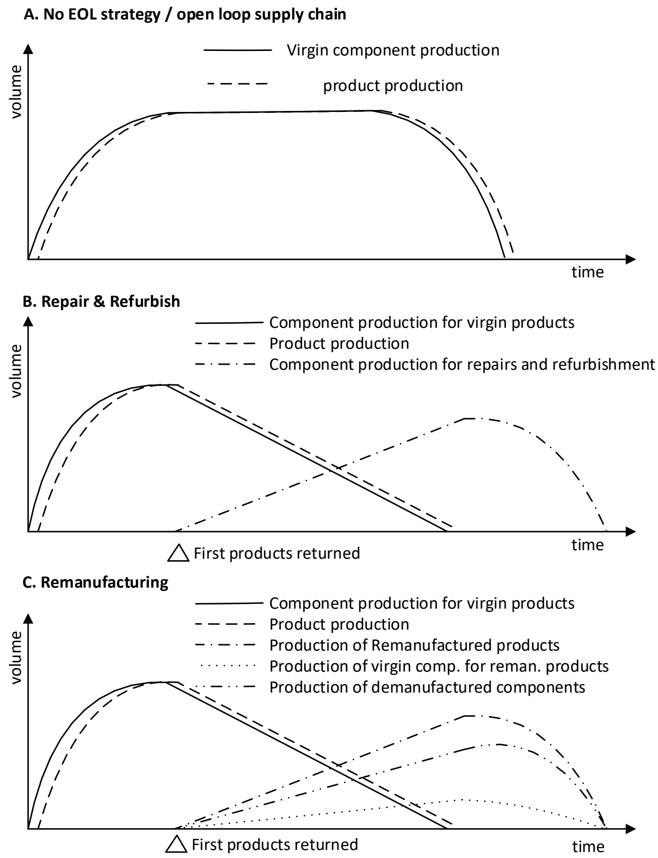

Fig. 2. Production volume profiles for different EOL scenarios.

5. Results of Evaluation of Changeability in Scenarios.

In this section, we evaluate which classes of changeability may be relevant when implementing different End-of-lige strategies formulated in three different scenarios.

5.1 Scenario A – No EOL strategy / open loop supply chain

This is the typical scenario that most companies that do not have an end-of-life strategy for their products in place would have. Assuming that the products manufactured have some degree of variety, changeover ability and flexibility will be required in order to manufacture varieties of components efficiently. Also, reconfigurability may be relevant in order to scale manufacturing capacity during growth and decline, to have sufficient but not excess capacity.

5.2 Scenario B – Repair and Refurbish

The requirements presented for changeability in scenario A, in terms of changeover ability and flexibility accommodating product variety is equally relevant in scenario B, as we assume the same products are manufactured. However in terms of reconfigurability accommodating scaling the manufacturing capacity, this is equally relevant during growth, however as the decline in demand for virgin products incurs earlier, due to substitution by repaired and refurbished products, scalability may be even more relevant, as the manufacturing system will be operating a maximum capacity for a shorter period of time.

If a company aims at utilizing repairs for extending product lifetimes, certain components with shorter lifetime will over time be in higher demand than those with longer lifetimes. This means that over time, the demand profiles for different components will change, where the most durable components may at some point not need to be manufactured at all, while other will be in steady demand throughout the lifespan of the manufacturing system. This implies a need for scalability in the virgin component manufacturing processes, which can be implemented through reconfigurability. This will also be true for refurbishing.

If a company goes for refurbishing, where products are taken back and systematically reconditioned to a near-new state, additional processes are required. First, an inspection process must determine the fate of a reclaimed product. Some products may be damaged to a degree where it is infeasible to restore it to a near-new condition. The following processes, actually refurbishing the product, must have a high degree of both changeover ability and flexibility. This is due to the fact that different products are likely to contain different component types, and therefore different operations are needed to either recondition or replace the components, implying the need for changeover ability. Futhermore, the different states that products must be expected to be in require different sequences of processes implying the need for flexibility by rerouting.

Additionally, companies are unlikely to be in full control of the quantities of products being taken back, which means that there is likely a volatile supply of EOL products, and as a consequence a volatile production of refurbished products, requiring scalability by reconfigurability. This further induces volatility on the demand for virgin components, stressing the requirements for scalability.

5.3 Scenario C - Remanufacturing

As with scenarios A and B, changeover ability and flexibility will accommodate product variety when manufacturing virgin products. Also, reconfigurability can provide scalability, which as in scenario B is even more relevant, as remanufactured products substituting virgin products shortens the period where maximum capacity is utilized. As with scenario B, at some point the mix in virgin component production will change, as fewer virgin products are assembled, and more products are remanufactured from a mix of virgin components and reclaimed components. This requires scalability, which may be implemented through reconfigurability.

As EOL products are taken back from the market, demanufacturing takes place, where products are disassembled and parts are inspected and possibly reconditioned. It must be expected that EOL products are in very different shape, depending on their age and usage. Also, if reclaimed products have some degree of product variety, the sequence of operations involved in demanufacturing will likely differ, and thus, changeover ability and flexibility are both relevant to accommodate the differences in processes.

Unlike scenarios A and B, this scenarios needs changeability in relation to the assembly process as well. Initially, the manufacturing system will need only to assemble virgin products, but once products are reclaimed, the manufacturing system will need to assemble products from a combination of virgin components and reclaimed components. A company may choose different options for structuring their systems to perform both assembly of virgin products and remanufactured products. Although the operations involved with assembling a virgin product and a remanufactured product should ideally be identical, the specific operations may be slightly different, as characteristics of reconditioned components may be different from virgin components due to wear and tear and due to possible generation updates of components. In some cases, the operations may be 100% identical, in which case there is not any major challenge, however if this is not the case, it may be practical to either have separate assembly systems for assembly of virgin products and assembly of remanufactured products. In this case scalability, and thus reconfigurability is important, as higher capacity would be needed early in virgin product assembly, but more capacity is needed for remanufactured product assembly later on. If the demand does not justify two separate assembly lines, and one line would need to handle both virgin products and remanufactured products, changeover ability and/or flexibility could be necessary to accommodate both products at the same time, or reconfigurability, to accommodate conversions from assembling virgin products in one period, and remanufactured products the following period.

6. Discussion & Conclusion

Circular economy and closed loop supply chains is broadly considered a significant means to achieve more environmentally sustainable industrial manufacturing and products. In most industrialized countries, systems are in place for recycling materials once products reach their end-of-life and are disposed of. This is obviously preferable over incineration or landfilling, however shorter loops, such as remanufacturing or are often even more favorable from an environmental perspective. Few companies traditionally not working with closing the materials loop, which are taking steps towards this often face challenges in doing this on an operational level, since their manufacturing systems are not prepared for this. This paper presents an analysis of the challenges in terms of required changeability for different scenarios representing different material loops. Although closing the material loops directly back to the manufacturer introduces challenges in the manufacturing systems, this paper also concludes that some of the mechanisms of changeable manufacturing such as changeover ability, flexibility and reconfigurability can be introduced to address some of these challenges. Hence this paper contributes with theories on how changeable manufacturing and circular economy are interlinked, and how one can support another.

The research presented in this paper is based purely on previous literature and the authors' analysis of three generic scenarios, and the mechanisms are thus not validated empirically. Future research should focus on elaborating the mechanisms described as well as reporting empirical evidence.

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