Changeable Closed-Loop Manufacturing Systems: A Case Study of Challenges in Product Take-Back

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Markus Thomas Bockholt[a], Ann-Louise Andersen[*a], Thomas Ditlev Brunoe[a], Jesper Hemdrup Kristensen[a], Michele Colli[a], Peter Meulengracht Jensen[b], Brian Vejrum Wæhrens[a]

[a]Department of Materials and Production, Aalborg University, Aalborg, Denmark
[b]Group Environment CoE, Group EHS, GRUNDFOS Holding A/S, Bjerringbro, Denmark
ala@mp.aau.dk

Abstract: Product take-back programs are becoming increasingly popular and widespread driven by continuous focus on sustainability and circular economy. As a result, manufacturing systems need to be designed to handle not only disassembly, but also reprocessing of materials, re-assembly, and remanufacturing in a cost-efficient way. Compared to traditional manufacturing, this involves higher need for changeability due to higher uncertainty e.g. in terms of timing, quantity, and quality of received items to handle, and in particular due to significant variety in returned items. Therefore, the aim of this paper is to provide empirical insight on how changeability and reconfigurability can be applied to meet challenges in development of closed-loop manufacturing systems for product take-back.

Keywords: Remanufacturing, Closed-loop manufacturing, Changeability, Reconfigurability, Product take-back

1 Introduction

Product take-back programs are becoming increasingly relevant for manufacturing companies, which is driven by a growing demand for more sustainable and environmentally friendly business models [1-3]. In this regard, a truly closed-loop supply chain can be defined as a supply chain with zero waste that reuses, recycles, or composts all materials [4]. Thus, a closed-loop supply chain involves both forward flow of materials and reverse flow of materials that are processed by the closed-loop manufacturing system, involving activities such as inspection, cleaning, testing, sorting, disassembly, repair, remanufacturing, re-distribution, and disposal [5]. Therefore, the closed-loop manufacturing systems should be designed not only for new processes such as cleaning, sorting, and disassembly, but also with high robustness against fluctuations and high levels of changeability in processing, handling, and routing of a large variety of products, parts, components, and materials [5]. As a consequence, business cases of such closed-loop systems are highly likely to become unattractive due to e.g. high changeover times, difficulty in automation, and high labor cost [1, 6], which makes it difficult for manufacturers to efficiently meet increasing demands for zero-waste and eventually make attractive business cases. Various approaches and solutions towards these closed-loop manufacturing challenges have been addressed in research, e.g. product design for remanufacturing, utilization of additive or industry 4.0 smart technologies, or forecasting, planning, and control models for remanufacturing [3, 7, 8]. However, while changeable and reconfigurable manufacturing concepts have been widely recognized and exploited for traditional manufacturing systems involving small batch sizes, high need for variety and product customization, short product life-cycle, and high variability/uncertainty in demand [9, 10], these principles have been less addressed specifically in the context of remanufacturing and design of closed-loop manufacturing systems. For instance, it has been widely covered in both research and practice how reconfigurability in terms of modular software and hardware with standard interfaces can be utilized in design of manufacturing systems to achieve both cost-efficiency and rapid reconfiguration [9, 11-13]. However, potential use of reconfigurability principles for activities in later stages of product lifecycles have received less attention, but appears relevant as well [14-16]. Therefore, the aim of this paper is to provide empirical insight on how changeability and reconfigurability as manufacturing system paradigms can be applied to meet challenges in development of closed-loop manufacturing systems. The remainder of the paper is structured as follows: Section 2 describes related research and Section 3 outlines the applied case research method. Section 4 presents the case study findings, and Section 5 concludes the paper and describes future research directions.

2 Related Research

The focus of this paper lies in the intersection between the following domains and search terms: 1) “Manufacturing system” or “production system”, 2) “Changeable manufacturing”, “changeability”, “reconfigurable manufacturing”, or “reconfigurability”, and 3) “Remanufacturing”, “closed loop manufacturing”, “circular economy”, “circular supply chain”, “sustainability”, or “product take-back”. By combining the search terms in each domain, a literature search was conducted in Scopus searching specifically in title, abstract and keywords. As a result, 31 documents were retrieved and screened for relevance. 19 papers were considered relevant and excluded papers covered mainly machine tool design or planning and control of traditional manufacturing with sustainability included as a general term. Further, a snowball approach revealed additional relevant papers to include. In the following, the findings of the review are summarized.

Initially, the concept of the Reconfigurable Manufacturing System (RMS) was introduced by Koren in the mid 1990’s with the aim of providing capacity and functionality on demand [17, 18]. However, competitive factors going beyond rapid responsiveness and lower cost increase the relevance of reconfigurability. Bi [11] addressed different manufacturing system paradigms and their abilities to support sustainability. Additional conceptual evaluations of RMS in the context of sustainable manufacturing have been proposed by e.g. Koren et al. [19] stating that e.g. modular machine tools and systems can increase sustainability and allow manufacturing systems to support easier redesign, conversion to produce from virgin and recycled materials. Brunoe et al. [16] investigated how circular supply chains can be supported by different changeability classes including reconfigurability for different end-of-life product strategies. Garbie [20, 21] considered not only the reconfigurable manufacturing system in a sustainability context, but the entire manufacturing enterprise. Going beyond reconfigurable manufacturing as a paradigm that can increase sustainability of manufacturing, some research particularly addressed traditional reconfigurability characteristics in this context. For instance, Barwood et al. [22] explored the adoption of RMS principles for electronic waste recycling systems and proposed a concept of reconfigurable recycling system (RRS) with the ability to rearrange and modify processes in order to match characteristics of the waste stream. Further, Huang et al [23] explored RMS characteristics in connection to sustainable manufacturing performance defined in terms of emission, waste, water use, and efficiency, as well as different types of cost. Particularly in relation to product development, Mesa et al. [24] addressed the application of modular product development principles as a basis for RMS and for increased sustainability. In relation to this, research on cascading use methodology provides insights on identifying new EoL solutions for products and materials [25]. Research in relation to reconfigurability and sustainability can also be identified on both hardware and software levels. On a machine level, Fan et al. [26] propose a reconfigurable multi-process combined machining method to solve the challenge of limited flexibility of machining equipment, low efficiency, and high cost of remanufacturing. Likewise, Bi et al. [27] considered how existing machines can be reconfigured to achieve higher sustainability of manufacturing systems, while Peukert et al. [28] proposed an approach for modular and reconfigurable machine tool frames to make a sustainable footprint [28]. In regard to planning, Touzout and Benyoucef [29] addressed process plan generation in a reconfigurable manufacturing environment considering emission criterion as an environmental factor. Several other works also address production and process planning in a reconfigurable manufacturing system aiming at improving different sustainability criteria [29-31]. To summarize, research on reconfigurability as support for closed-loop manufacturing covers: 1) reconfigurability on a system/paradigm concept level for closed-loop manufacturing, 2) exploration of RMS characteristics in connection with sustainability of manufacturing, 3) reconfigurable hardware design for closed-loop manufacturing, and 4) production and process planning in reconfigurable system considering sustainability factors. Furthermore, the review shows that reconfigurability is a means for closed-loop manufacturing, however, insights are primarily driven by conceptual explorations or mathematical representations rather than investigations in industry.

3 Case Research Methodology

In this paper, the strengths of case research is its ability to support a relatively full understanding of product take-back in a real-life manufacturing context, in order to identify and explore related challenges and the potential of changeability as means for meeting some of these challenges. The case company is a large enterprise with headquarters located in Denmark and numerous global manufacturing plants and sales offices. With an annual output of more than sixteen million products, the company is the market leader within its product domain. Due to the diverse condition of incoming products e.g. product age, type, wear and tear, the disassembly process is entirely manual (manual pressing tools) and the company has not yet identified or developed a more automated manufacturing system with sufficient degree of changeability. The unit of analysis in this paper is the take-back program of a small discrete manufacturing product, where returns are from both internal and external sources, e.g. End-of-Life, warranty cases, insurance cases e.g. pallet slip, etc. In the case company, the product take-back project has been running for several years, and longitudinal data is available to support this study. In this regard, each returned product type and its value recovery process was investigated to achieve comparability and to allow for extraction of prominent characteristics. All identified challenges have been extracted, compared, and discussed in four phases. The first two phases mainly focused on challenges and the last two on potential changes in the manufacturing system considering RMS principles. In the first phase, the researchers conducted semi-structured interviews with the lead project manager overseeing the circular economy initiatives, aiming at gaining an overview of the take-back project, the returned products, the reverse supply chain, and the recycling/remanufacturing process. The current system was mapped and assessed as well. Based on this, a workshop was conducted in the second phase with the regional sales representative, distribution center manager, production supervisors, and external waste handlers. The workshop was used to discuss the overview created during the first phase, as well as to identify challenges that affected design and operation of the system. In the third phase, data was collected to analyze identified disassembly processes in order to measure takt and cycle time as performance indicators. Here, various stakeholders within production provided data. The fourth phase consisted of analyzing the results and presenting the findings to the lead project manager in order to ensure validity.

4 Case Study Findings

4.1 Challenges in closed-loop manufacturing for product take-back

For presentation of the results, all identified challenges have been assigned to different superordinate categories using an Ishikawa diagram as a semantic tool (see Fig. 1).

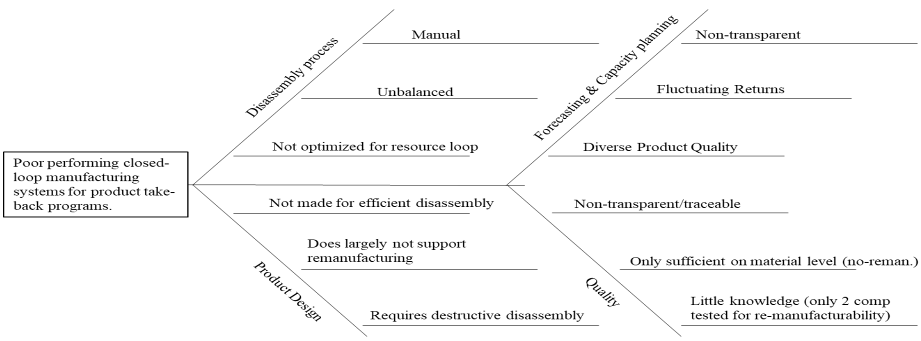

Fig. 1. Categorized challenges identified in the case study.

The first identified category is the disassembly process. An inefficient disassembly process is one of the main symptoms leading to the poor performance of the closed loop manufacturing system. On closer examination we found that three distinct challenges are responsible for this. First, the current process is purely manual, which has a significant impact on the economic performance. The root cause of the manual process design is the high demands on flexibility to heterogenous products and product conditions. The second challenge is the unbalanced disassembly steps. Root causes for this are the general layout of the line, which is not optimized for operation efficiency and the heterogenic condition of incoming goods, which leads to a fluctuation of takt times that creates or worsens existing bottle-necks. A third challenge which is responsible for the inefficient disassembly process is that the process is not optimized to the individual resource loops in which parts and materials circulate. Recycling only recovers raw material value, which allows for efficient, destructive separation of raw materials, albeit the case company disassembles products manually. However, as a general rule, disassembly only makes sense financially when functional value is recovered.

The second identified category is forecasting and capacity planning. The case company is not applying any forecasting methods, which hinders the ability to optimize the capacity planning of the disassembly line. Root causes for this is mainly non-transparent return flows. The external market acts as a “black-box” to the case company, which does not give any indication on potentially upcoming returns. Another root cause which leads to poor supply forecasting and capacity planning are fluctuating returns. Longitudinal case data allowed us to observe up to 42% fluctuation of incoming EoL products from the same system within a time frame of 5 years. A third identified root cause is the diverse quality of returned products. The return volume consist of a mix of 3 product types, where the share of each individual product type fluctuates from batch to batch. This in turn disrupts the workflow, as each type requires different steps/tools.

The third category playing a major role in the performance of the closed-loop manufacturing system is the product design. We observed three different root causes in this category. First, the product design process did not consider EoL handling, disassembly or any other value recovery strategies. This results in a complex and partly destructive disassembly process. Second, product design only allows remanufacturing on a component level, whereas the number of remanufacturable components is limited to two.

The fourth category of challenges is quality. Adapting the output quality of closed-loop manufacturing systems to the quality level of the case company’s conventional manufacturing process is a major challenge. One root cause is the low level of transparency in returned products. Currently, the case company struggles to identify remanufacturable components, as numerous incremental design changes have been conducted throughout a product’s lifespan. Also, in a majority of cases, value only remains in raw materials, since long and intense use phases wear down the product and demolish the functional value. Another challenge identified is the limited knowledge about technical and financial feasibility of remanufacturing. Only two components across the three different product types have been tested. Thus, arguably a lot of remanufacturing potential is currently lost due to lack of knowledge.

4.2 Reconfigurable system scenarios for closed-loop manufacturing

In order to meet the challenges reported in the previous section, redesign initiatives for the closed-loop manufacturing system were initiated in the case company. The aim was to develop a system capable of changing configurations to fulfill different functions in present and future applications. Evidently, not all challenges in terms of poor performance of the closed-loop manufacturing system can be met by designing a reconfigurable system. However, a reconfigurable line can in particular support challenges in the two first categories. The redesign largely followed the three steps of 1) requirement analysis, 2) concept design considering RMS principles, and 3) concept evaluation.

In the requirement analysis and specification, products or product families to include in the design process were determined, as well as their required processing tasks. Three distinct product groups were identified having significant impact on the disassembly process. These three processes varied between 9 and 12 processing steps and had current cycle times between 100 to 160 seconds. However, due to the heterogeneous condition of the products (e.g. corroded press connections or screws) deviations of up to 50% in cycle times could be determined in individual cases. The current line facilitates the three different products in parallel to each other, which results in significant movement of product and operators. A workflow analysis showed that 21% of the throughput time was non-value adding. Thus, increased convertibility of the layout was required in the new setup, which was solved by a modular approach to workstations and their integration. Moreover, in order to develop requirements, a scenario approach considering uncertainties in existing and future product commonality, product volume, product variety, and needed process changes was applied. The outcome of this was three distinct scenarios that system configurations should be designed to meet, covering not only the immediate requirements in output unit/hour and product mix, but also future more long-term changes. The three scenarios clearly showed a need for high scalability and convertibility of the system, i.e. being able to reconfigure the capacity and functionality of the system on both short term basis in terms of mix changes, and on long term-basis in terms of more significant volume changes. The first scenario considered only 25,000 units/year, while the third scenario considered 1,000,000 units/year. Thus, a modular system architecture was considered in the concept design phase in order to enable different alternative system configurations. By exploiting a potential modular system design, different levels of automation, different configurations of layouts, and different capacity levels could be reached by changing, adding, or removing system modules. Thus, considerations of alternating between modular system configurations in response to changes in demand were made, i.e. increasing capacity in a step-wise manner by adding more parallel workstations or automating some process steps e.g. inspection or some disassembly steps. Moreover, considerations of moving from pure recycling to recovery of functional value through remanufacturing was also included. In the final evaluation of concepts, the degree to which remanufacturing could be introduced significantly impacted the attractiveness of the scenarios and configurations of the closed-loop manufacturing system. As a remaining task not covered in this paper, the reconfigurable concept should be designed in detail and the performance evaluated.

5 Conclusions & Future Research

This paper contributes with insights from a case study on challenges in closed-loop manufacturing systems for product take-back programs and considerations on how reconfigurability can support and meet these challenges. The findings of the paper shows significant challenges in developing well-performing closed-loop systems, e.g. high degree of manual work, difficulty in balancing flows, limited ability to recover functional value rather than recycling, low transparency in incoming products, fluctuating quantity and quality of returns, and products not designed for EoL and disassembly. This paper considers how reconfigurability principles can be applied to aid at some of the challenges. In particular the low transparency, high uncertainty, and significant fluctuation in incoming products. Limitations to this study are first of all that solving these challenges requires efforts beyond manufacturing system design, involving various stakeholders in the company. Also, the challenges need to be validated in further industrial settings beyond the case company. Future research should also explore the performance of reconfigurable systems to support disassembly and remanufacturing.

References

1. Seitz, M.A., Peattie, K.: Meeting the Closed-Loop Challenge: The Case of Remanufacturing. Calif. Manage. Rev. 46(2), 74-89 (2004)
2. Subramoniam, R., Huisingh, D., Chinnam, R.B.: Remanufacturing for the Automotive Aftermarket-Strategic Factors: Literature Review and Future Research Needs. J. Clean. Prod. 17(13), 1163-1174 (2009)
3. Tolio, T., Bernard, A., Colledani, M. et al.: Design, Management and Control of Demanufacturing and Remanufacturing Systems. CIRP Annals 66(2), 585-609 (2017)
4. Golinska, P., Fertsch, M., Gómez, J. M. et al.: The concept of closed-loop supply chain integration through agents-based system. In: Information Technologies in Environmental Engineering, pp. 189-202. Springer (2007)
5. Kondoh, S., Nishikiori, Y., Umeda, Y.: A Closed-Loop Manufacturing System Focusing on Reuse of Components. pp. 453-457. IEEE, (2005)
6. Bockholt, M.T., Kristensen, J.H., Wæhrens, B.V. et al.: Learning from the Nature: Enabling the Transition Towards Circular Economy through Biomimicry. pp. 870-875. IEEE, (2019)
7. Matsumoto, M., Yang, S., Martinsen, K. et al.: Trends and Research Challenges in Remanufacturing. International Journal of Precision Engineering and Manufacturing-Green Technology 1(3), 129-142 (2016)
8. Dittrich, M., Schleich, B., Clausmeyer, T. et al.: Shifting Value Stream Patterns Along the Product Lifecycle with Digital Twins. Procedia CIRP 86, 3-11 (2019)
9. Koren, Y.: The Rapid Responsiveness of RMS. International Journal of Productions Research 51(23-24), 6817-6827 (2013)
10. ElMaraghy, H., AlGeddawy, T., Azab, A. et al.: Change in manufacturing–research and industrial challenges. In: Enabling manufacturing competitiveness and economic sustainability, pp. 2-9. Springer (2012)
11. Bi, Z.: Revisiting System Paradigms from the Viewpoint of Manufacturing Sustainability. Sustainability 3(9), 1323-1340 (2011)

12. Andersen, A., Brunoe, T.D., Nielsen, K. et al.: Towards a Generic Design Method for Reconfigurable Manufacturing Systems - Analysis and Synthesis of Current Design Methods and Evaluation of Supportive Tools. Journal of Manufacturing Systems 42, 179-195 (2017)
13. Andersen, A., Brunoe, T. D., Nielsen, K.: Reconfigurable Manufacturing on Multiple Levels: Literature Review and Research Directions. In: Umed, S., Nakano, M., Mizuyama, H., et al (eds.) Advances in Production Management Systems: Innovative Production Management Towards Sustainable Growth, pp. 266-273. Springer (2015)
14. Koren, Y., Gu, X., Badurdeen, F. et al.: Sustainable Living Factories for Next Generation Manufacturing. Procedia Manufacturing 21, 26-36 (2018)
15. Singh, A., Gupta, S., Asjad, M. et al.: Reconfigurable Manufacturing Systems: Journey and the Road Ahead. Int. J. of System Assurance Engineering and Mgt. 8(2), 1849-1857 (2017)
16. Brunø, T.D., Andersen, A., Nielsen, K.: Changeable Manufacturing Systems Supporting Circular Supply Chains. pp. 1423-1428. (2019)
17. Koren, Y.: General RMS characteristics. Comparison with dedicated and flexible systems. In: ElMaraghy, H.A. (ed.) Reconfigurable manufacturing systems and transformable factories, pp. 27-45. Springer (2006)
18. Koren, Y., Heisel, U., Jovane, F. et al.: Reconfigurable Manufacturing Systems. CIRP Annals-Manufacturing Technology 48(2), 527-540 (1999)
19. Koren, Y., Gu, X., Badurdeen, F. et al.: Sustainable Living Factories for Next Generation Manufacturing. Procedia Manufacturing 21, 26 (2018)
20. Garbie, I.H.: DFMER: Design for Manufacturing Enterprise Reconfiguration Considering Globalisation Issues. Int. Journal of Industrial and Systems Engineering 14(4), 484-516 (2013)
21. Garbie, I.H.: DFSME: Design for Sustainable Manufacturing Enterprises (an Economic Viewpoint). Int J Prod Res 51(2), 479-503 (2013)
22. Barwood, M., Li, J., Pringle, T. et al.: Utilisation of Reconfigurable Recycling Systems for Improved Material Recovery from E-Waste. Procedia CIRP 29, 746-751 (2015)
23. Huang, A., Badurdeen, F., Jawahir, I.S.: Towards Developing Sustainable Reconfigurable Manufacturing Systems. Procedia Manufacturing 17, 1136-1143 (2018)
24. Mesa, J.A., Esparragoza, I., Maury, H.: Modular Architecture principles MAPs: A Key Factor in the Development of Sustainable Open Architecture Products. International Journal of Sustainable Engineering , 1-15 (2019)
25. Khan, M.A., Kalverkamp, M., Wuest, T.: Cascade Utilization During the End-of-Life of Product Service Systems: Synergies and Challenges. In: Anonymous Cascade Use in Technologies 2018, pp. 1-7. Springer (2019)
26. Fan, X., Zhang, Z., Jin, X. et al.: Technology of Reconfigurable Multi-Process Combined Machining for Remanufacturing. pp. 1-4. IEEE, (2010)
27. Bi, Z., Pomalaza-Ráez, C., Singh, Z. et al.: Reconfiguring Machines to Achieve System Adaptability and Sustainability: A Practical Case Study. Proc. Inst. Mech. Eng. Pt. B: J. Eng. Manuf. 228(12), 1676-1688 (2014)
28. Peukert, B., Benecke, S., Clavell, J. et al.: Addressing Sustainability and Flexibility in Manufacturing Via Smart Modular Machine Tool Frames to Support Sustainable Value Creation. Procedia CIRP 29, 514-519 (2015)
29. Touzout, F.A., Benyoucef, L.: Sustainable Multi-Unit Process Plan Generation in a Reconfigurable Manufacturing Environment: A Comparative Study of Three Hybrid-Meta-Heuristics. pp. 661-668. IEEE, (2018)
30. Ghanei, S., AlGeddawy, T.: A New Model for Sustainable Changeability and Production Planning. Procedia CIRP 100(57), 522-526 (2016)
31. Khezri, A., Benderbal, H.H., Benyoucef, L.: A Sustainable Reconfigurable Manufacturing System Designing with Focus on Environmental Hazardous Wastes. pp. 317-324. IEEE, (2019)