Sustainable Production with Circular Equipment - Opportunities and Challenges in Practice

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Abstract. The importance of sustainability and reducing CO2 emissions to tackle climate change has long been recognized in the automotive industry. A key area of consideration is production itself. Until now, existing systems and equipment have often been put into storage or scrapped when products are changed, even though they could still be put to good use in other production lines. The potential lies in counteracting the waste of resources through circular resources, so that production itself becomes more sustainable. At the same time, production will become even more flexible, as it should be possible to book equipment as required and only pay for it during the utilization phase. This can become a competitive advantage for companies as it enables them to react to rapid product changes and fluctuating demand. The paper looks at the opportunities for companies to use circular equipment using the example of clamping fixtures but also highlights the current challenges that prevent their use in practice. In addition to identifying the potential of digitalization and the linking of individual life cycles, the complexity of a life cycle assessment of operating resources is shown on the one hand and what is possible with the result on the other. The new "Equipment as a Service" business model for renting equipment will also be highlighted and the associated issues of responsibility and billing will be discussed.

Keywords: Production equipment · Sustainable automotive production · Equipment as a service · Reconfiguration

1 Introduction

Managing climate change and, in this context, the importance of the circular economy is a major topic for the production industry[1]. The relevance of extending the scope of consideration to the entire value process has already been recognized. This means that production itself must also be included. One focus here can be the equipment used in production to manufacture products. Due to the constantly increasing customer requirements for innovations and the associated rapid introduction of new product variants,

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these also have a major impact on the associated production facilities. These are currently disposed of after use, which offers great potential for optimization in terms of saving resources [2]. This also includes the operating materials used, some of which are individually adapted to the respective production plant. However, great potential is seen here for further use, but also for the transfer of this equipment and the corresponding use by another user through appropriate adaptation. In order to achieve a circular economy, this can be used as an approach at the equipment level.

The potential, but also the challenges, extend across the entire product life cycle [3]. In the end, it must be a benefit for the customer and must not lead to higher costs, downtimes, or quality problems. It is therefore important to solve the current problems along the value chain and create further added value. The challenges and potentials in the respective phases are discussed using the example of clamping fixtures. Based on the evaluation and disassembly of a component, it becomes clear which materials have which influence. Engineers can be given direct feedback to design more sustainably, as there is still a lack of knowledge and understanding of how a particular choice of material affects CO2, for example. Another important factor is the new business model (renting instead of buying) and the associated questions: Who is responsible for the operating resources, or how is the billing done?

2 Fundamentals and Methods

For a common understanding, this section contains the definition of circular production and the equipment used in production with a focus on the use case of the clamping fixture.

2.1 Circular Economy

Resource scarcity, stricter environmental regulations and changing consumer expectations are pushing companies to develop alternative concepts to traditional linear production [4]. Many research projects see circular economy concepts as promising solutions [5]. Activities on the road to a circular economy can be structured using the 9R framework, whereby reduce, reuse, recycle and remanufacture are seen as particularly important for sustainable product development [6, 7]. In addition, remanufacturing is a promising approach for recycling used products and extending the lifespan of a product. The resources already used, and the energy value added during the original production of the products are retained. In addition to resource efficiency, this also increases productivity and profitability [8].

According to Fontana et. al., the intensity of research into the circular economy concerning production resources is low [4]. The existing approaches focus on product design[9], condition monitoring[10] and the automated dismantling of production equipment [11].

2.2 Production Equipment

According to the DIN 6300 standard, production equipment includes all material resources required to produce a product. Production equipment is clearly distinguished from production materials, which do not influence the end product [12]. The categorisation of operating equipment according to DIN 6300 within production equipment is shown in Fig. 1. This categorisation provides a systematic overview of the various elements that act as production equipment in the production process.

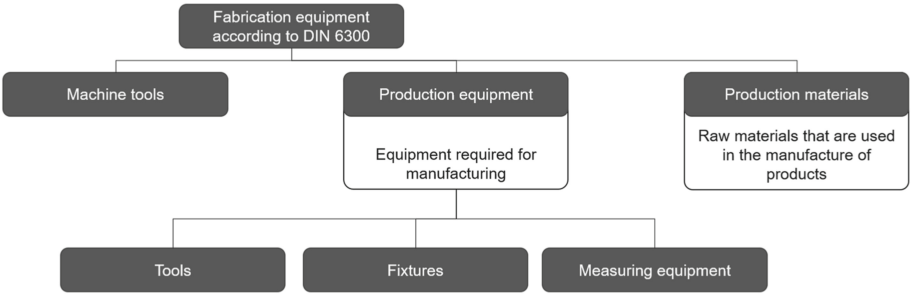

Fig. 1. Classification of equipment in the category of production equipment according to [13]

2.3 Fixtures

Alongside tools and measuring equipment, fixtures are an essential category of equipment in industrial manufacturing processes. These technical aids are used to hold a workpiece in a stable position, fixed alignment, or specific location. Their main function is not the direct execution of manufacturing processes, but rather to ensure precise positioning between different workpieces. Typically, fixtures are used primarily in multi-dimensional machining processes [14].

Various clamping principles can be used to realise fixtures. In the automotive industry, fixtures are primarily used in serial welding and assembly processes. They fulfil a crucial role in automated industrial production processes by ensuring that consistently functioning components can be manufactured. The use of fixtures in these processes helps to ensure the quality and reliability of the manufactured parts. Their use therefore not only enables efficient production but also standardised and repeatable production of assemblies and components.

3 Application

The opportunities and challenges in practice for sustainable production equipment are divided into five levels of consideration and are shown in Fig. 2. These five levels are further explained in the following section.

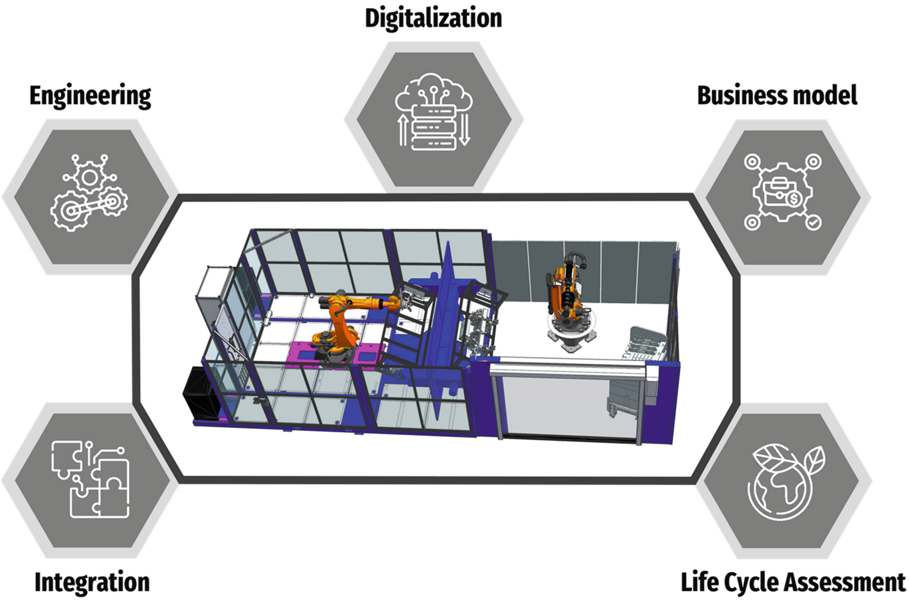

Fig. 2. Opportunities and challenges for circular equipment for the given use case

Based on a use case, a manufacturing cell, the levels of consideration relate to various aspects of this system. The production cell itself can be viewed as a closed system that has been specially developed for carrying out a joining process in the context of assembly production. Within this scenario, four different operating resources work together to successfully realise the manufacturing process.

The main players in this manufacturing cell are the three production equipment. A specially developed **gripper** on a handling robot and a **welding fixture** are two of these resources. The process begins with the provision of individual components, which are placed in a **load carrier**. These individual components are then precisely picked up by the handling robot and placed in the welding fixture. The specially designed gripper ensures precise handling and positioning of the components.

The actual joining process is carried out by a high-precision welding robot. This robot uses its welding tools to join the individual components together to create the complete assembly. The highest levels of precision and efficiency are considered to ensure high-quality production.

These levels of consideration make it possible to understand in detail the interaction of the operating resources in the specific contextualization of a use case production cell. The integration of handling and welding robots as well as the use of a load carrier and the provision of components by a shooter-like load carrier not only increases the efficiency of the process but also ensures precise and reproducible production. This structuring and automation of the production process helps to optimize the quality of the assemblies produced and increase the overall performance of the production cell.

The use case follows the primary approach of sustainable resources and a flexible production cell. The following chapters will therefore address the engineering of sustainable resources and a corresponding evaluation on the one hand and the business model behind a flexible production cell through a corresponding data-driven production network on the other.

3.1 Engineering

While the focus in the engineering of production equipment has so far been on implementing customer requirements as cost-efficiently as possible, other factors must be also taken into account for the development of circular equipment. Here, equipment manufacturers must weigh up how far the solution should be tailored to a specific application or whether a generally valid solution would be better in the context of a circular economy. The universal variants are often not aligned with company-specific guidelines, especially from the automotive industry. This also means that the use of operating resources across customers is made more difficult, although it is more and more requested by the industry.

Three key questions need to be clarified as part of the design process:

- Is a viable, modular structure of the production equipment possible and what does this look like?
- How can modifications be made as easily as possible?
- Which materials are used?

The first question focuses on how the equipment, which itself consists of individual components, can best be structurally designed so that it can be repaired and upgraded in line with the overarching goal of the circular economy, thus maximising the lifespan of the product. The second question addresses the point of repairability and upgradeability again and requires that the equipment can be easily assembled and disassembled. This also has a direct positive effect on user-friendliness and maintainability for the end customer. Easy accessibility and interchangeability of parts without specialised tools or specialist knowledge are of special interest here. The final question relates to the material. The material used must not only fulfil the technical requirements but must also be selected responsibly with regard to its environmental impact.

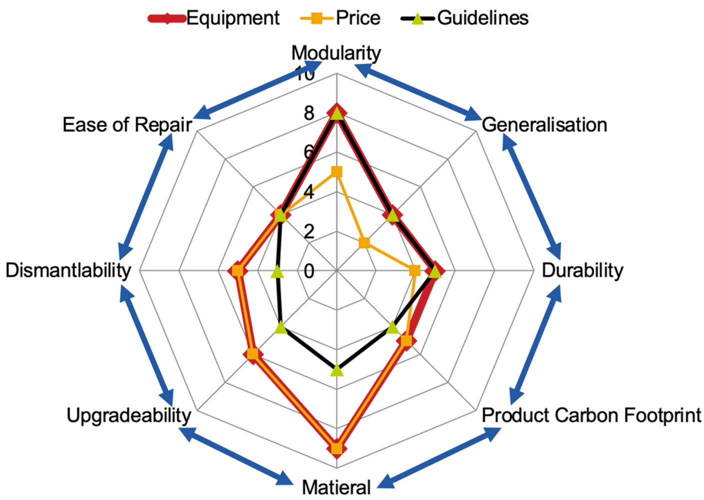

Fig. 3. Optimisation problem during the design of circular production equipment

Figure 3 illustrates the trade-off between eight factors during the design of circular production equipment. Due to dependencies, changes to one factor can have both positive and negative impacts on the others. In addition, each of these factors can be implemented to varying degrees, hence they are each assigned a value between zero and ten for quantification reasons. A ten means that this factor has been fully implemented. Further constraints, such as policy and price, often exist on top of this, resulting in an optimisation problem that needs to be solved. This leads to situations where the factors are constrained by either the price or the policy.

3.2 Integration

How (circular) production equipment can be integrated into existing and new production facilities is the subject of numerous research projects. To ensure that companies make use of the new approach, the efforts for the customer must be minimised. This raises the question of how intelligent an operating resource must be. Figure 4 Illustrates the two extremes. The left-hand side shows what is called simple equipment, which has no logic or control of its own. Every signal and every pneumatic connection must be integrated and parameterised in the existing system, in this case, the controller and valve terminal, which leads to increased integration costs. On the other hand, the costs for the operating resources are minimal. The opposite is shown on the right a smart equipment. It has its own controller, which controls the valves and subsequently the clamping device independently. The equipment only needs to be supplied with the required media (in this case: compressed air, electricity, and network) and then operates autonomously. This offers the advantage that the equipment manufacturer can guarantee the desired behaviour and is not dependent on any third party that it cannot control. However, it presupposes that the subordinate platform has the appropriate functionality to enable dynamic integration into a system and the cost are much higher.

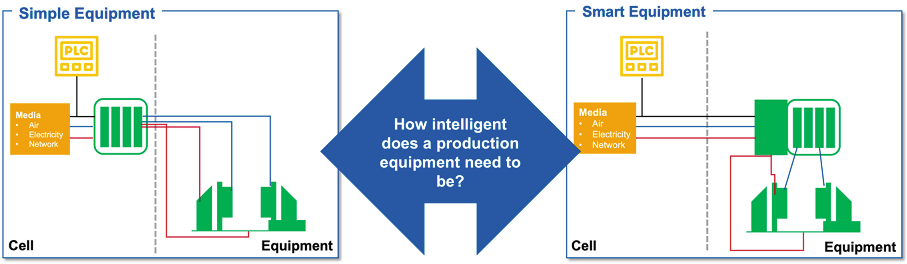

Fig. 4. How intelligent does a production equipment need to be?

One possible approach could be the development of a standardised platform with appropriately standardised connections. This platform is currently being developed in the ongoing research project.

3.3 Digitalization

Within this approach, digitalisation is an important enabler, as data must be exchanged between equipment manufacturers and end users in all life cycle phases. In the engineering phase, a link with the user's operation backbones is necessary so that the equipment fits into the existing system and can be integrated with minimal effort. During the utilisation phase, data from the equipment must be transmitted to the manufacturer for billing and maintenance. It is therefore essential to have a higher-level platform that enables data exchange and provides the corresponding services. Since every company has different IT systems and data structures, it is necessary to create a common data basis and understanding. Open standards, such as the Asset Administration Shell, are ideal for this purpose. The existing sub-models, which represent standardisation within the AAS, provide a good basis for mapping individual elements and activities but are still insufficiently defined in many cases. These gaps need to be closed so that a corresponding interaction, as outlined in Fig. 5, is possible. This shows, on the one hand, which services are required in the various entities and, on the other hand, the different ways and levels in which they must interact with each other.

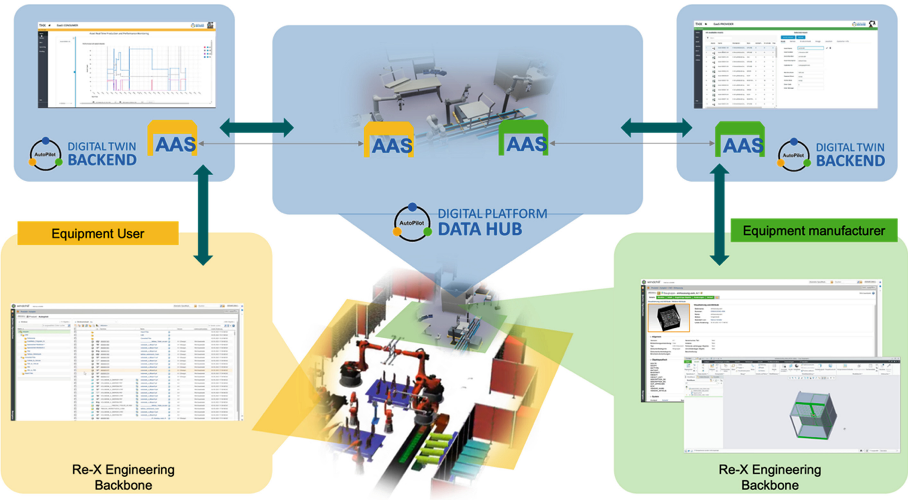

Fig. 5. System architecture of a digital platform for circular equipment

3.4 Life Cycle Assessment

Life Cycle Assessment (LCA) is a methodical approach to analysing the environmental impact of products or processes along their entire life cycle. The analysis ranges from the extraction of raw materials through production to utilisation and disposal (see Fig. 6). This holistic approach enables the LCA not only to identify environmental impacts but also to derive targeted measures to minimise the ecological footprint and resource consumption, as well as to identify and compare granular ecological and economic hotspots along the life cycle of a product.

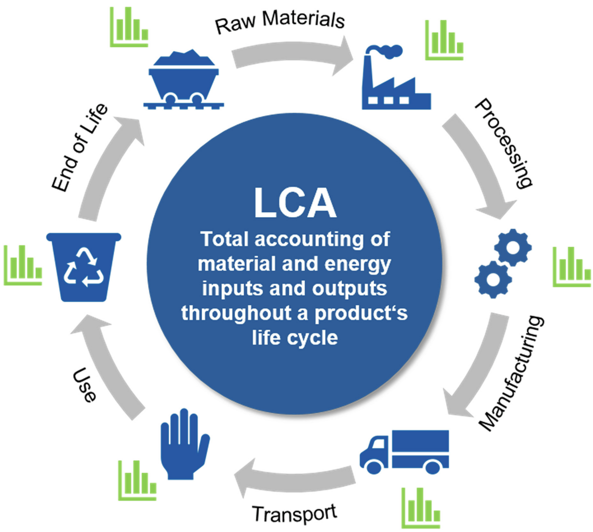

Fig. 6. System architecture of a digital platform for circular equipment. (Source: Capgemini Engineering)

A key challenge in the LCA analysis approach is the sometimes-extensive data gaps, which make it difficult to take a holistic view and increase the potential for distortions in the analysis. Data must be collected over the entire life cycle, as shown in Fig. 7. Another critical aspect is the heterogeneity of the available data, which can come in different forms and formats. This leads to considerable additional work in data preparation and integration, as the same information from different sources has to be standardised. The data processing challenges are further compounded by the need to convert the available data into the specific formats of the LCA models. This conversion requires a deep understanding of the model structure and a precise adjustment of the data to ensure a coherent basis for the analysis. Among other things, this is necessary to achieve comparable results.

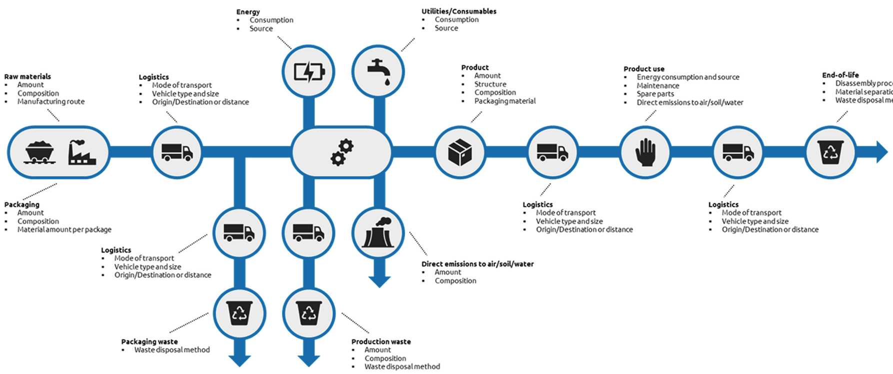

Fig. 7. The data required for the LCA comes from a variety of sources along the product life cycle. (Source: Capgemini Engineering)

However, some opportunities can improve both data quality and the analysis process. The elimination of data gaps can be achieved through an extended integration of LCA data requirements in different company departments. Comprehensive data exchange between production, procurement, logistics and other relevant areas enables holistic data collection across the entire life cycle of a product. This not only helps to eliminate data gaps but also promotes a more comprehensive and accurate analysis of environmental impacts. The introduction of digital twins and the automation of data collection and processing offer another promising opportunity. By creating digital replications of physical products and processes, data can be captured and continuously updated in real-time. Automating data collection and processing not only reduces manual effort but also enables a faster response to changes in the production process. This leads to a more efficient and cost-effective implementation of LCA.

According to the use case described in Sect. 3, an LCA was carried out for the load carrier by the project partner Capgemini Engineering. It should be particularly emphasized here that a load carrier made of plywood was developed in line with the focus on sustainable resources. This load carrier is compared directly with a conventional steel load carrier. In Fig. 8, the steel load carrier is declared as the status quo, while the plywood load carrier represents the innovation. Figure 8 shows the corresponding calculations for CO2 emissions in kilograms per unit based on three levels of consideration. Firstly, the individual life cycle phases that the load carriers go through, from raw material extraction, logistics and production through to the end of their life, are shown in direct comparison. This shows that the status quo load carrier made of steel has significantly higher CO2 emissions per unit during raw material extraction. The middle figure shows a comparison of the individual components that make up the load carriers. Both load carriers consist of steel components and steel connecting elements, as well as wheels and packaging, but to varying degrees. The proportion of steel components in the status quo load carrier is significantly higher due to its complete steel construction than that of the innovation load carrier, due to the fact that the latter is largely made of wood.

The last diagram is intended to show a direct comparison of the CO2 consumption of the individual materials in the two load carriers. Here too, due to the different materials of the two load carriers, the status quo load carrier with a significantly higher proportion of steel elements also has a correspondingly higher CO2 consumption. In contrast, the Innovation load carrier consists mainly of wooden elements and therefore has a significantly higher consumption for the material “wood”. Overall, however, it is clear from all three figures that the CO2 consumption of the innovation load carrier has significantly lower CO2 emissions per unit, both along the life cycle phases and in a direct comparison of the components. This is mainly due to the high proportion of wooden components and the associated lower CO2 emissions than steel.

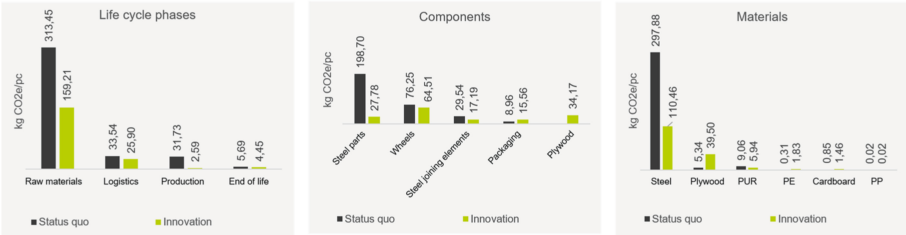

Fig. 8. Influence of the material on the life cycle phases and components. (Source: Capgemini Engineering)

3.5 Business Model

A new, customised business model is required to implement the presented approaches for the circular operating resources. A change in industrial processes must be brought about by aiming to create a closed-loop system. The business model therefore aims to maximise the use of operating resources in production by implementing innovative solutions for the highest possible degree of reuse.

The existing business models for operating resources face several challenges that affect both environmental and economic aspects. One of the central problems is the low utilisation rate of existing operating resources. Inadequate utilisation not only impairs economic profitability but also contributes to inefficient use of resources. A sub-optimal product life cycle exacerbates this problem, as complete production lines, including the associated equipment, are often completely disposed of. These short life cycles increase the need for new purchases and therefore the consumption of resources. Another significant obstacle is the lack of end-of-life concepts for operating equipment. Insufficient planning for the end of the useful life makes recycling or disposal difficult, which leads to considerable environmental impacts. At the same time, the high capital commitment in conventional business models places a financial burden on the user, as cost-intensive operating resources must be procured. Subscription-based business models for recyclable operating resources can offer added value here and promote sustainability.

This is increasingly focussing attention on the need for sustainable business models in the context of circularity for operating resources. Subscription-based approaches offer a wide range of potentials that promote the circular economy and reuse of equipment and thus save resources. Improving the utilisation of operating resources is a central aspect of subscription-based business models. By creating access instead of ownership, the efficiency of resource utilisation is maximised. Users have the opportunity to utilise resources only when they are needed. The self-interest of users in long product life cycles is strengthened by subscription-based models. Subscription-based models offer users the advantage of gaining access to high-quality products without tying up large amounts of capital. This leads to greater planning security, as users can calculate exactly what costs will be incurred in a certain time. At the same time, the equipment manufacturers are responsible for the end-of-life concepts or reuse.

Such an approach, where the equipment remains the property of the manufacturer and can be rented directly from the manufacturer as required and only the actual use is paid for, is called “Equipment as a Service”.

The most important components of the new business model approach are determined with the help of the business model canvas. In addition to the value proposition, the required infrastructure and the potential customer base are also identified. Based on this description, the further development towards an "Equipment-as-a-Service" business model is pursued. Figure 9 shows the results of the business model canvas with the corresponding inputs.

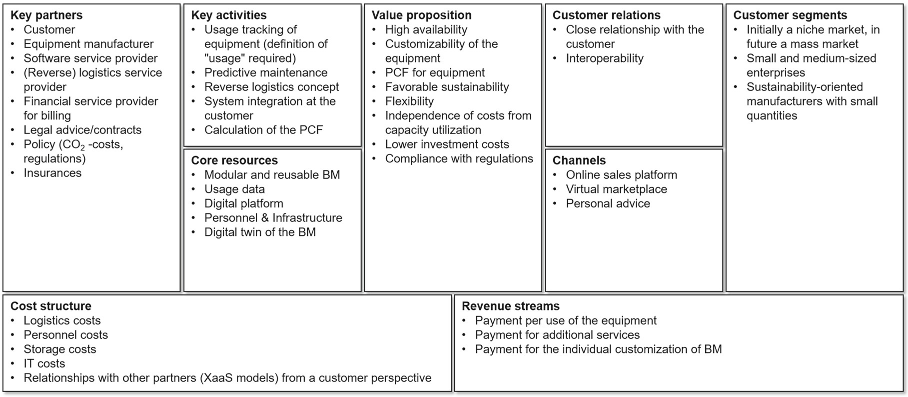

Fig. 9. Business Model Canvas for the "Euqipment as a Service" approach

4 Conclusion and Outlook

The use of circular production equipment is a promising approach to making the production of the future sustainable. It can also be integrated into existing production facilities and also provides an opportunity to take into account fluctuating demand and the ever-shorter product life cycles.

Using the example of a manufacturing cell, five aspects (engineering, integration, digitalisation, business model and LCA) were discussed that must be considered when developing and introducing circular production equipment. It became clear that some fundamental questions still need to be answered in the individual aspects to create verifiable added value for the customer. Despite the challenges that still exist, there are also many opportunities and possibilities that are currently not possible. For this, it is necessary that this innovative business model is implemented in its full complexity with a real use case so that it can serve as the basis for further products.

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References

1. E. Lindahl, J.-E. Dahlin, and M. Bellgran, "A framework on circular production principles and a way to operationalise circularity in production industry," Cleaner Production Letters, vol. 4, p. 100038, 2023, https://doi.org/10.1016/j.clpl.2023.100038.

2. W. Walla and J. Kiefer, “Life Cycle Engineering – Integration of New Products on Existing Production Systems in Automotive Industry,” in pp. 207–212.
3. C. Brecher, O. Petrovic, Y. Dassen, P. Blanke, M. Trinh, and S. Wurm, “Sustainable Production-as-a-Service,” 2023.
4. A. Fontana et al., “Circular Economy Strategies for Equipment Lifetime Extension: A Systematic Review,” Sustainability, vol. 13, no. 3, p. 1117, 2021, https://doi.org/10.3390/su13031117.
5. E. Suzanne, N. Absi, and V. Borodin, “Towards circular economy in production planning: Challenges and opportunities,” European Journal of Operational Research, vol. 287, no. 1, pp. 168–190, 2020, https://doi.org/10.1016/j.ejor.2020.04.043.
6. J. Potting, M. P. Hekkert, E. Worrell, and A. Hanemaaijer, Circular Economy: Measuring innovation in the product chain, 2017.
7. B. Xu, S. Liu, and H. Wang, “Developing remanufacturing engineering, constructing cycle economy and building saving-oriented society,” J Cent. South Univ. Technol., vol. 12, no. 2, pp. 1–6, 2005, https://doi.org/10.1007/s11771-005-0002-4.
8. A. P. Barquet, H. Rozenfeld, and F. A. Forcellini, “An integrated approach to remanufacturing: model of a remanufacturing system,” Jnl Remanufactur, vol. 3, no. 1, 2013, https://doi.org/10.1186/2210-4690-3-1.
9. PengjiaWang, Y. Liu, S. K. Ong, and A. Nee, “Modular Design of Machine Tools to Facilitate Design for Disassembly and Remanufacturing,” Procedia CIRP, vol. 15, pp. 443–448, 2014, https://doi.org/10.1016/j.procir.2014.06.085.
10. A. Zacharaki et al., “RECLAIM: Toward a New Era of Refurbishment and Remanufacturing of Industrial Equipment,” (in eng), Frontiers in artificial intelligence, vol. 3, p. 570562, 2020, https://doi.org/10.3389/frai.2020.570562.
11. J. Liu, Z. Zhou, D. T. Pham, W. Xu, J. Cui, and C. Yang, “Service Platform for Robotic Disassembly Planning in Remanufacturing,” Journal of Manufacturing Systems, vol. 57, pp. 338–356, 2020, https://doi.org/10.1016/j.jmsy.2020.10.005.
12. DIN 6300:2009-04, Vorrichtungen für die Fixierung der Lage von Werkstücken während formändernder Fertigungsverfahren_- Benennungen und deren Abkürzungen, Berlin.
13. S. Hesse, Betriebsmittel Vorrichtung: Grundlagen und kommentierte Beispiele, 2nd ed. München: Hanser Verl., 2012. [Online]. Available: http://ebooks.ciando.com/book/index.cfm/bok_id/291650
14. F. Fiedler et al., “Jigs and fixtures in production: A systematic literature review,” Journal of Manufacturing Systems, vol. 72, pp. 373–405, 2024, https://doi.org/10.1016/j.jmsy.2023.10.006.