Circular Manufacturing Systems in Learning Factories

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Abstract. Circular Manufacturing Systems (CMS) have emerged as a paradigm for integrating disassembly and potential remanufacturing processes into factories. This is also a relevant topic for learning factories whereas studies indicate that limited concepts are available nowadays. Given that, the paper explores the integration of CMS principles as well as specific processes and system setups into learning factories. A methodological approach is introduced to facilitate the systematic development of CMS approaches for learning factories. The proposed approach is exemplarily applied in the Learning Factory of the University of Twente to test functionality and feasibility.

Keywords: Circular Manufacturing · Circularity · Sustainability · Disassembly

1 Introduction

Manufacturing value chains are connected to a significant share of environmental impact, e.g. responsible for about a third of Global Greenhouse Gas emissions (GHG) [1]. The major share of that is related to the energy demand for producing the necessary (raw & auxiliary) materials. Thus, facilitated using materials with reduced environmental backpack and material efficiency are crucial strategies for improving the environmental impact of manufacturing [2]. In line with that, circularity stands out as a promising strategy to address environmental challenges and aims at reducing the demand of primary materials through maximize the longevity of products, parts or materials. Circularity concepts are also connected to other potential benefits such as material independence or lower raw material costs. But of course certain obstacles like higher planning complexity, uncertainty of supplies and establishing appropriate business models need to be overcome [2].

To fully understand the potentials and challenges of circularity, it is imperative to distinguish the different levels within the "Re-X" options – e.g. reduce, reuse, recycle, remanufacture, recover. As illustrated in e.g. the Comet Circle by Ricoh [3], these options necessitate a comprehensive approach that considers the entire lifecycle of products and materials. Each "Re-X" level offers unique opportunities for improving sustainability and must be integrated strategically into industrial value chains.

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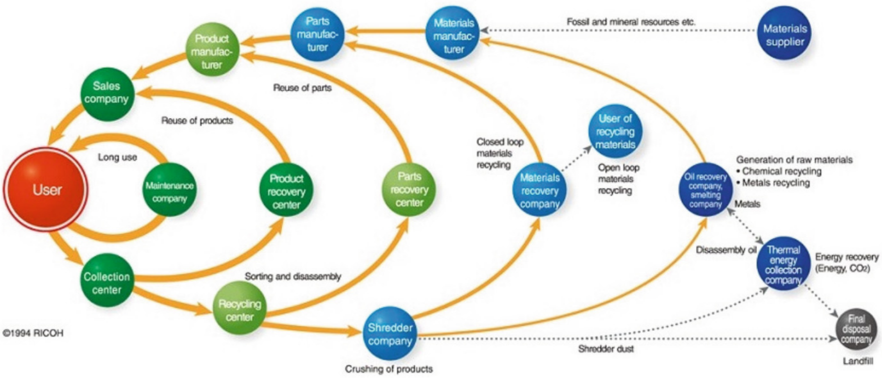

Fig. 1. Comet Circle illustrating Circularity [3].

As illustrated in Fig. 1, realising circular economies involves diverse – and new compared to linear economies – stakeholders taking over dedicated roles in closed loop value chains. Nowadays more integrated approaches can be found in research but also industrial practice (e.g. electronics, automotive), e.g. where traditionally manufacturing focused companies start to integrate Re-X technologies in their own facilities.

Implementing circularity requires new technologies and, thus, also new knowledge in order to be able to design and operation respective technical systems. And typically Learning Factories (LFs) are ideal educational environments designed to simulate real-world industrial processes and integrate academic knowledge with practical skills, e.g. for preparing students for careers in engineering, technology, and industrial management [4]. However, studies show that circularity concepts are rarely considered in LFs so far [5] and even less to the extent of bringing manufacturing and Re-X options together in an integrative manner. Against this background, this paper proposes the concept of circular manufacturing systems (CMS) as paradigm for LFs. The focus is on providing definitory background and also dedicated methodological support to set up those integrated manufacturing systems.

2 Technical Background

2.1 Circular Manufacturing Systems

Due to their nature and role in the life cycle of products, manufacturing and Re-X-Options inherently incorporate differing characteristics which seem to make it difficult to bring them together [2, 6]. First of all, there is of course a long time delay between manufacturing of products and their potential return to the origin. Additionally, a lot of uncertainty is involved since the types, volume and state of returning products is difficult to predict. Manufacturing and assembly are characterised through rather known production demand, a converging material flow (single parts towards product assembly) and determined process technologies and times. Disassembly and recycling processes are characterised through diverging material flow (from product/sub-assembly to parts or even raw materials) and face volatile volumes of diverse types of products with unknown state ranging from as-new to completely worn out. This naturally has strong implications for the design and operation of the Re-X system while process times, required technologies and knowledge as well as the resulting utilisation of equipment is uncertain.

Given the potential benefits through bringing both perspectives together, first concepts for an integration of e.g. assembly and disassembly system were already described many years ago [6]. More recently, other authors addressed the idea of whole circulation factories which extend the scope of activities even more [7, 8], as Fig. 2 shows. Following this concept, production and re-production are sharing one facility and use synergies e.g. when it comes to technical building services (energy/media supply, HVAC system, etc.). Remanufactured components or recycled materials can be seamlessly integrated back into the production [8]. Quite classical examples that illustrate the idea and potential are e.g. metal foundries where production waste or potentially also returning parts could be rather easy smelted and brought back into the production cycle. But it gets of course way more challenging with it comes to more complex, multi-component (and material) assembled products.

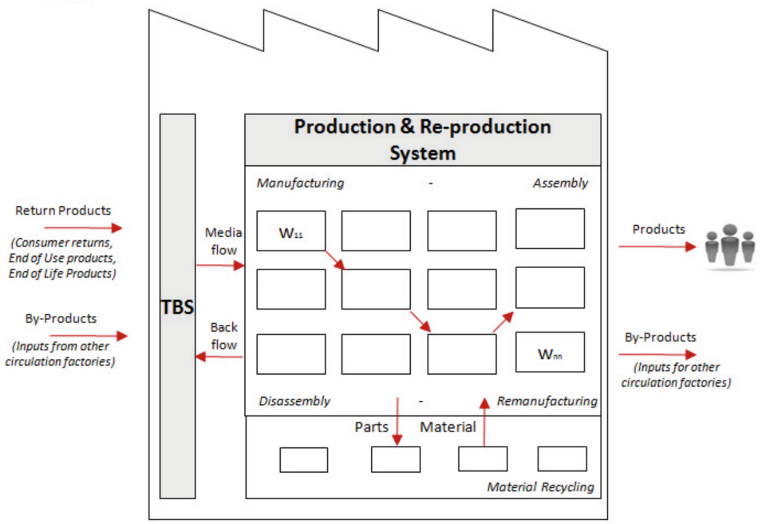

Fig. 2. Circulation manufacturing systems and factory [7].

2.2 Circularity in Learning Factories (LFs)

In contrast to the rising general relevance of circularity concepts, recent studies [5] underline that altogether there are very few approaches that address this field of action in Learning Factory (LF) environments. Recently first contributions can be found that e.g. suggest didactic concepts to facilitate circular thinking [9], methodological approaches, (e.g. C-VSM [10]) or specific LF setups with focus on disassembly and/or remanufacturing [11]. However, there is no contribution that explicitly focusing on bringing manufacturing and Re-X together in one LF environment. That would be beneficial in order to show differences but also the potentials and challenges through integration. Besides that, especially for LF there is even a very practical demand –many LF produce certain products only for demonstration purposes so disassembly and sorting back components to the workstations and warehouses is necessary anyway. Against this background, this paper addresses the topic of circular manufacturing for LFs. That incorporates a taxonomy that allows a strategic alignment but even more methodological decision support to design balanced circular manufacturing systems.

3 Conceptual Framework and Methodology

3.1 System Understanding

The proposed approach follows the system and functional understanding as illustrated in Fig. 3. Learning Factories typically comprise of a process chain to produce a certain product which might range from manufacturing/supply of components over to (final) assembly including aspects like e.g. quality checks. For realizing circularity concepts, additional functionalities and process steps are necessary: this could start with first check/characterisation of incoming products, product disassembly, remanufacturing (e.g. cleaning, machining) of components and/or the recycling of materials. Remanufactured components or even recycled material can conceptually be seamlessly brought back into the manufacturing process chain whereas this typically involves sorting and storing steps. This is specifically true for varying volumes and variants of incoming products.

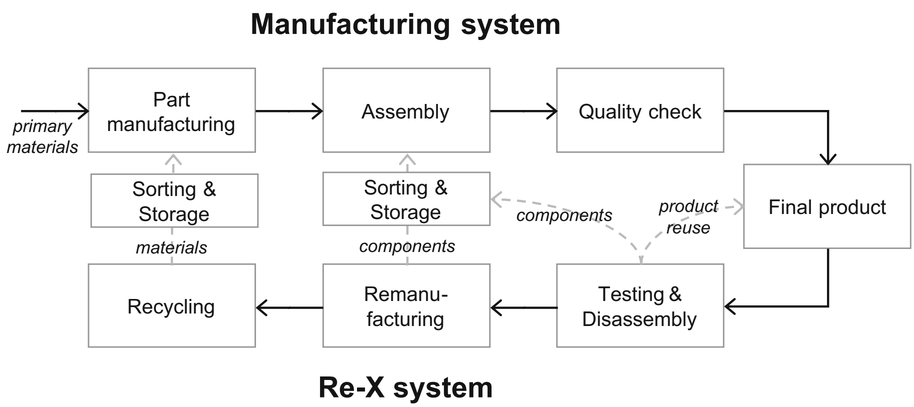

Fig. 3. Functional view on circular manufacturing systems (CMS) for learning factories.

It is important to realize that this is a functional view on necessary process steps which are of course product specific. All process steps need a dedicated time for execution whereas this depends on aspects like experience of worker, potential automation solutions, state of the component/product or availability of tools.

All those steps could be potentially executed manually by only one worker on one workstation but for more realistic larger scale industrial scenarios the design of dedicated circular manufacturing systems is necessary. This involves a number of workstations or machines operated by several workers with defined and distributed tasks. From an idealistic perspective on CMS, those operations would be perfectly aligned and would allow a continuous production based on incoming supply with returning products and therewith components. This requires dedicated consideration of process times, involved resources and therewith the overall system setup.

3.2 CMS Archetypes and Design in Learning Factories

Based on the functional and system view as introduced above, different characteristic archetypes for combining manufacturing and Re-X options in Learning Factories can be derived (Fig. 4).

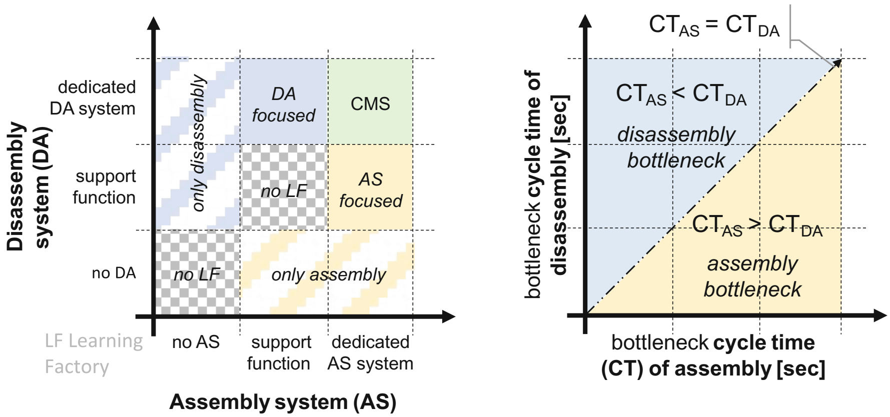

Fig. 4. CMS archetypes in learning factories (left) and time-based alignment of assembly and disassembly systems (right) (for simplification/clarification reasons assembly/disassembly are used as terms but principle applies also to other process steps).

As of today, assembly focused learning factories are dominating. In those cases circularity options are not at all integrated or only as support function, e.g. to get back components from products that were produced for training/demonstration purposes. First LFs can be found that explicitly focus on disassembly/remanufacturing whereas then again the manufacturing part has at most a support function. Explicit circular manufacturing systems (CMS) address both manufacturing and circularity with explicit infrastructure and in an integrated manner.

However, it does not indicate whether the manufacturing process steps and the Re-X process steps are configured in a way that is aligned or even synchronized in time. To facilitate the integrated design of CMS, Fig. 4 introduces the utilization of the cycle time of the respective bottleneck process. As know from traditional manufacturing system planning, the bottleneck cycle time typically determines the maximal output of a manufacturing system over time. Thus, it can serve as decisive variable to align CMS related process steps. The process cycle time is a function of the physically necessary technical time (for e.g. the specific assembly process) but also of the involved workstations and/or workers. So if e.g. two workstations would perform the same tasks, the cycle time would be halved and the output doubled compared to just one workstation. Therewith the suggested methodology directly reflects system design aspects. As shown in Fig. 4 an ideally synchronized CMS would have equal bottleneck cycle times for both manufacturing and Re-X thus leading to similar output over time. Relatively higher cycle times on the manufacturing side would lead to sufficient continuous supply with returned components whereas the opposite case would lead to waiting times since not enough components are brought back.

4 Case Study

To test the functionality and feasibility of the approach, an exemplary case study was conducted at the Learning Factory of the University of Twente. Within this environment, several workstations are available which are used to assembly a mini-drone as primary product. The drone is characterized by the complexity of its components, which include both mechanical and electronic elements, and the handling challenges posed by their small size. These drones are fully functional but in the end mostly only used for demonstration purposes and need to be disassembled and brought back to the workstations in a sorted manner. Even more, new courses around circularity in manufacturing are currently under development at the university. Thus, related CMS principles and technologies shall be integrated in the Learning Factory environment. In order to achieve that, the methodology as introduced above was applied. Intensive time studies with different participants and several runs (to capture learning curve effects) were conducted for both assembly and disassembly. With this knowledge of total time requirements (Fig. 5, step 1 as initial starting point), the assembly system was designed which included the division of task over three or four workstations in order to realise an intended cycle time of around 400 s (step 2). The total time for drone disassembly is lower than for the assembly. However, still significant time is needed since sensitive and small parts are involved and careful sorting/distribution to the workstation is necessary. And given that assembly was now distributed over several workstations, conducting all disassembly processes at one workstation would lead to a bottleneck and non-balanced CMS (step/point 2 in Fig. 5). It turned out that additional resources are necessary to realise a synchronously operating CMS (step 3) such as adding another workstation, use of a cognitive assistance system that provides information on task execution or the involvement of a robot. With this setup, a continuous assembly and disassembly could be realised which is an interesting scenario for demonstrating CMS benefits and challenges.

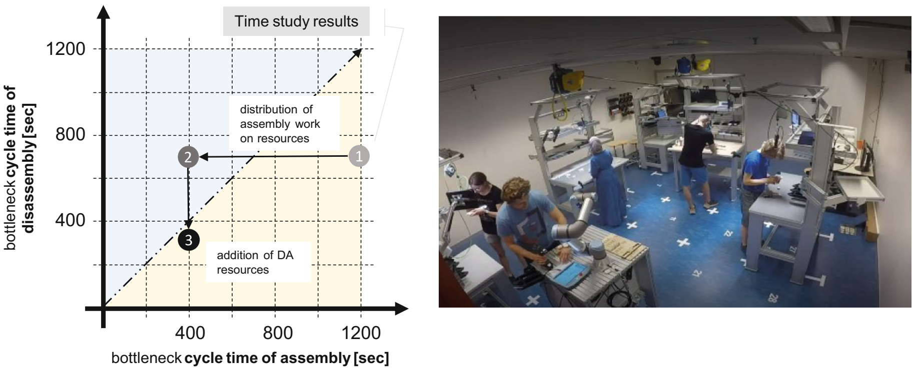

Fig. 5. Exemplary application of CMS design methodology for Learning Factory at the University of Twente.

5 Summary and Discussion

Circularity is a promising strategy to address environmental challenges in manufacturing. The concept of circular manufacturing systems (CMS) is proposed as a paradigm for learning factories, providing a comprehensive approach to integrating manufacturing and "Re-X" options (reduce, reuse, recycle, repurpose, remanufacture, and recover) in Learning Factory environments. The paper introduces a CMS framework for learning factories as well as a design methodology towards alignment of manufacturing and circularity process steps. The approach is exemplarily applied at the University of Twente's Learning Factory.

The case study underlined the functionality and feasibility of the approach. However, it inherently incorporates some assumptions and simplifications that require further work. As example, process times (especially for disassembly) might be volatile and a balanced distribution of task is not always possible. There are also more influences like spatial/layout aspects or the availability and expertise of workers. Last but not least, the necessity and specific CMS characteristics naturally depend on the specific product and intended use case.

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