

Ready for Circular Manufacturing? Metal Forming Processes Studies and Research Agenda

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Abstract. The mitigation of primary resource exploitation and their usage within linear economies ultimately leads to systematic leakages from economy and the depletion of natural resources. In contrast, a circular instead of a linear economy aims towards minimizing these leakages by reintroducing all resources to economy without negative externalities. Within the circular economy (CE), manufacturing plays a vital role for the conversion of resources towards products. For a manufacturing system, it is hence of critical importance to understand the implications and requirements of CE for production. The present study develops the *Ready4CM* “Ready For Circular Manufacturing” principle. Manufacturing systems are considered in the light of serving the needs of CE, where manufacturing flexibility, scalability and reconfigurability may pave the way but need to be controlled sufficiently to achieve resilience towards more drastic uncertainties of used materials. Not only focusing on process, but also on machine and tool, this paper contributes towards CE by identifying systematic aspects of circularity in manufacturing systems. We embedded our contribution in existing frameworks that calculate and balance sustainability potentials within circular economy while our approach, *Ready4CM*, aims to identify and summarize a comprehensive understanding of technical premises for manufacturing processes to serve and facilitate CE.

Introduction

The principle of circular economy (CE) introduces systematics to overcome nowadays key needs to mitigate excessive usage of primary resources and to restrict energy consumption as much as possible. According to ELLEN MACARTHUR FOUNDATION [1], the CE agenda is subdivided into three design-driven principles:

- i) Elimination of waste and pollution,
- ii) Circulation of products and materials at their highest value,
- iii) Regeneration of nature.

CE consequently stands in strong contrast to conventional linear economy, where materials are captured from the environment, products are manufactured using these materials and ultimately disposed of as waste after a products lifetime. Practically, for technical management of product stock, loops are closed for reintroducing products at different economical stages with the recycling principle being the most prominent among them. Yet, recycling represents the largest loop where materials are gathered from disposed products in order to be reintroduced to the earliest manufacturing stages of new products. In contrast, for instance the repair loop connects a narrower margin within the stage of product usage. Consequently, these loops given as maintain, share, reuse, refurbish and recycle by the ELLEN MACARTHUR FOUNDATION.

Essentially, besides these aforementioned loops in stock management of finite materials, the renewables flow management is studied in circular economy. Where the technical loops are considered in stock management, cascades of materials utilization are focused in circular flows of

renewables. Both circular flows are overall intended to minimize the systematic leakage of resources and energy. A summary of this theory is graphically presented commonly in the butterfly diagram according to the ELLEN MACARTHUR FOUNDATION [1].

Conventional linear economy may also be expressed as cradle to grave principle. In contrast, according to BRAUNGART and MCDONOUGH [2], the cradle to cradle (C2C) concept draws a holistic, economic, industrial and social framework for the high-quality use and circulation of organic and technical nutrients. Correspondingly, the aforementioned loops, e.g. recycling and repair, belong to the technical cycle. In addition to that, within CE, the C2C concept also comprises a second, biological cycle of renewable resources. In this cycle, the flow of renewables is focused. Both cycles of the cradle-to-cradle principle are commonly graphically illustrated according to Fig. 1.

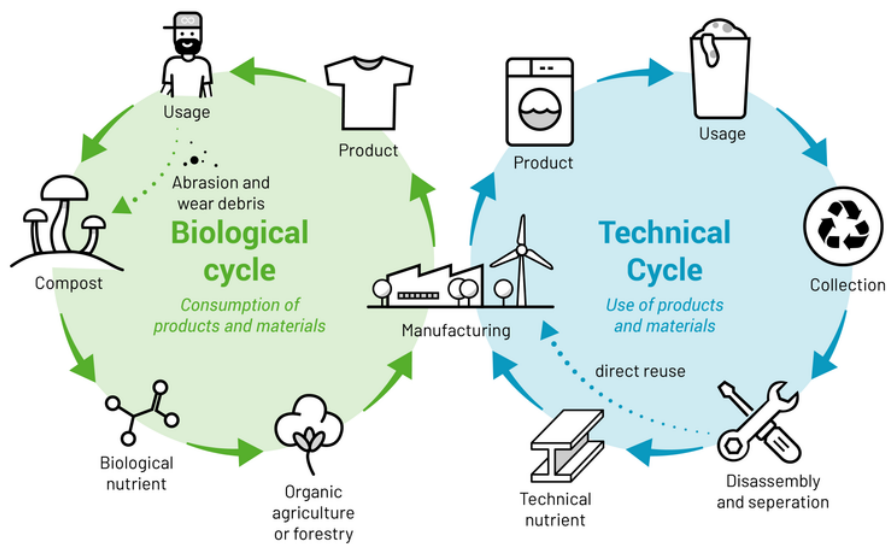


Fig. 1. Cradle-to-cradle concept by Baumgart and McDonough.
Image Source under CC BY-SA 4.0 [3].

For the engineering domain, MELDRUM suggests an engineering life cycle approach for complex and certified products [4]. Repair, maintenance, reliability etc. are some of the core engineering principles that drive circularity. In addition, standardization towards reusability and recyclability as well as modularity are identified as new circular principles supported on the existing product life cycle in engineering ranging from innovation over production until operations and eventually, disposition. Indeed, the engineering domains of design, manufacture, usage and end-of-life management of products have direct consequences on resource consumption, contribution to climate change and waste accumulation according to LEAL et al. [5]. In their study they assess and review the implementation of CE in German production industry during year 2023 coming to the conclusion that for the adoption of CE practices, industry, in particular SME, still face significant challenges while their findings emphasize the particular importance of Recovery and Redistribution efforts.

In deeper detail, JAWAHIR & BRADLEY explain that historically the principle of 3Rs – Reduce, Reuse and Recycle – significantly evolved during the 1990s [6] with the 1st R, Reduce, originating even earlier from the 1980s. The 1st R consequently corresponds to the principle of lean manufacturing while including 3Rs corresponds to green manufacturing. In addition to these aspects, the 6R principle brings along the aspects of Recover, Redesign and Remanufacture and is commonly denoted as sustainable manufacturing. Only with the inclusion of these additional three aspects, a closed-loop, multiple product life cycle system is achievable according to JOSHI et al. [7]. To achieve these goals, more recently, BADUREDEEN & JAWAHIR suggested strategies for value creation through sustainable manufacturing with the key aspects of education, integrated decision toolsets based on lifecycle sustainability assessment, risk and uncertainty modelling, lifecycle management and others being among them [8]. With particular regard to the manufacturing domain, it is pointed out in their

study that flexibility, scalability and reconfigurability play crucial roles in enhancement of the evolution of sustainability performance.

More specifically for fitting of manufacturing systems within a CE, ANDERSEN et al. postulate that these systems have to be designed and developed for disassembly, reprocessing of materials, re-assembly, and remanufacturing [9]. According to their claim, changeability is required to tackle higher degrees of uncertainties by closed-loop manufacturing systems for product take-back. The findings of this study highlight, that key challenges are fluctuating quantities, varying states of qualities, and a high mix of incoming end-of-life products.

When leaving the focus of closed-loop manufacturing, sustainable manufacturing must also consider energy consumption since any form of energy is inevitably linked to resource consumption, primarily (e.g. fossil fuel consumption) or secondarily (for instance manufacture of solar cells). In this regard, DUFLOU et al. have developed energy assessment methodologies [10] and eco-labelling [11] for the machines and machine tools used in manufacturing processes. With regard to the (manufacturing) process level, their studies show, how – from an energy point of view – adjustable machine tool designs can help to reduce energy consumption in most significant ways [12]. Particularly, for the more complex system level including all periphery, the exergy measure is adapted to manufacturing according to the 2nd law of thermodynamics to capture resource efficiency in manufacturing. By doing so, uniform units are achieved in assessing both energy and material consumption obtaining a comprehensive measure for both different efficiencies with the conclusion that the reduction of external exergy losses plays a crucial role for achieving resource efficient processes [12], [13].

Concludingly, with perspective drawn towards the manufacturing domain, processing of a) limited, finite materials and b) renewable resources needs to be focused on for circular manufacturing. Within the area of stock management of finite materials, the “R principles” of waste management are identified with repair, reuse, refurbish, remanufacture and recycle being amongst those [14]. Consequently, modern, circular manufacturing needs to fit processing of used products and materials. According to current definitions, the 9R framework provides a comprehensive structure for circular economy strategies by explicitly ranking environmental preferences, more specifically including steps for high level circularity, prioritizing refusing and rethinking and positioning the recycling loop as last resort in the CE hierarchy: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose and Recycle [15].

Contribution and Procedure

In the present study, we investigate premises and possibilities to enable and integrate a manufacturing system into a circular economy focusing on the domain of forming technology. Hence, we spotlight the scope of circular manufacturing on the micro scale within the hierarchy of production value-chain systematics [16], where the micro scale denotes the machine and production process, the meso scale refers to the production line within a facility and the macro scale indicates the uppermost hierarchy and encloses the whole supply chain. Driven by the megatrend of individualization [17], manufacturing engineering science has made large leaps by introducing flexible production techniques [18]. Flexibility indeed allows us to adjust manufacturing techniques to process non-primary resources. Following the necessity for research and development in flexibility, scalability and reconfigurability identified in the introduction [8], [9], we carefully consider highlighted cases where flexible, scalable or reconfigurable processes are assessed to upcycle used products or to process raw materials from non-primary origin. Based on process versatility, this study complements existing studies where metal forming process sustainability is valued based on exergy calculations [12], [13]. Closing, we derive critical obstacles on the micro scale with respect to machine and process and summarize the potential of a manufacturing system towards circularity.

Circularity enablers in tooling

Manufacturing processes are being carried out on machines using tools in order to process materials and products. Consequently, circularity not only concerns the processed objects but also

machines and tools. With probably the most long lasting consequent background, machines are not only being scrapped and recycled when passing their lifetime but also – with regards to the introductory mentioned technical CE loops and corresponding R-principles – being maintained, reused, repaired or even refurbished/remanufactured [19].

Tool materials. Looking at the inner technical CE loops, refurbishment of tools, to some extent, is state of the art in industrial practice if these are made from resilient and expensive materials for long lasting operation such as tool steel. Yet ultimately, out-of-life tools sooner or later end in the recycling loop. More recently, due to the introduction of additive manufacturing technologies, FROHN-SÖRENSEN et al. demonstrated an additively manufactured tool set based on fully recycled polymer waste for deep drawing of sheet metal cups [20] as a promising alternative for production of small lot sizes. Also, looking at the cradle to cradle concept, disassembly of technical nutrients seems promising for a perspective of manufacturing tools due to the abundant usage of standardized components.



Fig. 2. Wood-based tooling approaches for profile bending. Two common profile bending processes are schematically shown along to a set of wood-based forming tools.

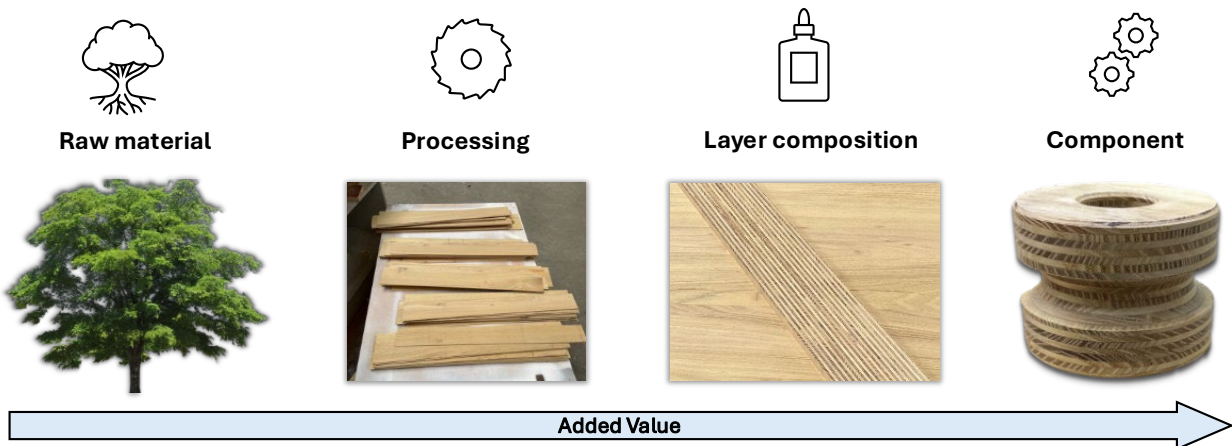


Fig.3.From trunk to tool. Schematic value creation along the production of wood-based forming tools.

In addition to the technical principles of the CE cycle, circularity in the biological cycle can be achieved by using renewable, robust base materials to manufacture tools. Wood is a renewable and bio-based raw material whose increasing versatility is opening new areas of application, apart from its use in construction or in combustion units [21]. In line with the 9R strategies, using wood as a substitute for conventional steel-based components in tools and structures offers the possibility of providing sustainable alternatives [22]. Additionally, cascade usage in conjunction with downgrading from raw wood to the chip or fibre stage enables multiple usage to be achieved in a resource-saving manner [23]. While the isotropic properties of conventional tool materials such as steel are relatively

easy to handle, the strong anisotropic and inhomogeneous properties of wood make it harder to characterize and model, for example in finite element analysis. Whereas an almost homogeneous material like tooling steel does not vary in its properties except for the rolling direction due to the manufacturing process, wood has several structural issues and difficulties, such as microcracks, growth zones, branches and capillary structures. The presence of these impurities varies depending on the wood species, growth location, and other environmental factors during growth. To overcome these issues and potential disadvantages, the design and layout process for wood-based forming tools and structural components needs to be investigated more widely and in greater depth. In construction work and building with timber products, for example, the partial safety factors for the strength properties of wood are higher than for steel due to the inhomogeneous structure [24]. The orthotropic material properties of wood are direction-dependent anisotropic properties that differ according to the growth direction by a factor of ~5–8. However, strength and durability are dominant in the growth direction. Due to the variation in strength of solid timber, suitable stacking or composite strategies are required to obtain an ideal or load-dependent layer arrangement. This procedure adds value to wood products at each stage of production and enables the creation of a tailored, optimized structural building material for mechanical applications such as tooling or structural components. (see Fig.3).

Several studies have investigated wood-based tooling approaches and structural components [25], [26], [27], [28], [29], [30]. With respect to forming tools and structural applications, GEUEKE et al. studied the performance of wood as a bio-based, renewable substitute for conventional profile and sheet metal forming applications (see Fig.).

GEUEKE et al. evaluated die geometries made from black locust wood and compared the forming performance and dimensional accuracy of these to a solid polylactic acid (PLA) die in a rubber pad forming process with DC04 steel sheets. The results showed comparable forming behaviour overall, improved radius accuracy for steel-hybridised dies and minor permanent deformation in wooden tools under high contact stresses [31]. In an additional study, Geueke et al. investigated the feasibility of using wooden freeform bending tools for EN 1.4301 stainless steel tubes. They found that the tools could bend the steel tubes with a performance comparable to that of conventional steel tools. However, they also found that tool orientation and the anisotropic wood structure significantly influenced deformation behaviour, process force capacity and circumferential uniformity. This offers enhanced flexibility and potential for mass customisation in profile bending [32]. Following a feasibility study of deep drawing applications using wooden forming tools on 1 mm DC04 sheet metal, GEUEKE et al. found that they performed satisfactorily for small-scale batch production. However, horizontally stacked tools showed inadequate dimensional accuracy due to the anisotropic mechanical limitations of the wood layers [33].

In summary, the use of wood-based forming tools and structural applications is a suitable way to enable CE in mechanical engineering (see Figure 2). Using renewable and carbon-neutral materials in production and manufacturing ensures cascade usage in the cradle-to-cradle concept. Combining micro-scale information from analysis techniques such as scanning electron microscopy (SEM) or X-ray with macro-scale knowledge from the construction and building industry will help to develop meso-scale applications for wood-based tools and structures, thereby extending renewable resources in the CE. Although there are still some difficulties to overcome and adjustments to make when dealing with wood-based structures, feasible components that use sustainable and economical materials have already been demonstrated in mechanical areas such as forming tools and structural components.

Tool operation principle. Besides the materials a tool is made of, its universal applicability has been identified as critical premise to enable circular manufacturing. Flexibility, as per definition characterized by physical variation, lot size variability, number of DoF and complexity [18]. While conventional rigid and solid tools are usually highly specialized to a certain geometry and therefore limited in their flexibility with respect to realizable component geometries and are not designed for sustainability, adjustable tools actively allow for variable manufacturing by adding significant degrees of freedom. At the same time, batch-size variability is passively increased, as product variants

can be manufactured using the same tool. This approach reduces the fixed costs associated with tool manufacturing and saves time otherwise for tool changes, while simultaneously enabling flexible, efficient, and sustainable resource efficient production.

To increase the flexibility of tools, adjustability of the tool contour is required. One approach to realizing such contour modifications is the segmentation of conventionally closed tool surfaces and the targeted adjustment of these segments. In this way, reconfigurability of the tool contour is enabled, allowing different component geometries to be manufactured using a single tool. In particular, segmentation offers the potential for adjusting individual segments. This adjustment can either be performed prior to the process (static adjustment), enabling the production of different component geometries from one operation to the next, or during the process (in-process adjustment). The latter additionally provides the opportunity to deliberately vary the forming path, thereby positively influencing both the process behavior and the resulting component quality, as well as extending the process limits.

Approaches to segmentation as well as reconfigurable and adjustable tools are well known from multi-point forming (MPF), also referred to as digitized die forming (DDF), particularly in the field of sheet metal forming, and have been extensively investigated in numerous studies [34], [35], [36], [37], [38], [39], [40]. Corresponding approaches to segmented and adjustable tool concepts have also been investigated in the field of profile forming and are gaining increasing importance, becoming the subject of several research studies [41], [42], [43], [44].

HEFTRICH et al. [45] developed a systematic method for reducing and simplifying bending tools. Based on numerically computed contact pressure distributions during rotary draw bending using conventionally closed tool surfaces, surface regions that contribute little or negligibly to the forming process are identified. This leads to simplified tool designs which, due to the additional available installation space, can be equipped with further adjustment axes. As a result, existing tool concepts can be extended, enabling the manufacture of multiple component geometries using a single tool set.

Furthermore, in extensive studies [46], [47], [48], [49], the segmentation of forming bending tools was investigated both experimentally and by means of numerical simulations. REUTER [50] developed a deformation-mechanism-based method for the design of segmented tool surfaces aimed at increasing the flexibility of bending processes. Based on the investigation of the interactions between tool surface topology, the mechanical and geometric properties of the semi-finished product, and the resulting forming phenomena and mechanisms, a systematic design approach for segmented tools was developed using compression bending as a representative process example. The resulting segmented tool enables the adjustment of different bending radii from one bending operation to the next. Both constant radii and radii that vary along the bend line can be realized (see Fig. 3). Owing to the additional degrees of freedom provided by the tool, the potential for in-process adjustment is also introduced. Compared to conventionally closed tool surfaces, this significantly extends the range of possible applications.

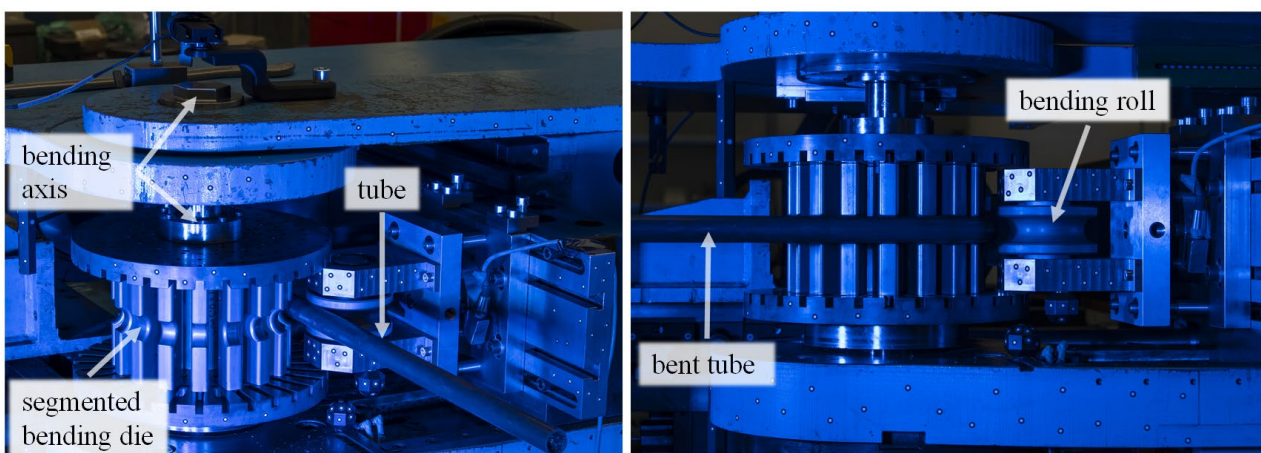


Fig. 4. Segmented and adjustable bending die for compression bending [50]

Concludingly, segmented forming tool concepts offer the possibility to adjust tooling towards a variety of products but also, in the light of the present approach, varying materials to be processed. Prospectively, even used products may be processed by an adjustable toolset; both aspects therefore contribute to circular economy.

Circularity enablers in exemplary forming processes

Free-form bending (FFB). FFB techniques provide high degrees of flexibility with respect to manufacturing flexibility in profile bending. While conventional approaches for profile bending use dedicated die systems. In die bending, the full geometry of the product is resembled within a dedicated press tool which restricts geometry adjustments and variability for the sake of process simplicity and robustness as long as no supply chain changes may disrupt the process tolerances. Next, rotary draw bending [45], [51] and, similarly, compression bending [52] are profile bending processes for the production of challenging, narrow geometries with highly dedicated tool sets. With respect to variability, the bending angle may be adjusted to process fluctuations to compensate for elastic springback in these processes. However, both processes are only capable of processing straight profiles which is a strong limitation towards reprocessing of used materials after disassembly of End-of-life (EOL) products. A number of different FFB technologies has been developed in the past, mainly to overcome geometrical limitations by means of variable manufacturing. Three-Roll-Push bending [53] allows to flexibly adjust the product radius or variable radius distributions by supporting initial state of the product between rollers and the positioning of a bending roller whilst feeding the tube in a longitudinal way. While the procedure leads to very large flexibility, that is almost only restricted by the machine dimensions, minimum radii that may lead to buckling effects and the profile's cross-sectional outline which needs to be resembled in the roller profiles, control, radius prediction and process modelling have been recent challenges to master the resilience of the process [54], [55]. However, once the cross-section of a profile is variable over its length, FFB processes are still under development and bring along enormous process complexity and, again, a higher dedication of tooling [56].

Concludingly, FFB processes exhibit readiness potential for circular manufacturing by means of strongly elevated flexibility and sufficient control concepts to master resilience. In particular, FFB operations would allow to in-situ adjust the process towards shifting material qualities which holds the potential to minimize any scrap production. Limitations are identified with regards to processible used materials which might originate from EOL products.

Incremental forming methods. In incremental forming, the manufacturing tool size is only a fraction of the whole product geometry dimension. Consequently, shaping is conducted by repetitive approaches with successively increasing straining. From a technological perspective, very small forming zones with strong strain gradients result compared to continuous, conventional methods with dedicated tool sets. For instance, single-point incremental forming (SPIF, aka incremental sheet forming ISF) is a process, where a small spherical tool is mounted to the tip of a robotic arm, which successively forms a piece of sheet metal along dedicated concentric paths [57]. Within the domain of sheet metal forming, hardly any process exceeds the degrees of geometrical freedom of this technology owing to the variability of process conduction. Even more, it is well known that incremental forming methods allow higher strain values than possible with conventional forming methods [58]. Similar to FFB processes, control, process modelling and geometrical prediction are crucial premises to master an efficient and accurate process operation of SPIF [59]. In addition, due to the discontinuous nature and the very small forming zone, incremental forming methods inherently require higher process times than continuous processes. On the bright side, high product variability and universal tooling allow for valuable, economic production of even unique parts. With more specific regards to sustainability and environmental benefits, COOPER & GUTOWSKI demonstrate in their study that the ISF process potentially avoids large tooling and therefore saves time, money and energy [60]. Based on an extended anticipatory LCA, they present a methodology how to assess the potential industry level impacts of an emerging technology. More specifically for the incremental forming method, they demonstrate high energy and cost saving potentials for an implementation

scenario of the forming technology in the U.S. car industry by 2030. Other studies such as AMBROGIO et al come to the conclusion, that the energy efficiency of SPIF can be significantly improved by adopting high speed variations of the process since the high cycle times still limit the industrial applicability of this incremental method [61]. Both studies are confirmed by the findings of SIMONCELLI et al.: they attribute the sustainability potential of SPIF to low volume production and the avoidance of large die sets and the associated provisioning times, while the large dependence of the sustainability potential is highly related to the processing time of this manufacturing process [62].

Similar advantages and limitations are observed for the incremental forming methods of shear spinning [63], [64], open die forging [65], incremental folding or v-die bending (bumping) operations [66], [67] or incremental profile bending [68], [69]. Recapitulatory, incremental forming methods provide highest degrees of geometrical freedom. Process control, high processing times and, in addition to that, surface imperfections due to the successive nature of this class of processes are challenges that need to be overcome. Moreover, the shape of the material to be processed is often dedicated to a certain die geometry for clamping – or vice versa – so that manufacture of cheap or recyclable clamping dies may be a solution. Overall, these degrees of freedom contribute to these processes' readiness for use in circular manufacturing while the geometrical dedication towards clamping and mastering the process layout are current challenges.

Findings and Discussion

The exemplary case studies from the metal forming domain presented above show us that – within the process unit scope or value-chain micro scale scope – circular manufacturing is enabled at two different layers: i) the manufacturing system by means of machine and tooling and ii) the manufacturing process conducted on this system. The considerations show, that the Cradle-to-Cradle C2C theory [2] is applicable to both layers i) and ii) with respect to the technical and the biological cycle.

Firstly, under technical consideration, a machine and its tooling may be re-introduced after End-of-life EOL according to the 9R principles ranging from maintenance and repair up to recycling. If not so, resources leak from the cycle – as in linear economies. On the other hand, a manufacturing system may as well be part of the biological cycle if its structure is composed of cascable natural and renewable resources. Even if these resources leak or cannot be used in purposeful applications after the last cascade, the biological cycle still allows to make use by thermal or natural degradation.

Secondly, manufacturing by means of the production process is an element within the lifecycle of a product made from technical or renewable resources. Conventionally, in linear economy, the manufacturing process converts primary resources to products, which ultimately leak their resources after EOL. For the technical resource cycle, the manufacturing system is expected to process recycled resources with potentially larger uncertainties regarding the quality and properties of materials (3R). In addition to that, upcycling of used products or parts of disassembled used products is a vital aspect in the relation of the 6R systematics. Within a cycle of renewable materials, processing of natural materials is expected. In a nutshell, looking at the manufacturing process, key enablers for circular manufacturing are its manufacturing flexibility, scalability and reconfigurability as well as the process' resilience against uncertainties. Fig. 4 summarizes these findings.

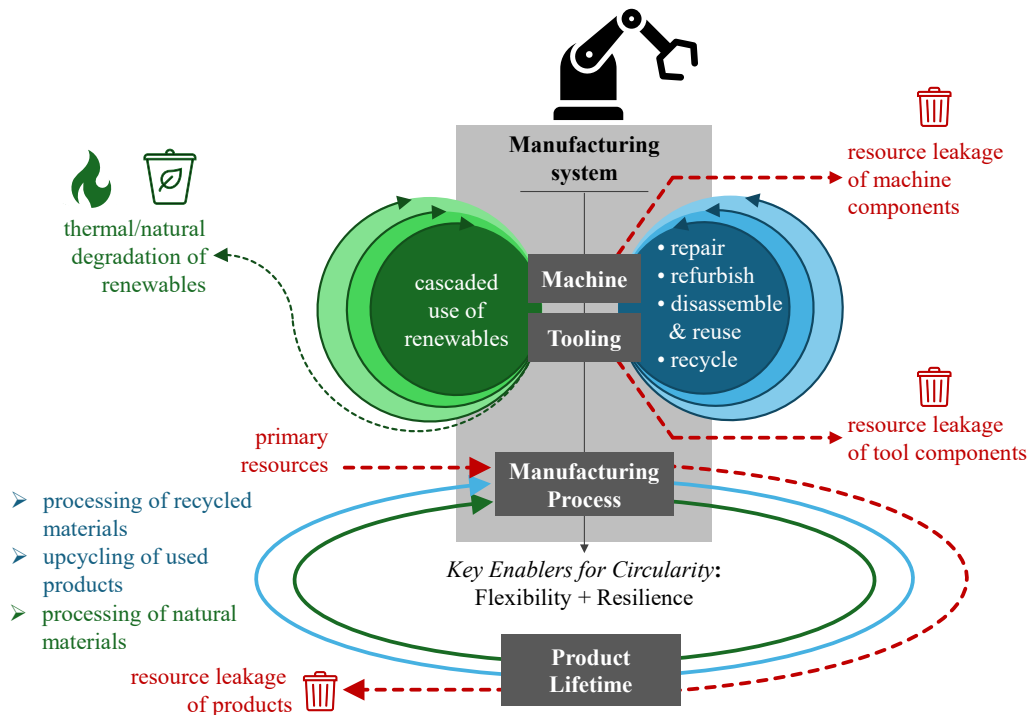


Fig. 5. Circular manufacturing on the micro scale of value-chain hierarchy systematics.

Evidently, the resource leakages shown above must be mitigated to conserve resources. Consequently, a manufacturing system may be designed and operated in a way to achieve and facilitate one or more of the four central aspects indicating the system's readiness for circular manufacturing "Ready4CM":

- Machine and tooling are within technical cycles (9R): They are maintained, refurbished, reused etc.
- Machine and tooling are from cascadable, renewable resources such as tools from wood.
- The manufacturing process facilitates reprocessing of used materials originating from EOL products.
- The manufacturing process is capable to process renewable natural resources.

It is worth noting the machine's and tooling's dual role as a product and as a production system which is reflected by the presented systematics and in-line with literature findings [11].

Conclusions

Circular economy is introduced to overcome the ongoing exploitation and systematic leakages of primary resources as it has been undertaken intensely since the age of industrialization. Within the circular economy, manufacturing is one vital cornerstone in the evolution of products besides design, distribution, usage, collection, etc. It has been indicated that circular manufacturing systems must be capable of processing disassembled parts of used products. To complement existing sustainability considerations based on exergy balances, the present study reviews in depth observations on the process unit / value-chain micro level and derives necessary premises of manufacturing systems to serve circular economy based on the system's versatility by means of flexibility, scalability and reconfigurability. The ready for circular manufacturing "Ready4CM" theory developed in this paper comprises i) the manufacturing system and ii) the operated process. Key indicators for circularity are the material origins of the machine and tool as well as their wholistic maintenance and reuse principles. Moreover, the process' capability to re- and upcycle used materials and the necessary flexibility, control and resilience to use materials from non-primary or renewable resources are found to be indicative for circularity. Embedded in existing CE and sustainability frameworks that primarily

balance sustainability potentials, the Ready4CM systematic identifies technical premises for manufacturing processes to serve and facilitate CE.

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