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Procedia CIRP 70 (2018) 180–185

www.elsevier.com/locate/procedia

28th CIRP Design Conference, May 2018, Nantes, France

Integrated Product, Production and Material Definition for Conventional versus Generative Manufacturing Technologies

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Abstract

Generative or additive manufacturing is today getting more and more an appropriate de-facto standard in industrial production. The often-cited “industrial revolution from the printer” exhibits enormous potentials even concerning a creative design freedom as well as huge varieties in flexibility (e.g., a broadening diversification of the individual product spectrum associated with small lot sizes). In contrast, however, conventional manufacturing technologies within the automotive industry, for instance, still point out benefits with regard to process stability, automation, productivity, but also quality assurance.
Set against this background, and to support the systematic and increasingly industrialized application of additive manufacturing (AM) in industry, this contribution presents a scientifically detailed view on a methodological set-based approach, which provides a technical, economic and ecological significance in terms of choosing the right manufacturing technology, associated with its principle design and appropriate material already in the early phase of product development.

Keywords: additive manufacturing; decision making; conceptual design; process selection; integrated assessment; set-based engineering

1. Introduction and Motivation

Today, with the ever-increasing internal, but also external requirements on engineering design (e.g., market-driven demands for an increasing diversification of the product spectrum), actual component geometries are becoming more and more individual and at the same time complex, not merely from a designing perspective, but especially from the production point of view [1]. However, the individual components cannot be designed arbitrarily, since they must be commercially producible with an available manufacturing technology. Thus, particularly in light of conventional subtractive processes, special attention has to be paid to production-side requirements, whereas the emerging additive manufacturing (AM) processes considerably increase the geometric flexibility (e.g., previously common manufacturing restrictions such as intricate contours, undercuts or cavities), all without any additional manufacturing costs [2,3]. In this way, the 3D printed geometry follows the proper functionality and not - as usual - vice versa, which ultimately leads to hitherto unprecedented optimization potentials (e.g., size and weight reduction, performance increase, and skillful integration of functions). In contrast, however, conventional manufacturing technologies within the automotive industry, for instance, still point out benefits with regard to process stability, automation, productivity, but also quality assurance, as displayed in Fig. 1.

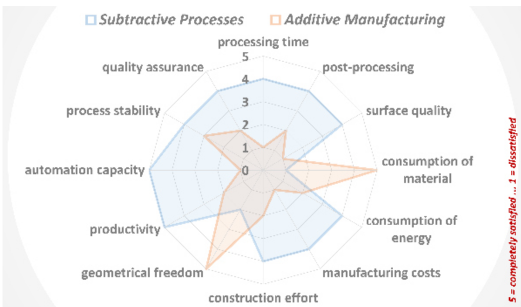

Fig. 1. Potential analysis - subtractive processes vs. additive manufacturing

Set against this background, a prospective challenge lies in a holistic and integrated assessment of the right manufacturing technology (production definition) bearing in

10.1016/j.procir.2018.03.140

mind a tailored geometry (product definition) along with a further optimized material definition, finally based on the individual application (e.g., requirements, load case, legitimate expenses). Or, put another way, when and under which conditions or rather aspects is the generative manufacturing technology a worthwhile approach to be used?

Therefore, and to overcome this hitherto considerable uncertainty, this contribution presents a methodological set-based approach originating from a holistically integrated product, production and material engineering framework (section 3), after the initially related state of the art in literature was clarified in section 2. Validated by a re-design application example of a shock absorber (section 4), finally section 5 discusses the findings and provides an outlook.

2. State of the Art in Literature

First, the following chapter reviews fundamental scientific approaches for (mostly) selecting product solutions, manufacturing technologies, and materials individually, but also with regard to a simultaneous engineering. After that, contributions to an evaluation and/or assessment of AM potentials are analyzed in-depth.

2.1. Selection of Product Solutions, Manufacturing Technologies and Materials

The selection of product solutions, manufacturing technologies and materials is a crucial step in product creation, since it massively determines the later success of the product as well as its sustainability. For this reason, a systematic approach that considers multiple criteria is inevitable.

A systematic strategy for the selection of product solutions is described in Pahl and Beitz [4]. Herein, the deployment of solution-neutral functions based on the requirements is the initial step. Alternative solutions for each function have to be developed, subsequently. Thus, methods like the morphological chart are able to support the developer by selecting the best solution. Accordingly, an assessment is required according to objective values to reduce the negative impact of subjective influences on the design process. VDI 2225-3 [5], for example, presents such an approach that assesses possible solutions in terms of technical and economic values with a range from 0 to 4 to qualitatively fulfill the individual constraints. Subsequently, both values are arranged in a diagram for each solution, wherein the developer can select the most promising solution. An extension of this approach to ecological values is an option to realize a multidimensional assessment.

Apart from that, the selection of manufacturing technologies and materials determines the technical, economic and ecological performance of a product to a high degree. However, narrowing potential processes and materials is a huge challenge for developers due to the high number of potential solutions.

Approaches like material selection according to Farag [6] or Ashby [7] support design engineers in selecting appropriate materials and processes. Referring to the latter and starting with the translation of material-related requirements into specific material properties, the complete material variety is screened by using constraints and material indices that describe the ratio between two properties. In doing so, the Cambridge Engineering Selector (CES) [8] supports the screening and eliminating of potential materials with a two-dimensionally visualized selection window (so-called material property chart). Subsequently, the remaining materials are ranked according to their performance, and finally suggested specifically to be used on the singular material point of view. Moreover, and according to this deficit, this approach is extended to a first integrated perspective of process selection [9]. Herein, the selection strategy is similar and the variety of manufacturing processes is narrowed by means of adequate process constrains. In addition, Ashby [10] integrates product-related aspects like possible (profile) design geometry into the material selection. However, a real concurrent selection is missing up until now.

2.2. Simultaneous Engineering

Simultaneous engineering (SE) is a well-known approach that focuses a parallel development of products and production systems. Initial approaches emerged already in the 1969, although the topic achieved a wide attention in science in the 1980s [11]. Thus, reducing time and costs by a parallelization of tasks and a better communication between product and production development are the main targets of concurrent engineering [12]. Additionally, and according to Andreasen and Hein [13], a deeper integration of methods and processes is required, instead of a simple integration of organizational units to face the challenges of distributed tasks in modern companies. As a result, the prestigious design for manufacturing and assembly (DfMA) integrates manufacturing aspects into product development [14]. Furthermore, the set-based concurrent engineering approach works with solution sets in the product and production engineering that are being narrowed systematically along the development process, but not totally eliminated until the end [15]. This is because a greater flexibility concerning unexpected changes is still a resulting benefit, particularly to handle initial uncertainties within the early product development. In addition, and compared to the predecessors, Benders [16] presents an approach that focuses material aspects explicitly within an integrated material, manufacturing process and geometry synthesis. Herein, the geometry of all product parts are determined based on the working principle. Afterwards, potential manufacturing processes and materials are selected successively, and finally the solution combinations are assessed according to technical, economic and ecological criteria.

2.3. Evaluation/Assessment of AM Potentials

Since additive manufacturing offers new or rather innovative realizations of designing structural, but also functional geometries by its revolutionising manufacturing process, there are certain advantages of these specific technologies compared to conventional, i.e., subtractive processes, which result in evident benefits for part fabrication.

To approve this statement, several contributions focus on miscellaneous comparative investigations. Thus, the approach by Newman et al. [17] takes into account comparative considerations within the initial planning phase of the process chain for both additive and subtractive manufacturing. Moreover, e.g., Paris et al. [18] and Yoon et al. [19] evaluate environmental impacts of both different technologies.

Nevertheless, most significant potentials for using AM in both an independently substituted technology or in process chains are identified considering first of all constructive aspects (i.e., basically mechanical properties), cost effects as well as environmental impacts of products and production in general, which is comprehensively highlighted, e.g., in [20].

Dealing with this new technology in more detail, potential benefits regarding geometrical aspects emerge from the design freedom and the achievable complexity of the individual part and assembly design. Considering this, Bikas et al. [21] and Klahn et al. [22] emphasize the meaning of AM for the design of lightweight structures by reducing mass and cutting material consumption to a minimum necessary degree, which immediately results in cost savings due to a reduced material invest and profusion. In order to exploit the potential of AM processes in the meaning of lightweight design, Klahn et al. also insist on the necessity to identify parts and assemblies, which are suitable for an advanced function integration (so-called “integrated design”) as well as load-specific “efficient design” [22]. A further aspect of potential discovery lies in the assessment of individualization needs referring to “complex parts with a high variability” that need to be individualized in order to meet customer requirements, such as distinction and exposition of, e.g., status or wealth.

Apart from that, Schmidt [23] focuses on the three pillars of “lightweight design”, “function integration”, and “cost/time” that are embraced by the technology as “enabler” for productivity and efficiency, particularly highlighted on the aviation industry. Thus, and in order to establish a reliable process selection, Schmidt analyses and evaluates available materials and processes that potentially can be used for the specific use case, always ensuring a strict correlation with economic issues by defining strict guidelines from the lightweight design and economic point of view.

Considering cost savings, different approaches are proposed. While some authors concentrate on costs emerging solely from a production perspective, other scientific contributions demand a more holistic treatment of costs as part of the lifecycle assessment (LCA). Thus, Cunningham et al. [24] explicitly emphasize the importance of both direct and indirect costs, which include material, machine, overhead, and administration costs on a time-related basis. Moreover, the urgent significance of post-processing costs is underlined, which again shows possible AM potentials in a process chain where post-processing costs are minimized by an optimized part positioning, build space utilization, and build direction strategy considering relevant part characteristics (e.g., influence on mechanical properties and quality aspects) [25].

Current research efforts in sustainability concerns concentrate on a holistic indication of energy consumption from material resources, over process execution (including secondary processes like powder generation and provision) and machine operation to post-processing activities, which are necessary for the generation of end-use parts with acceptable surface finish. Kellens et al. [26] highlight especially post-processing activities and their effect on energy consumption, and thus the sustainability of the AM process, whereas a main portion of the overall invested energy emerges from the machine operation, as stated in several contributions on this topic (e.g., [26-28]), also for polymer processes.

To sum up, the aforementioned research status represents different contributions regarding an overall comparative or sole AM technology evaluation based on a technical basis, specific economic issues, and ecological effects. Nevertheless, an easy but holistically true assessment approach considering the comparable selection of conventional (subtractive and/or formative) processes versus the innovative application of an additive manufacturing technology could not be traced for an integrated product and production engineering for early phase (conceptual) developments. Thus, this contribution presents the application of an integrated product and production engineering approach on the basic screening of additive and subtractive manufacturing processes in a rather processual than technological manner, which is now dedicated below.

3. Integrated Product and Production Engineering Framework

Although the integrated product and production engineering (IPPE) framework previously developed by the authors [29] basically contains the two fundamental domains of product and production development, material selection is an essential part within the engineering design, and thus is equally considered as a (third) domain [30,31]. The definition process in each domain contains four phases. At first, the specification phase determines all respectively relevant requirements. On this basis, the concept phases develop promising concepts in each domain, which are further refined for all involved components within the component/detailed phase. The system integration phase finally integrates all components to the total system and evaluates, for example, the interplay of different adjacent materials.

3.1. Integrated Process Model

Based on a consistent description of the domains (see [32]), a general process model regarding the integrated definition of product, production, and material is presented in Fig. 2. Herein, integrated assessment and selection steps complement the domain-specific definition processes.

Thus, the procedure is as follows. Based on the assigned requirements, the concept phase of the product definition generates alternative working principles that fulfill the functions of the product. The production and material definition deploy alternative manufacturing technologies and material subclasses equally. Design catalogues, collections of potential manufacturing technologies, and material databases (e.g., CES [8]) support this solution generating process.

The integrated concept phase (1) subsequently assesses and narrows alternative combinations of working principles, manufacturing technologies, and material subclasses. Technical, economic and ecological criteria like the technical value, carbon dioxide emissions, energy consumption or costs are calculated by means of databases and normalized to a scale (0-10) for a better comparison and the consideration of different lifecycle phases. Thus, an appropriately weighted and summed average value (0-10) represents the performance regarding each criteria, and ultimately enables the developer to select the best (constructive and technological) solutions regarding technical, economic and ecological criteria.

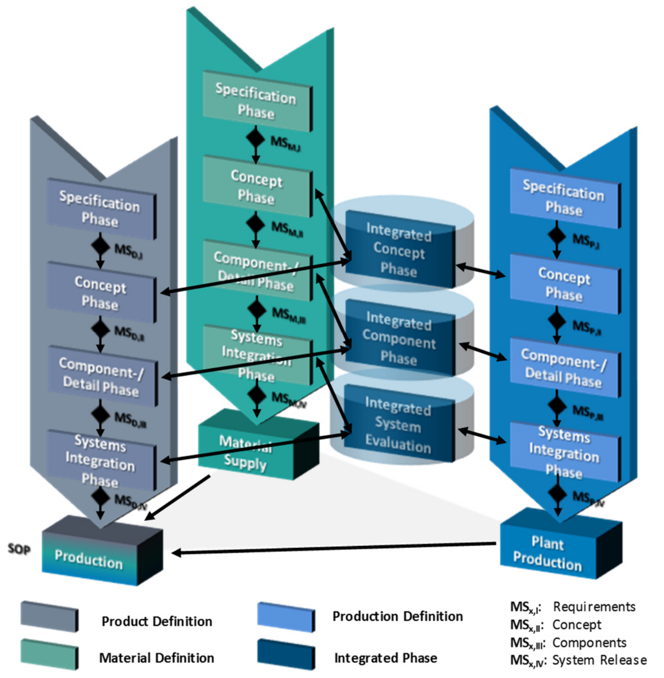

Fig. 2. Integrated definition of product, production, and material [32]

The integrated component phase (2) applies the same process to the component level. Here, the focus is on the assessment and selection of more detailed alternative product components, production systems, and materials. The domains develop alternative solutions and perform specific simulations, such as FEA and CFD analysis (product view) as well as NC simulation (process view), in order to gain information for the performance assessment of the individual solutions. At this point, the integrated morphological chart is also used to select the best ones. Subsequently, the domains integrate the developed components to the respective systems.

The interplay of the product, the production system, and the used materials is finally evaluated in the integrated system evaluation phase (3). Herein, methods such as process simulations, lifecycle costing, and lifecycle assessment (LCA) provide detailed information.

3.2. Methodological Selection Approach

The integrated morphological chart supports the developer by processing the generated multi-dimensional assessment results. A 3D-cube represents the alternative combinations of product, production, and material solutions along with their technical, economic and ecological value (see Fig. 3).

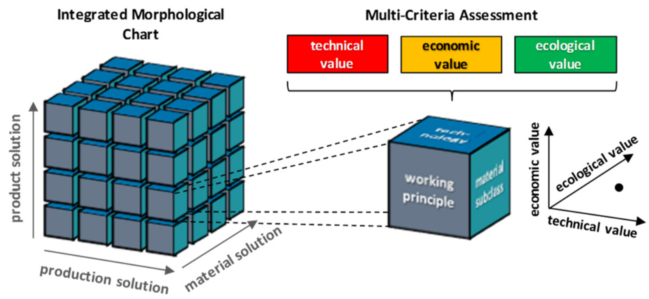

Fig. 3. Integrated morphological chart method [33]

This method is applicable in the concept as well as component phase and calculates the best solutions for each level based on 72 individual criteria derived from considerations in section 2.C, partly shown in Fig. 4. Due to three solution dimensions in combination with three assessment dimensions, the complexity is very high. For this reason, an innovative software tool is required for the efficient use of the integrated morphological chart. Thus, the authors developed an on-line analytical processing (OLAP) based tool displaying potential solutions for each domain in a three-dimensional graph originating from aggregated considerations of subjacent sequence levels, as already stated in [32]. In doing so, this structure enables a sequential but integrated selection of set-based solutions, where users are able to select the best solutions systematically or manually.

A manual selection enables the consideration of expert knowledge. The actual user-interface with its screening area shown in the application example in Fig. 6 and 7 rather focuses on the conceptual phase, why the tool up to now has a low-level character. There, the settings are arranged on the right side, where users are able to select the displayed criteria and choose the desired selection sequence. Additionally, an export function is given to export the recorded selection data.

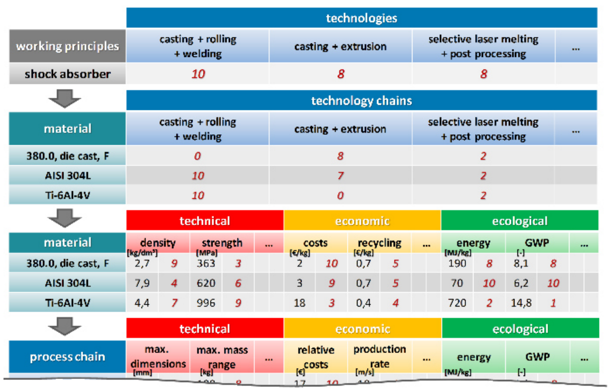

Fig. 4. Extract of technical, economic and ecological assessment criteria and its calculation framework within the OLAP system

4. Application Example

This section presents the application of the aforementioned integrated approach on the development of a shock absorber for automotive industry (as displayed in Fig. 5), initially also with regard to the use of AM technologies. In doing so, the focus is on the most beneficial manufacturing process of the base body, whereas the product concept is fixed, and thus the integrated component phase (2) is executed.

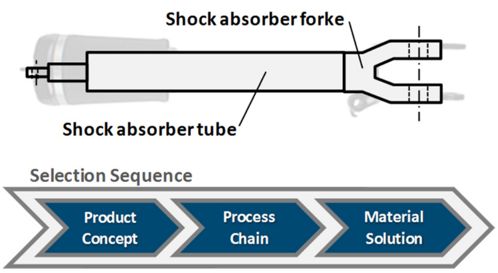

Fig. 5. Validation example “shock absorber” (automotive industry)

At first, the authors deployed a variety of alternative additive (e.g., metal fused deposition vs. selective laser melting) as well as conventional (e.g., casting and rolling vs. casting and extrusion) manufacturing technologies along with its feasible materials to assess all potential combinations according to their technical, economic and ecological performance. The results are processed and visualized with the integrated morphological chart software as outlined for the technology level in Fig. 6. In this example, a potential technology chain is represented as one (combined creating and changing shape) process to fulfill the required production function. The fact that different numbers of required functions are needed depending on the respective technology, the potential technologies are aggregated. Alternatively, several production functions are determined, whereas not required functions are assessed with a higher score than 10 [34].

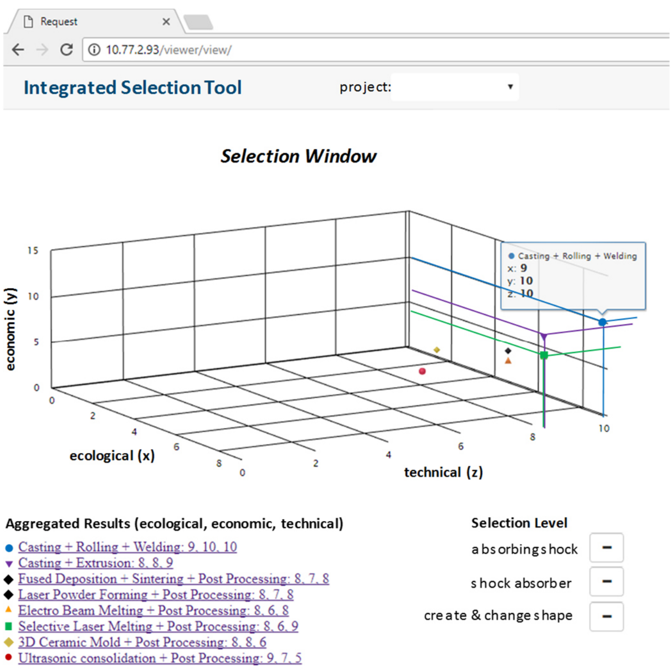

Fig. 6. Assessment results of the technology level

As shown in Fig. 6, the conventional manufacturing technology chains (casting + rolling + welding as well as casting + extrusion) have the highest technical, economic and ecological scores for standard (economic) batch sizes in the first level. These facts logically result from the long-term optimization for the manufacturing of these components in industry, especially in terms of the economic performance. Now, however, the question still remains: when additive manufacturing technologies are applicable for such a use case in combination with which exact material?

Thus, and against the background of a high number of non-variable parts, additive manufacturing technologies are considerably less beneficial in comparison to traditional mass production technologies due to its huge capital invested in production systems, even if the process chain may be essentially reduced for AM. In contrast, and with respect to an increasing diversification of the product spectrum along with the decreasing unit quantities of each production lot (changed starting requirements), the expenses per part increase, whereas the costs for AM remain unchanged for small batch sizes.

From a technical view, the selective laser melting technology is able to realize similar results like conventional technologies. For small batch sizes, for example, in motor sports, this technology is equal to conventional technologies or (mostly) even more advantageous because of the high geometric flexibility according to the direct manufacturability of a load case and path dependent, topologically optimized design and - of course - its unique selling proposition (USP). Accordingly, a break-even point need to be determined.

Fig. 7 shows the material level of the selection process in the software tool. At this point, stainless steel (AISI 340L) as well as aluminum (380.0) are appropriate materials regarding to their technical, economic and ecological performance, which can be processed with both conventional and additive manufacturing technologies.

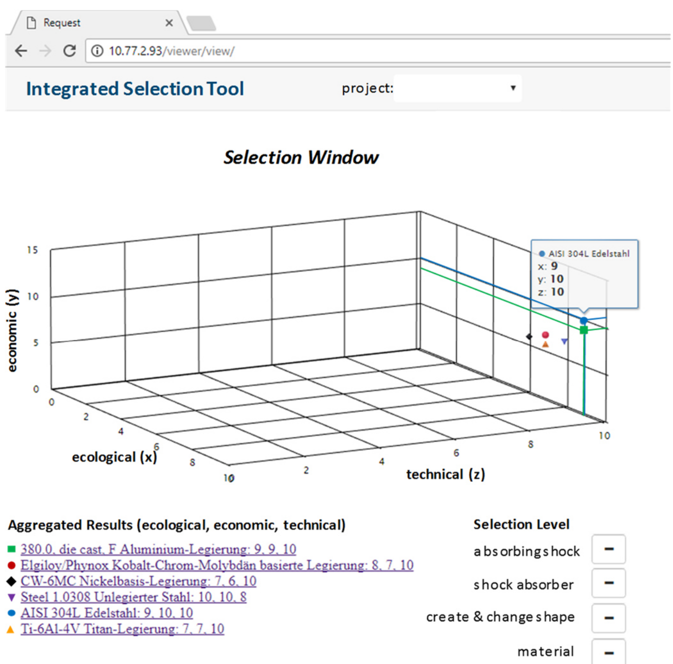

Fig. 7. Assessment results of the material level

This means that the shock absorber should be manufactured by a AISI 304L stainless steel from a casting + rolling + welding process (total value: 18,20,20) for large-scale productions, whereas a selective laser melting process along with its necessary post-processing fabricated as well by stainless steel (total value: 17,16,19) achieves much more benefits with respect to lot sizes below 100 parts (+1 point in economic value for each decimal power below 100.000 parts).

5. Discussion and Outlook

To sum up, starting from a broad range of fundamental scientific approaches for (mostly) selecting product solutions, manufacturing technologies (including a deeper view on the evaluation/assessment of AM), and materials individually, this contribution stresses the need for a holistic and integrated product and production engineering (IPPE) approach with initial regards to additive manufacturing. Thus, the herein integrated and set-based selection of the right production process bearing in mind an optimized material definition is supported by an on-line analytical software tool based on the concept of an integrated morphological chart, which additionally takes into account a potential analysis of AM technologies already within the early phase of product development. In doing so, the methodological set-based approach provides a multi-criteria decision-making (MCDM) in terms of technical, economic and ecological aspects.

In future work, the present database will be enhanced systematically in quality and quantity to deal with a greater variety of development tasks. At the same time, the concept will be lifted to a completely new level of cross-dimensional (i.e., more systemic) aspects as an indispensably issue to increase the capability in terms of prospective multi-material lightweight systems [35]. Thus, also more geometry-specific aspects come to the fore. However, this contribution already significantly adds value to an efficient and integrated choice of product, process and material design on the bottom line, particularly with respect to the holistic implementation of the nowadays more and more demanded potential analysis of AM technologies. This is now further on investigated on a more individual, step-by-step process (chain) selection in [34].

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