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Procedia CIRP 61 (2017) 594 – 599

www.elsevier.com/locate/procedia

The 24th CIRP Conference on Life Cycle Engineering

Sustainable Value Roadmapping Framework for Additive Manufacturing

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Abstract

Recent developments around the use of additive manufacturing (AM) for making components and end-products is radically changing the way manufacturing activities are organized. Many researchers are now turning their attention to AM technology and its potential benefits for boosting economic, social, and environmental sustainability. However, there is still much uncertainty on the full impact from a life cycle perspective. Previous work has reviewed the implications of AM from a sustainability and life cycle point of view, but it is unclear whether the technology can fully realize the potential benefits identified, and whether it will lead to unintended consequences such as increased material consumption, thereby further straining the planet's carrying capacity and pushing society towards unsustainable, more materialistic values. This research builds on previous work to customize a tool, the Sustainable Value Roadmapping Tool (SVRT), which combines the strategic roadmapping technique with the sustainable value analysis tool. Roadmapping is a well-established approach for businesses to strategically plan activities for the short-, medium- and long-term; combined with the value analysis tools, it can identify opportunities for sustainable value creation for all stakeholders, including society and the planet. While SVRT has been developed and tested in a more generic context (i.e. not technology-specific), it also has good promises to help companies to explore the potential benefits and challenges of AM adoption across products' life cycle and the associated business model implications. This paper will present the prototype version of SVRT for AM. The findings consolidate and expand the opportunities and challenges already identified in the literature. Further work will conduct case studies to use the SVRT with companies adopting AM technology and better understand the sustainability impacts from a business perspective.

Keywords: sustainability; additive manufacturing; 3D printing; roadmapping; sustainable value; framework; tool development

1. Introduction

Additive Manufacturing (AM) is a "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [1]. AM consists of a broad range of technologies which can process various materials such as plastics, metals, ceramics and composites [2,3]. AM has historically been used for rapid prototyping and rapid tooling, and more recently for direct part manufacturing, also called rapid manufacturing [4], especially in the aerospace, jewelry and medical sectors [2,5]. With the development of new processes and materials, it is expected that AM will become a pervasive manufacturing method [6]. However, there is still much to learn about AM technologies, and how companies could adopt them to support innovation, increase competitiveness and improve their sustainability performance.

Technology and business model innovation are widely recognized as key enablers for improving companies' competitiveness and sustainability performance [7]. Such innovations require businesses to envision the future at a company and industry levels. Roadmapping is a well-established tool which can help companies to integrate technology management and strategic planning for building such visions [8]. This research makes use of a hybrid roadmapping tool, the Sustainable Value Roadmapping Tool

doi:10.1016/j.procir.2016.11.186

(SVRT) [9], to help envision the future business opportunities and challenges in adopting AM. More specifically, this paper presents a framework for AM adoption based on a life cycle perspective [10] and the SVRT [9]. The framework aims to integrate sustainability considerations into the innovation and strategic planning process for AM adoption. The framework proposes a pick-and-choose approach whereby the company can select which aspects they need to focus on, prioritize the most important issues.

2. Literature Review

2.1. Additive manufacturing technologies

AM builds 3D objects on a layer-by-layer basis from a CAD model. ISO/ASTM52900-15 defines seven categories of AM processes: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization [1]. Some of the most common AM processes include stereolithography, fused deposition modelling, inkjet printing, and selective laser sintering [2,11].

AM has been used since the late 1980s [11,12] in three broad areas of application [12]:

- Design and product development: concept modelling, design validation, prototyping for fit and functional testing;
- Tooling: patterns for castings, parts for mold and die tooling, fixtures, guides, and assembly tooling;
- End-use product: high-value and/or highly customized products in low-volume production.

Some studies have shown that AM can be used economically for producing end-use parts at low volumes [13,14], in a distributed manner [15,16] or personalized products [17] as no tooling is needed and designs can be changed for each individual products at no (or low) additional cost.

The benefits of AM are realized across the product life cycle rather than purely in the manufacturing process itself [16,18,20,21], making it difficult to assess the actual economics behind AM adoption [22]. Thus cost remains one of the biggest barriers to adoption for AM technologies along with the skills required for designing and producing AM products [12].

The digital nature of AM enables on-demand manufacturing directly from CAD files, eliminating product inventory and the associated costs. It can also encourage collaboration and open innovation, bringing closer together customers and manufacturers closer and sometimes blurring the line between the two, leading to the concepts of prosumers [23] and maker movement [24].

AM is currently considered as one of the most disruptive technologies [6,15,22] as it allows companies to create and respond to new markets for ever more complex, customized, high-value products which could not be produced using traditional manufacturing methods.

AM technologies are developing quickly. Current technology limitations are being challenged and pushed further. It is becoming clear that AM will grow at an unprecedented rate in the coming decade. Thus it is crucial to develop tools and methods to guide the adoption of AM technologies in a well-informed and sustainable manner.

2.2. Roadmapping and technology management

Roadmapping is an approach to technology management and strategic planning [25] for supporting innovation at both company and sector levels [26]. It helps to identify the technology and other resources required to develop products, services and systems in line with the companies' objectives and in response to market drivers. It also links the commercial (pull) and technological (push) perspectives [26] and integrates the five processes for technology management—identify, select, acquire, exploit and protect technology assets [27].

The two main features of a roadmap are: (1) time-based on the horizontal axis, from past/present state (where are we now), short-, medium- and long-term, to a vision of a desired future state (where do we want to go), and the pathways to realize this vision (how do we go there); (2) Multi-layered on the vertical axis, with context and drivers at the top (market pull), products and services in the middle (business opportunities), and enablers at the bottom (technology push).

The roadmapping process is flexible and can easily be customized by changing the time horizon and layer structure to fit the purpose and context of its use [26]. The time horizon stretches far into the long term to explore new business opportunities and accounts for uncertainty in future scenarios. The time scale can vary greatly depending on the product or sector considered. The layers can also be customized to capture various relevant dimensions for the company or sector considered.

Roadmapping brings together technical and commercial experts, and provides a clear visual format to support communication and cooperation. The strengths of roadmapping and its broad use in industry make it an ideal tool to form the foundation of the tool presented in this paper [9].

2.3. Business models and sustainable value

A business model "describes the rationale of how an organization creates, delivers and captures value" [28]. Business model innovation is an emerging approach to improve sustainability in companies [29].

Value typically refers to economic and customer benefits [28,30]. But with increasingly complex value networks, it is recognized that value should be generated for all stakeholders inside and outside the company [31] and that a more holistic approach to value considering all dimensions of sustainability (economic, social and environmental) is needed [32].

Previous research has identified sustainable business model archetypes [33] but they have not been widely adopted in industry despite the significant potential for economic, social and environmental benefits, and the clear and urgent need for action to address the issues of resource scarcity and pollution society is facing. This highlights the need for tools and methods to support companies in considering all dimensions of sustainability into the innovation and business planning process.

3. Methods

This paper presents the second phase of an exploratory study on the role AM in improving the sustainability of industrial systems. It follows an initial literature and practice review to better understand what adopting AM entails in terms of business model transformation and industrial system reconfiguration [10,21]. This initial review was performed using a life cycle perspective. It explored on how AM can enable more sustainable production and consumption, and resulted in a list of benefits and challenges [21].

The framework proposed in this second phase paper builds on a hybrid version of the roadmapping approach [8] to combine strategic planning with sustainable value analysis [9]. The framework provides a structured approach to consider the sustainability implications of AM technology adoption on various stages of the product's life cycle. Various industry examples and theoretical scenarios based on the list of benefits and challenges of AM are provided to prompt reflection and critical thinking on sustainable business opportunities.

The validation phase of the research is still ongoing: interviews with experts from academia and industry will be conducted to validate the framework. Once the framework is consolidated, the SVRT for AM will be finalized so it can be delivered in facilitated industry workshops.

4. Framework

Sustainable Value Roadmapping Tool (SVRT) consists of two templates and three sets of cards as shown in Figure 1 [9]. It aims to support the identification of sustainable business opportunities and pathways to realize them by analyzing the value and uncaptured throughout the product's life cycle: beginning of life (BoL), middle of life (MoL), and end or life (EoL) [34]. SVRT was tested on fictional company cases (using examples from automotive and food industry) in facilitated workshops with industrial and academic participants from various backgrounds. The findings show that the tool can effectively support the integration of sustainability into strategic business planning with the following key benefits:

- Create ambitious business vision(s) for sustainability;
- Analyze the value captured and uncaptured across the entire product life cycle and across all dimensions of sustainability (economic, social and environmental) and thereby develop a better understanding of the concept of sustainable value;
- Encourage creative solutions to identify sustainable business opportunities;
- Support communication and collaboration between people from commercial and technological perspectives.

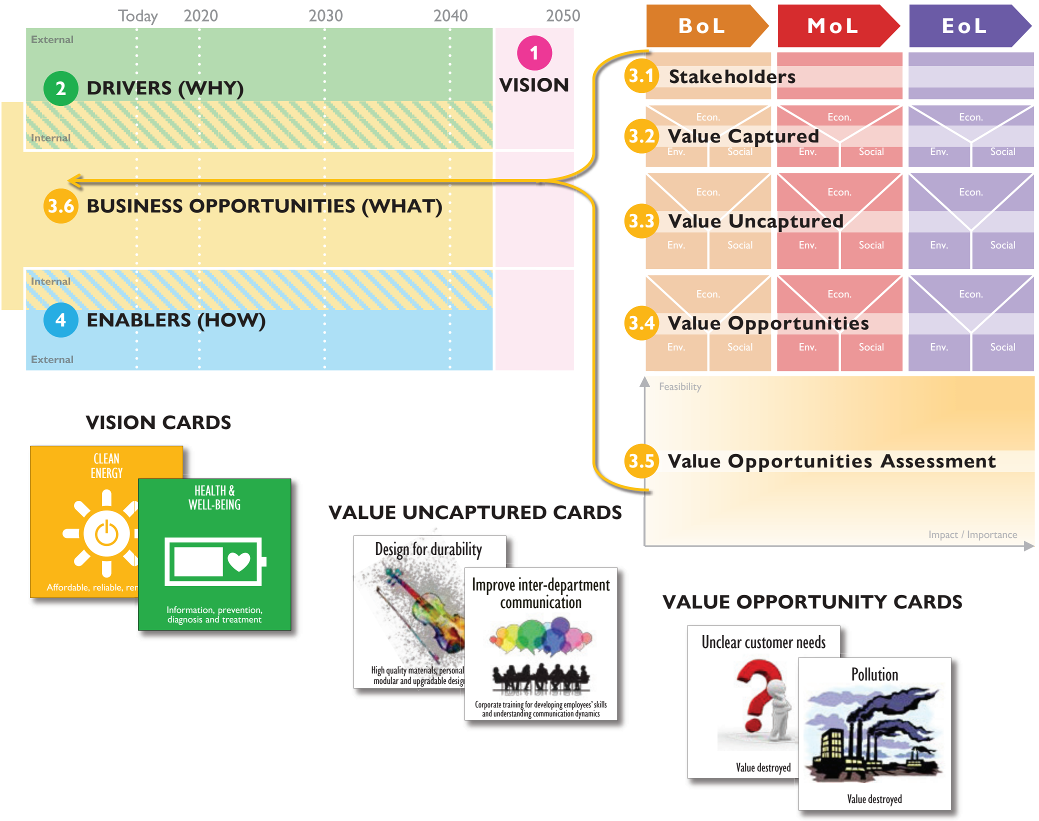

Fig. 1. SVRT tool templates and sample of cards (adapted from [9] and [34]). **Step 1:** create a sustainable vision for 2050 using the VISION cards for inspiration. **Step 2:** identify the drivers for AM adoption. **Step 3.1-3.5:** identify sustainable value opportunities using the VALUE UNCAPTURED and VALUE OPPORTUNITY cards, prioritize and select the opportunities for the roadmap. **Step 4.** identify enablers to realize these opportunities.

The tool is composed of four steps as shown in Figure 1:

1. Create a sustainable vision for 2050;
2. Identify drivers for AM technology adoption;
3. Identify and prioritize sustainable business opportunities;
4. Identifying enablers to realize these opportunities.

The following sub-sections present the SVRT process for AM and the prompts to support idea generation.

4.1. Vision

The first step of SVRT sets a vision for 2050. Example of goals are provided to encourage participants to consider social and environmental goals. The following examples are based on the UN Sustainable Development Goals [35]:

- Meet basic needs and provide human dignity, accounting for population growth stabilizing at 9 billion people by 2050;
- Provide lifelong learning and free access to knowledge;
- Ensure decent work and economy through fair employment and remuneration, and good working conditions;
- Ensure gender equality with equal rights and opportunities;
- Ensure social equity for current and future generations with equal distribution of resources within and among countries;
- Increase health and wellbeing through information, prevention, diagnosis and treatment;
- Support peace and freedom through inclusive societies and access to justice;
- Enhance mobility through safe, clean and efficient transportation systems;
- Enable access to affordable, reliable, renewable energy;
- Support the development of sustainable cities with inclusive, safe, resilient and green infrastructure;
- Stabilize atmospheric concentrations of greenhouse gases by reducing CO_2 emissions and adapt to new conditions;
- Support the circular economy and eliminate of the concept of waste (i.e. see waste as a resource) through reuse, recycling, remanufacturing, etc.
- Contribute to ocean conservation and preserve marine ecosystems through marine pollution clean-up and responsible fishing practice;
- Regenerate biodiversity by reversing land degradation and halt biodiversity loss.

4.2. Drivers

The second step identifies the drivers for AM adoption. There is a distinction made between external and internal drivers although some drivers can be considered as both internal and external. The following dimensions are proposed (from the most external to internal drivers):

- Political and economic context;
- Social and environmental aspects;
- Industrial ecosystem and competitors;
- Market and customers;
- Company milestones for 2020, 2030 and 2040.

More specifically, examples of drivers for AM adoption include:

- Legal implications on IP and product liability;
- Internalize all processes from design to manufacturing;
- Enhanced capability for innovation;
- Product differentiation;
- Reduced operating cost and lower risk;
- Need for distributed, on-demand production;
- Demand for customized/personalized goods;
- Flexibility/responsiveness to fulfill economies of scope;
- New design freedoms to create optimized geometry;
- Integration of new functionalities;
- Decreased time-to-market / lead times;
- Reduced material cost through waste elimination.

4.3. Business opportunities

The third step makes use of the second template to provide a structured guide in identifying sustainable value opportunities for all stakeholders. In the context of AM, the opportunities for sustainable value go beyond the manufacturing process itself with benefits being realized across all stages of the product's life cycle. The examples of opportunities proposed in this section have been categorized as follows:

- BoL: (a) design of products and processes, (b) manufacturing system configuration, (c) business model;
- MoL: (d) efficiency in use phase, (e) product life extension;
- EoL: (f) closing the loop.

a) Design of products and processes for efficiency

Current AM technology can already achieve superior results to conventional manufacturing methods, with the ability to integrate new functionalities into products and print using graded materials to achieve the desired properties. As AM aligns with biomimicry concepts with a layer by layer buildup of material, it reduces material waste from the process itself but also enabling improved product performance with novel functionalities (mechanical, thermal, chemical, optical, magnetic, electrical, etc.). More optimized tools and molds can also be produced using AM to improve manufacturing process efficiency. New hybrid manufacturing processes can enable automation and further improve process efficiency.

b) Manufacturing system configuration

AM allows goods to be produced on-demand at the point of use in space and time to the exact specifications required. This access to local, on-demand manufacturing improves flexibility and responsiveness to fast changing market demands. The digital nature of AM also reduces time delays between design, manufacturing and application through direct access to the digital designs. AM integrates multiple process steps into one to obtain near-net shape (sometimes even net shape), resulting in material, energy, time, and cost savings. Furthermore, AM reduces or eliminates inventory waste including unsold and obsolete goods, thereby reducing material inputs and handling costs as well as reduced lead time and quality issues

c) Business model

AM allows low-cost customization and personalization with the possibility to produce different products in one batch to maximize built volume utilization. This creates opportunities for new, innovative business models with increased collaborations within the AM business ecosystem (e.g. direct interactions between consumers and producers). In addition, the complexity and higher value embedded in products can create the incentive for organizations to adopt product-service business models, e.g. see *e) Product life extension.*

d) Efficiency in use

The new design freedom enabled by AM allows for more optimized geometries and simplified assemblies which provide further improvements to products' energy efficiency in use, e.g. lightweight products. In addition, AM enables the use of new materials with higher levels of performance.

e) Product life extension

By enabling more complex parts with graded and functional materials, products can be made of fewer parts (i.e. simpler assemblies as mentioned earlier), AM can produce more robust and more durable products. It also provides incentives to adopt new business models to generate profit in the product's use phase through repair, remanufacturing, modular and upgradable products.

f) Closing the loop

AM processes are largely based on recycled materials [36-38], thus the adoption of AM technology can strongly contribute towards a more circular use of natural resources. Distributed networks can further support the move to a circular economy by maximizing the efficient use of local resources.

In addition, AM enables simplified product assemblies with less material diversity which can lead to simpler supply chain configurations and improved recyclability.

4.4. Enablers

The fourth and last step identifies the enablers to realize the opportunities identified (step 3) and move towards vision set in the beginning (step 1). Example of enablers for AM include:

- Design software;
- New machines and new processes;
- New material properties and new materials;
- Production planning and control;
- Quality standards;
- Education for designers and engineers;
- Open innovation, collaboration and partnerships;
- Consumer relationship;
- Demonstrators and other research initiatives.

4.5. Summary

There are six ways in which AM can provide sustainability benefits across the product's life cycle (Figure 2). The framework presented in this paper provides a structured approach to envision sustainable future scenario(s) (step 1) and consider the drivers (step 2), business opportunities (step 3) and enablers (step 4) to move towards the sustainable vision identified in step 1. Prompt cards with examples are provided to help in creating this vision and in identifying potential business opportunities and challenges arising in these six broad areas.

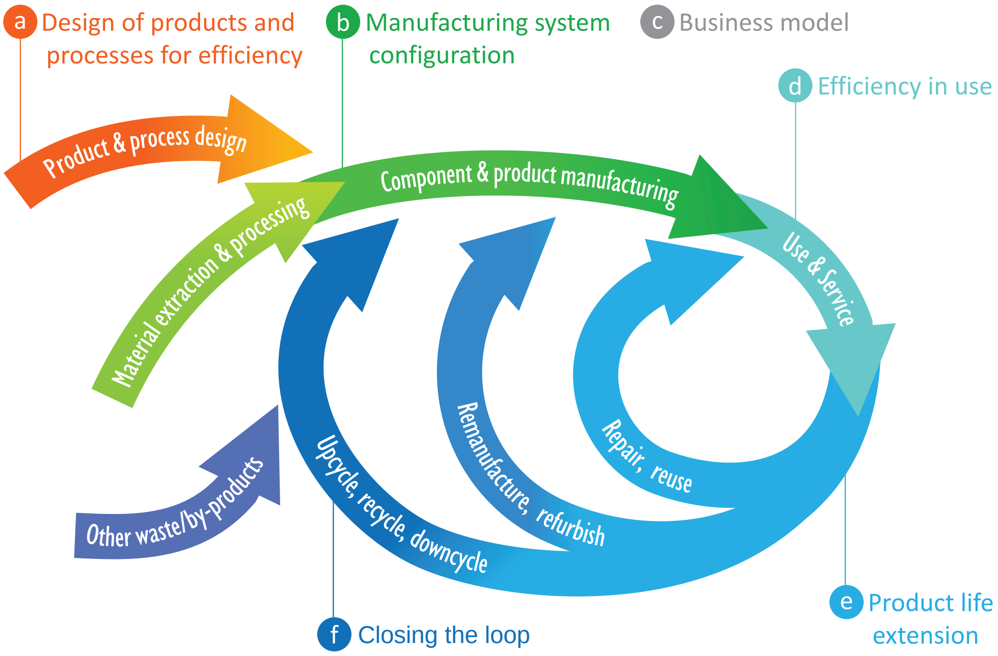

Fig. 2. Six areas for sustainability benefits using AM (adapted from [10]).

5. Conclusions

Many studies have looked into the sustainability of AM technologies [15,16,18-21,23]. These benefits are being realized in various industries and across products' life cycle. The main benefits of AM technologies include new design freedom, integrated material functionalities, improved product and process performance, reduced lead times, and low-cost customization. Further developments of AM technologies are required to reduce process duration (including automation for post-processing), increase reliability, quality and aesthetics, integrate functional materials, and expand scale of application. In addition, there is still much work needed to fully assess the environmental performance of AM systems and their social impacts (e.g. employment and lifestyles).

This paper proposes a framework building on the roadmapping approach [8] and sustainable value analysis [9]. It provides a structured approach to systematically consider the sustainability implications of AM on all stages of the product's life cycle. Further work needs to be carried out to test and refine the framework so it can form robust foundations for a tool and workshop to assist companies in AM technology adoption.

Acknowledgements

This work was supported by the Engineering and Physical Sciences Research Council [grant number EP/K039598/1] and the STIM consortium. The author also wishes to acknowledge contributions from participants of the R&D Management Conference 2016 and the STIM consortium in the testing of the SVRT tool.

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