Sustainable Manufacturing: Challenges, Approaches and a Roadmap

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Abstract Manufacturing is an important pillar of the society providing goods and services of primary importance for supporting the quality of human life. One of the most pressing challenges facing Europe and the world is the need for a transition to resource-efficient economy. Sustainability, in a manufacturing context, means enabling a diverse pool of industrial participants to pursue economic growth without undermining social and environmental issues of workforce management, building community relations, use of natural resources, carbon dioxide emissions, waste management and product and services responsibility. This chapter discusses on the relevance of sustainability from manufacturing perspective, sustainable manufacturing definition, strategies, impacts and approaches and describes a roadmap for sustainable manufacturing.

1 Introduction

Manufacturing is an important pillar of the society as 'it provides goods and services of primary importance for supporting the quality of human life' (Garetti and Taisch 2012). It is a complex and material and labour intensive sector influenced by the economic,

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political, social and technical developments with significant contribution to the world economy. In fact, manufacturing contribution to GDP in 2013[1] ranged from 12.4 % in the USA, 15 % as an average in EU countries and 22 % in East Asia and Pacific countries. Skinner (1969), recognising the need for a definition of manufacturing that reflected the proper concept, argued that 'manufacturing is generally perceived in the wrong way at the top, managed in the wrong way at the plant level and taught in the wrong way in the business school'. Miltenburg (2005) defines manufacturing as 'large numbers of employees—skilled and unskilled, line and staff, flexible and inflexible—work in a network of domestic and foreign facilities, formal and informal systems, good and bad practices, and old and new cultures coexist'.

Manufacturing is not only treated as a process but also referred to as a system (Robinson 1998). It includes an amalgamation of various aspects—production systems[2] (Miltenburg 2005), factory roles[3] (Ferdows 1997), manufacturing networks (Shi and Gregory 1998) and the manufacturing infrastructure and structure decision areas[4] (Hayes and Wheelwright 1984). Gregory (2005) has provided an integrative perspective of manufacturing—'manufacturing is a cycle that starts with understanding markets, product design, production, distribution and ends with manufacturing-related services within an economic and social context'. As such, the perception of manufacturing, initially, was on production activities. However, this has changed and the current focus of interest on the study of manufacturing has evolved to include a myriad of stages and activities from processing of raw materials to the production and delivery of a new product and finally to the reuse, recycling or disposal of the product, encompassing the whole product life. This perspective is adopted in recent publications, such as Garetti and Taisch (2012) who state that 'manufacturing is much more than production', integrating 'industrial activities from the customer to the factory and back to the customer, thus including all the different kinds of services that are connected to the manufacturing chain'. Extending manufacturing scope towards responsibility, overall product life cycle has risen an enormous interest in new service offerings. A range of service-oriented concepts can be found to address more customer-oriented approaches, such as integrated solutions (Tan et al. 2010). The following sections will elaborate on the relevance of sustainability from manufacturing perspective, sustainable manufacturing definition, strategies, impacts and approaches and will describe a roadmap for sustainable manufacturing.

[1]World Bank Open Data, related to 2013 GDP (Gross Domestic Product), accessible from: http://data.worldbank.org/indicator/NV.IND.MANF.ZS.

[2]Job shop, batch flow, operator-paced line flow, equipment-paced line flow, continuous flow, just in time, flexible manufacturing system.

[3]Offshore, source, lead, outpost, contributor and server.

[4]Infrastructure decision areas: resource allocation and capital budgeting systems, human resource systems, work planning and control systems, quality systems, measurement and reward systems, product and process development systems, organisation. Structural decision areas: capacity, sourcing and vertical integration, facilities, information and process technology.

2 Relevance of Sustainability from Manufacturing Perspective

Manufacturing includes industrial activities from the customer to the factory and back to the customer, either in the form of a business-to-business (B2B) or business-to-consumer (B2C) relationship. Likewise, different industrial services are also an important constituting part of the manufacturing activities. The constant evolution of manufacturing networks—coordination and cooperation between the capabilities and configurations—become vital for growth. External (macroeconomic stability, trade policies) and internal factors (process innovations, cost benefits, competition, corporate culture, organisational structure) have both led companies to change production systems and locations in order to maximise benefits (CEN 2014). Globalisation—expansion of manufacturing operations to developing economies and the ever-changing business environment, which affects the wider society and environment, highlights the requirement for manufacturers to look for new approaches to manage sustainability. As such, complexities of interactions between various stakeholders along a product life emerge, which raises a myriad number of challenges for sustainability. The challenges include social and environmental concerns such as labour practices, community involvement, waste generation, product end of life, packaging, climate change and partnerships, further propagated by demand, global competition, consumer preferences and behaviour.

In the quest for new approaches to manage sustainability impacts effectively in manufacturing—from sourcing and production to distribution, product logistical support and end of life, many methodologies to assess and plan manufacturing activities based on the product life cycle perspectives have been developed. Sustainability assessment methodologies in literature are currently numerous. Some of them propose theoretical approaches, others specific industrial cases. The majority of them are focused on a specific sustainability dimension (economic, environmental or social), within which only few impact categories are addressed. It is rare that methodologies reach complete integration over the triple bottom line, even if many authors express its desirability (Kloepffer 2008; Rebitzer and Hunkeler 2003; Hunkeler and Rebitzer 2005). It is worth highlighting that economic, environmental and social assessment of the product life are not yet mature at the same level. For example, economic sustainability is assessed from the conception of a business, where financial assessments are known for their importance in decision-making in companies. The life cycle perspective is claimed to avoid selecting an alternative with lower initial costs but higher operations and maintenance costs; indeed, usage costs may be equal to many times the initial purchase or investment costs (Woodward 1997; Markeset and Kumar 2003). The most common environmental assessment technique is the life cycle assessment (LCA), described in the International ISO 14040 standard (ISO 2006). Social sustainability is still poorly considered, as social issues are difficult to quantify in relation to flows related to the product life. Moreover, it is complex to obtain and manage the

required information type: It is tightly linked to company's conduct and its impacts; thus, it is very highly context specific (Dreyer et al. 2005; Jørgensen et al. 2007).

Many research projects and industrial activities consider products, processes and services along their complete life cycle. The role of information sharing along the life cycle has become an important issue for achieving sustainability (Terzi et al. 2010). In particular, information sharing is a base for various activities such as designing products for sustainability, sharing knowledge between customers and suppliers (two main among stakeholders) and optimising operations by closing the information loops with the involvement of product-service users. Manufacturing characteristics have altered or advanced according to the changes in the global business environment over the last decades, also building on the challenges arising from the sustainability perspective.

The relevance of manufacturing industry has been outlined by the European vision for the future 'Competitive and Sustainable Manufacturing': it promotes the transformation of the European manufacturing industry into a high added value and knowledge-based industry, which is competitive in the globalised world (European Commission 2010b). Manufacturing industry is crucial for the European economy. However, the ongoing economic crisis has hit the industry severely both in terms of industrial output and number of jobs. In several industrial branches, a general problem is the overcapacity and low return on investment. Manufacturers' search for new markets, increased efficiency and low-cost production has led them increasingly to invest in non-EU countries leading to the development of global value chains (European Commission 2010a). One of the most pressing challenges facing Europe and the world is the need for a transition to resource-efficient economy. These trends reflect in the European vision for the future 'Competitive and Sustainable Manufacturing'. Accordingly, some of the challenges anticipated for the future to support the vision are as follows:

- A key factor in the development of the manufacturing systems will be the ability to achieve cost-efficiency, high performance and increased resilience to meet varying and segmented customer demands in dynamic and fluctuating markets (Foresight 2013);
- In terms of asset management, the key issues are dynamic and continual life cycle management, optimal capacity development and utilisation, higher overall equipment effectiveness, reliability and flexibility of physical assets, and lower maintenance cost (Komonen et al. 2012);
- There is also a need to develop strategies to help manufacturing industries to cope with the challenges of a low carbon economy (European Commission 2010b);
- The existing business models predominantly create, deliver and capture economic value for a few stakeholders such as customers and shareholders, with limited or no attention to environmental and social value. These business models are linear and externalise environmental and social impacts.

As summarised above, the relevance of sustainability in manufacturing is evident. Moreover, the focus of various research supported by the European Commission has encouraged thinking of new perspectives in manufacturing associated with sustainability challenges and, more recently, developing correspondent approaches, systems and tools. In relation to the new perspectives, it is worth mentioning research initiatives such as the *IMS international project IMS 2020: supporting Global Research from IMS 2020 vision*, which was in charge of preparing a roadmap for future manufacturing research, and the *Factory of the Future Strategic Multi-annual Roadmap* (European Commission 2010b), prepared by the Industrial Advisory Group for the Factories of the Future Public-Private Partnership.

3 Sustainable Manufacturing: Definitions, Strategies, Impacts and Approaches

3.1 Definitions and Current Strategies Towards Sustainability

The National Council for Advanced Manufacturing (NACFAM 2015) has defined sustainable manufacturing as 'the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources and are economically sound and safe for employees, communities and consumers'. Some definitions proposed in academic literature include the following:

- Hutchins and Sutherland (2008), define sustainable manufacturing as 'the design and operation of industrial systems to ensure that the use of natural resources does not lead to reduce the life quality either due to losses in future economic opportunities or due to adverse impacts on social conditions, human health and the environment'
- Despeisse et al. (2012) recognise sustainable manufacturing as 'a new paradigm for developing socially and environmentally sound techniques to transform materials into economically valuable goods'
- Garetti and Taisch (2012) state that sustainable manufacturing is 'the ability to smartly use natural resources for manufacturing, by creating products and solutions that, thanks to new technology, regulatory measures and coherent social behaviours, are able to satisfy economic, environmental and social objectives, thus preserving the environment, while continuing to improve the quality of human life'.

These are few examples that underline the emergence of economy, society, environment and technology as leading factors in order to orienteer manufacturing towards contributing to sustainability. As such, sustainability, in a manufacturing context, means enabling an eclectic pool of industrial participants (primary, public and secondary stakeholders) to pursue economic growth without undermining

social and environmental issues of workforce management, building community relations, use of natural resources, carbon dioxide emissions, waste management and product and services responsibility. Industrial sustainability, for a long time, has been entrenched solely in economic sustainability with limited concern over social and environmental issues and impact on the wider society. However, undermining social and environmental issues is no longer acceptable to supporting industrial growth (Ashford et al. 2012). This process towards extending the concept of sustainability is ongoing (Valkokari et al. 2014).

Based on the three pillars of sustainability—environmental, social and economic, Jovane et al. (2008) have defined the following key challenges that sustainable manufacturing needs to respond to:

- Economic challenges, by creating products effectively and efficiently and creating new services that ensure development and competitiveness through time;
- Environmental challenges, by promoting minimal use of natural resources (in particular, non-renewable energy) and managing them in the best possible way while reducing environmental impact;
- Societal challenges, by promoting social development and improved quality of life through renewed quality of wealth and jobs.

Different strategies have been proposed to deal with these challenges, either focusing on one of the concrete aspects of them or addressing many of them from a more holistic perspective. An example of different strategies that can be applied by practitioners regarding the effective use of materials are those studied by Rashid et al. (2008) which are waste minimisation, material efficiency, resource efficiency and eco-efficiency. From a systemic perspective, Seliger et al. (2008) propose three strategies that manufacturing companies could pursue to contribute to sustainable manufacturing:

- The implementation of innovative technologies, which are used for resource-saving applications;
- The improvement of use intensity of products, by increasing the utilisation ratio of a product and its components through either service-oriented business models or distributed use of products and components;
- The extension of product life span, which can be achieved by expanding the use phase or by the realisation of multiple use phases.

The transition towards sustainable manufacturing will require significant shifts in the design, manufacture and use of products and services. Initiatives till date around eco-efficiency, eco-innovation, waste management, social responsibility are helpful but incremental and limited in their ability to drive system-wide changes. As suggested by Ijomah et al. (2007), ‘companies must design products for longevity and ease of recovery at end of life and must consider the business potential of processing used products to harness the residual value in their components’. Garetti and Taisch (2012) recommended ‘new strategies and solutions to obtain a better overall performance of high-tech engineering and manufacturing assets’. This

would then enable longer equipment life cycles and higher performances in respect to resource and energy consumption, product quality and equipment availability, achieved through effective and efficient maintenance.

The transition is progressively induced by the consumer influence. Concern over social and environmental issues has resulted in rising consumer pressure for responsible corporate behaviour. Fréry (2006) writes about how scandals, like Enron and WorldCom, have highlighted the need for responsible corporate behaviour to prove that complete focus on short-term financial results can lead the company towards jeopardy and total closure. However, complete focus on best value to consumers and minimal consideration of financial results can also lead to problems for the long-term survival of the company. Hence, the author concludes that for 'sound strategy', both ends of the 'spectrum–shareholder value and customer satisfaction' need consideration (Fréry 2006).

Overall, the concept of sustainability recognises the linkages between social, economic and environmental issues. Therefore, in a company, the corporate strategy, as well as the manufacturing strategy, should realise how policies and decisions need to incorporate a broader view that encompasses environmental and social issues for longer-term benefits. As a report on global manufacturing states, 'a more productive and reliable approach involves a framework for decision-making that takes into account the many possible scenarios in an uncertain future' (Deloitte Research 2007). Although the report was towards building on strategy and scenario planning, its implication to the sustainability approach is the idea of incorporating the various factors towards a more united approach in dealing with uncertainty of today's business environment.

3.2 *Current Impacts of Manufacturing Industry from a Sustainability Perspective*

Industry is estimated to be responsible for some 30 % of the CO_2 emissions on the planet, is a major consumer itself of primary resources and non-renewables, and is the primary driver of end-user consumption of material goods (Evans et al. 2009). The impact on sustainability is also demonstrated by the relevance of energy consumption in manufacturing, primarily due to electrical energy and oil. The consumption of energy and other resources often represents a major part of the cost of manufactured products. It has been argued that energy and materials represent the largest costs for manufacturing companies at 45–55 % of total expenditure. Thus, energy and materials are the most critical cost factors and the competitiveness will be to a great extent determined by its capability to use resources as efficiently as possible (Greenovate 2012). Manufacturing has also a strong impact on water consumption. Industrial use of water accounts for 19 % of the global water extraction with the demand of water from manufacturing estimated to rise 400 % by 2050 (Royal Society 2012; OECD 2012). Besides a great impact on energy and resources consumption, the manufacturing sector is responsible for 38 % of total

direct and indirect CO_2 emissions and emissions to the environment, as reported by the International Energy Agency (IEA 2008).

Industry also develops and promotes demand for products that through their use engender significant additional CO_2 emissions and other forms of subsequent pollution and waste. For example, the annual consumption in UK was around 13.2 million tonnes of paper and board products in 2008, 5 million tonnes of plastics are estimated to be annually used and 1.54 million tonnes of electronic and electrical equipment bought (WRAP 2011). This offers an overview of the impact of manufactured products on the environment at the end of their life as mostly these products do not get recovered, recycled yet.

Furthermore, the magnitude of the industrial sector, its global nature, use of natural resources for production, its role in technological innovation, its driving influence in most societies and its primary position in a consumer-based culture makes it central in impacting sustainability. Influencing positions of corporations becomes an important factor, with respect to both environmental and social contexts. Many corporations now wield considerably more influence than most sovereign states. Continuing business as usual, this power and influence could prove catastrophic for environmental and social sustainability.

Fulfilment of ambitious emission goals, especially the CO_2 emission targets, requires awareness and conscious decisions at all levels of the society. However, energy and resource efficient operation model should not be a burden to the European industry but to increase its competitiveness in the global market. Strengthening the competitiveness of the European products and companies via improved environmental profile requires measures that enhance use of environmental alternatives with lower CO_2 footprint to improve the energy efficiency without negative impact on industrial production and job opportunities in Europe.

While the EU has shown that progress on resource efficiency is possible and sustainability has gained importance on the agendas of industrial decision-makers, the rate of improvement in resource efficiency has been between 1 and 2 % a year, which is below the rate of economic growth (European Commission 2011). A radical shift is required, where manufacturing industry is considered pivotal in pursuing sustainable consumption of energy and natural resources and production solutions for energy and resource efficiency (Krantz et al. 2011).

3.3 Approaches to Integrate Sustainability in Manufacturing

3.3.1 Sustainability in Manufacturing Companies

Understanding of the term ‘sustainability’ still varies significantly between firms. Some consider mere compliance with environmental legislation to be sustainability; others see waste and cost reduction, or reduction of carbon emissions as sustainability,

while others view workplace and employee rights or community engagement as sustainability (Bonini et al. 2010). The identification of energy, materials, waste and regulations to comply with allows manufacturing practitioners to establish their baselines and to identify the different impacts of their manufacturing activities. Willard (2005) proposes a 'corporate sustainability continuum', through which firms' progress on the path towards sustainability (Fig. 1).

Companies can go along the path towards sustainability by taking also proactive actions. In this regard, the application of new technologies can offer support to initiatives addressing sustainability challenges, for example for resource-efficiency applications (Seliger et al. 2008). Evans et al. (2009) discuss the potential additional benefits of applying new thinking of existing practices and knowledge considering a whole system perspective to achieve energy and resource efficiency as a first priority for manufacturing companies. Garetti and Taisch (2012) discuss another complementary vision that considers technological development as a part but not enough for a comprehensive view of sustainable manufacturing. A final perspective is related to education as 'the prerequisite for consumer and people in general to correctly address the sustainability objectives through appropriate lifestyles and the appropriate use of products and technology' (Garetti and Taisch 2012).

In summary, a mutual interaction can then be envisioned between manufacturing technologies and the economic pillar (i.e. technologies supporting the development and offering of new customer-centred solutions), the social pillar (i.e. technologies supporting changes in lifestyles/living models) and the environmental pillar (i.e. technologies affecting—positively or negatively—the use of natural resources).

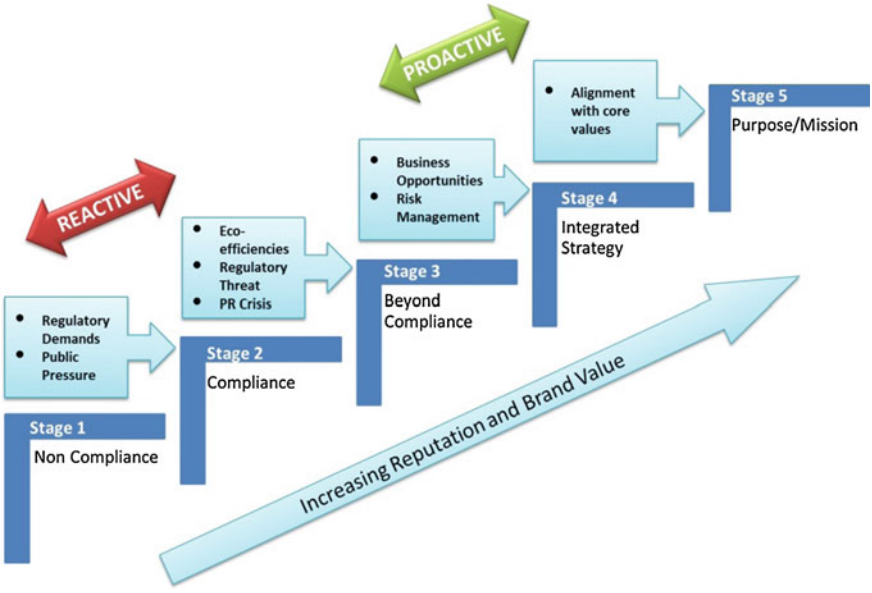

Fig. 1 Stages in corporate sustainability continuum (adapted from Willard 2005)

The 'corporate sustainability continuum' and the presence of educated/skilful people within the business ecosystem are some of the relevant means in the industrial context to understand, manage and monitor manufacturing technologies for sustainable purposes, thus facilitating the effective integration of sustainability in a manufacturing company.

3.3.2 Sustainability in Manufacturing Networks

In traditional manufacturing network operations of suppliers, lead producers (such as OEMs) and customers are seen as independent sequential tasks, which form a value chain. Since the 1990s, however, this pattern has been changing and the theoretical discussion has emphasised the transfer from value chains to value networks (Normann and Ramirez 1993; Peppard and Rylander 2006). In manufacturing industries, a value network consists of organisations cooperating with each other to benefit all network members. Lead producer and its suppliers and customers form a typical value network. Value system consists of the suppliers' value networks (who provide input), core company's value network (that produces products), the distributers' and retailer's value networks (who distribute products to customers) and the customers' value networks (who use the products in their own activities) (Miltenburg 2005). Thus, the whole system view will encompass groupings of different interconnected value networks.

At the network level, Van Bommel (2011) presented a framework for the analysis of the implementation of sustainability-oriented strategies considering network dynamics. He identified three types of strategies that an organisation within the network could follow:

- Resign strategy, which does not start any implementation activity related to sustainability;
- Defensive strategy, which includes supply chain management for risk and performance;
- Offensive strategy, which regards supply chain management for sustainable products.

These strategies are very ambivalent in practice and could actually be applied separately to different products within the same network. From the author's perspective, implementing sustainability can be seen as a whole system innovation with two key concepts: innovation pressure and innovation power. The innovation pressure exists from the stakeholders of the system and is closely related to the specific sector, product, service and its supply network. The innovation power is closely related to the strategy and activities decided to carry out by the organisation.

4 Sustainable Manufacturing Roadmap

The SustainValue project defined a roadmap for sustainable manufacturing industry in Europe. Literature on business models and value networks in the manufacturing industry defined the research background. An expert workshop provided the data for the roadmap analysis, which then went through several iterations by the project core group. Valkokari et al. (2014) and Kortelainen et al. (2015) present and discuss the roadmap in depth. The following paragraphs provide a short summary of the main findings.

Roadmaps are strategic tools for creating deeper understanding and setting agendas for development and change. Visionary socio-technical roadmaps are visualisations of knowledge based on expert assessment. They combine economic, societal and technological issues with explicitly stated visions of the future. The roadmap process is planned to identify elements and issues of development that have strong potential for producing the outcomes that the vision presents. Roadmaps are not intended to forecast the future in a deterministic way but they are based on the assumption that future development is likely to include some elements that are presented in these roadmaps (Ahlqvist et al. 2007; Ahola et al. 2010).

The visionary roadmap process guided the work on the SustainValue project that dealt with broad concepts such as sustainability, value and networks. The chosen time periods were short, middle (5 years) and long term (10 years). The future development was assessed from five perspectives, namely stakeholders, business ecosystem, success criteria, benefits/value and catalysts/obstacles. The roadmap process starts by defining a vision which serves as a target against which the current state is compared and the needed changes discussed. The vision for sustainability within the manufacturing industry was stated as new forms of business models and value networks, which together enable knowledge-based transformation of the manufacturing industry and improve the three dimensions of sustainable value (economic, environmental and social) (Valkokari et al. 2012).

The road mapping process started from definition of the current state of sustainability within the European manufacturing industry, followed by discussion and road mapping of the changes that are required for a transition towards a sustainable manufacturing industry. The roadmap was split into three sub-roadmaps (Valkokari et al. 2014):

- Empowerment of stakeholders in the European manufacturing industry.
- Increasing efficiency at network level.
- Creating new performance criteria, models and means of measuring success at actor level.

The key features of the roadmaps are summarised in Table 1.

Sustainability should be seen as a key criterion for decisions that will create value today and in future. The three sub-roadmaps emphasise importance of wider adoption of system thinking. Many companies are taking some steps towards sustainable manufacturing, but seldom in a holistic manner. Every participant in the

Table 1 Key characters of the three sub-roadmaps (adapted from Valkokari et al. 2014)

Sub-roadmap	Key features
Empowerment of stakeholders in the European manufacturing industry	• Need for better awareness and changed behaviour in relation to sustainability issues such as limited resources, the three sustainability pillars and life cycle thinking • Standardisation and legislation that supports sustainable manufacturing • Improved ways to demonstrate the benefits for customers and companies of developing their actions, products, processes and services so as to be more sustainable
Increasing efficiency at network level	• Efficiency in production and manufacturing, as well as operational efficiency of products, systems and services, has to rise • New types of relationships and collaboration are needed between manufacturers and stakeholders • The focus of manufacturing has to move from products to new kinds of services and solutions • Effective ways to deal with the new sustainability requirements of product–service systems have to be implemented in product development processes
Creating new performance criteria, models and means of measuring success at actor level	• Updating of current business models • Making sustainability measurable • Measuring business success through consideration of all sustainability pillars

manufacturing network must have an understanding of the challenges and opportunities of sustainability. Currently, network level sustainability governance mechanisms are not well suited for managing sustainability. There is a need for collateral, horizontal relationships and a joint development process among stakeholders. Rethinking business models at network level is essential, and sustainability is one possible enabler of future competitive advantage within the manufacturing industry. An important key is collaboration between stakeholders for change. Development of common approaches and shared transparent KPIs for sustainability within manufacturing networks can enable collaboration among network partners and stakeholders for sustainability (Valkokari et al. 2014).

5 Conclusions

Manufacturing companies must take into consideration not just the economic goals but also the need to meet environmental and social goals in carrying out business, while recognising that economic, environmental and social impacts occur at all stages in the value network. This implies not only being able to manage internal activities and operations of the producing organisation but also getting the value network partners to collaborate on principles and performance standards that have positive and implicit or explicit influence on the sustainable products and services delivery performance. Sustainable value creation is the key contribution of companies to sustainability, i.e. to create long-term environmental, social and economic value. Developing attractive and common approaches for sustainable products and services can assist in enabling collaboration among partners and stakeholders.

The existing business models are often based on creating, delivering and capturing economic value for customers and shareholders, with limited or no attention to environmental and social value and to a broader range of stakeholders. These business models are linear and externalise environmental and social impacts. They cannot support the sustainable value creation that is required to meet the future needs of the planet and of increasingly discerning customers wanting features other than economic value or product ownership.

It is important to provide tools and methodologies for companies to fully embrace sustainability. It also is important to do this at the level of the network, as the impacts do not mainly occur inside one company. The emerging sustainability megatrend is becoming a central factor in companies' long-term competitiveness, and when doing this, it will affect their production networks. The business partners and stakeholders within these networks make planning, coordination and management a challenging task. The decision-making setting is difficult due to the decentralised nature of business decisions and operational activities. In this context, a major impact on the networked manufacturing environments could be achieved through holistic and integrated solutions for sustainability of complex value chains, rather than isolated and ad hoc solutions.

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