Part I
Challenges

Field of Research in Sustainable Manufacturing

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Abstract Sustainability has raised significant attention in manufacturing research over the last decades and has become a significant driver of the development of innovative technologies and management concepts. The current chapter aims to provide a structured overview of the wide field of research in sustainable manufacturing with a particular focus on manufacturing technology and management. It intends to describe the role of manufacturing in sustainability, outline the complementary approaches necessary for a transition to sustainable manufacturing and specify the need for engaging in interdisciplinary research. Based on a literature review, it provides a structuring framework defining four complementary areas of research focussing on analysis, synthesis and transition solutions. The challenges of the four areas of research manufacturing technologies ("how things are produced"), product development ("what is being produced"), value creation networks ("in which organisational context") and global manufacturing impacts ("how to make a systemic change") are highlighted and illustrated with examples from current research initiatives.

1 The Role of Manufacturing in Sustainability

Humanity is increasingly confronted with the challenge of dealing with a finite earth—a world with a limited "carrying capacity" (Arrow et al. 1995) and with "planetary boundaries" (Rockström et al. 2009), with some expecting "limits to growth" (Meadows et al. 1972). Owing to the unprecedented growth in population and economic output experienced since the 19th century (respectively six and sixty-fold, Maddison 2006), the stress imposed by humanity on natural equilibria

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has reached alarming levels at the same time that it fortifies increasing inequality between early industrialised and emerging countries. The limited capacity of the atmosphere to take stock of the emissions produced by our carbon-based economies, poses a threat not only to natural equilibria, but also to our own daily conditions of living (Edenhofer et al. 2015). The flows of some elements due to human activities, such as phosphor and nitrogen, now exceed natural flows, thus threatening the balance of the metabolism of natural ecosystems (Vitousek et al. 1997). Hence, the risk of "overshooting", i.e. drawing on the world's resources faster than they can be restored, while releasing wastes and pollutants faster than the earth can absorb them, is very real and the ongoing, unresolved challenge of our time (Meadows et al. 2004).

Although the concept of "sustainable development" (as defined for example by Brundtland et al. 1987) has received significant attention and motivated numerous initiatives in favour of, e.g. recycling, energy efficiency, the need for action is now nevertheless greater than ever before. This is particularly underscored by the observation that, despite international efforts to combat climate change, the global energy system is carbonizing due to a global renaissance of coal (Steckel et al. 2015). Further and more innovative decarbonisation solutions are therefore urgently needed.

As a major stakeholder in several areas of human living, industry has a great role to play in sustainability. It first contributes significantly to the overall environmental impact of human activity. It represents 26 % of the final energy consumption in the EU 27 (Lapillonne et al. 2013, data from 2013), emits 28.5 % of the greenhouse gases produced in the EU 27 (European Commission 2013) and uses energy which is still generated from fossil energy sources by up to 56 % (Lapillonne et al. 2013, data from 2013). In 2006, the European Commission estimated an overall European energy saving potential of 20 %. In the case of industries, the potential savings are estimated to be 25 %, representing annual losses of about 100 billion euros (European Commission 2006). At the same time, while the precision of production processes reaches ever smaller scales, the energy consumption of corresponding production systems is increasing exponentially (Gutowski et al. 2011). Meanwhile, further increases in energy consumption are anticipated.

Beyond its direct environmental impacts, the discrete product manufacturing sector also influences the resource consumption of its products over their entire lifecycle, and therein plays a critical and complex role in sustainability (Duflou et al. 2012). This role is particularly relevant considering that households in early industrialised countries face a literal "rise of the machines" and are equipped with more products and appliances than only a few decades ago (Energy Saving Trust 2006). The average household in early industrialised countries may own thousands of material items, so managing the volume of the possessions becomes a stress factor (Arnold et al. 2012).

With respect to the social aspects, the industrial sector employs 17 % of the European workforce (Eurofound 2012) and represents more than 23 % of worldwide total employment (International Labour Organization 2014). On the other hand, while working conditions in the manufacturing sector have improved steadily over the last decades (World Health Organization 2013), poor working conditions persist in resulting in as many as 300,000 work-related deaths and economic losses of 4 % of the gross domestic product of the European region every single year (WHO 2016). Globally, industries are responsible for 7.2 % of child labour, or 12 million people (Diallo et al. 2013).

That said, manufacturing stands strong as a crucial sector for the development of economies. Manufacturing generates 14 % of the gross domestic product (GDP) of OECD countries and of Europe according to the OECD (2016),[1] and 31 % of the world GDP according to the US central intelligence agency (2016).[2] Beyond this quantitative contribution to the GDP, whose reflection of actual wealth is debatable (see e.g. Costanza et al. 2014), it has been shown that stable specific and sequential sectoral patterns can be observed in economic development processes across the spectrum of countries, with specific manufacturing sectors furthermore playing an important role in initializing economic development processes in poor countries (Radebach et al. 2014). On the whole, thus, basic manufacturing activities seem to be a necessary enabler for the development of modern economies.

To summarize, manufacturing as a subset of the industrial sector (see glossary for disambiguation of the terms) has a threefold impact on sustainability:

- it plays a major role in the creation of wealth;
- it directly contributes to the material metabolism of human societies as it requires material input and produces outputs;
- it indirectly contributes to the material metabolism of human societies as it produces outputs having their own metabolism even after having left manufacturing systems.

2 Existing Approaches of Sustainable Manufacturing

As a counterpoint to this tripartite observation, sustainable manufacturing is defined in the present publication as (see also the glossary for more information on this definition):

> creation of discrete manufactured products that in fulfilling their functionality over their entire life cycle cause a manageable amount of impacts on the environment (nature and society) while delivering economic and societal value.

The international research community has been particularly active in the last decades in the development of conceptual or concrete solutions toward sustainable manufacturing (see for example Arena et al. 2009). The objective of the current contribution is to deliver a framework for providing a structured overview of the existing field of research in sustainable manufacturing, with a particular focus on industrial engineering. It intends to outline the complementary approaches required

[1] Accessed 09.03.2016. Figures for EU-28/2015 and for OECD/2014.

[2] Accessed 22.08.2016, last updated 04.02.2016.

for a transition to sustainable manufacturing and their necessary interdisciplinary modus operandi. While Sect. 2.1 provides an overview of previous attempts in this direction, Sect. 2.2 introduces an original framework of sustainable manufacturing, according to which the present book publication is structured. Section 3 is specifically dedicated to the discussion of the challenges of multi-, inter- and transdisciplinary approaches faced by researchers in sustainable manufacturing.

2.1 Review of Published Frameworks

Since the emergence of the first initiatives explicitly termed as green engineering or sustainable manufacturing, several reviews of the field have been undertaken and frameworks have been proposed that identify the complementary areas of research that need to be addressed. Jayal et al. (2010), for example, deliver an overview of strategies for sustainable manufacturing with a particular focus on the modelling and assessment techniques for the development of sustainable products, processes and supply chains. Duflou et al. (2012) provide an extensive review of strategies for energy and resource efficiency in discrete part manufacturing, considering five complementary levers: unit process, manufacturing line, facility, manufacturing system and global supply chain. Based on the evaluation of the potential of these techniques, they estimate potential energy savings of 50 % in the overall consumption in the manufacturing sector. Garetti and Taisch (2012) furthermore published an overview of trends affecting the manufacturing sector, highlighting the challenges raised by sustainability in this sector and the corresponding strategies. They identify four complementary research clusters with a broader focus: enabling technologies, resources and energy management, asset and product lifecycle management, business model and processes. Finally, Haapala et al. (2013) made recommendations for further research on sustainable manufacturing, based on the review of existing initiatives and considering two foci: manufacturing processes and equipment along with manufacturing systems.

It is worth noting that all these reviews identify both sustainability assessment methods and technical strategies (*analysis* and *synthesis*) as necessary and complementary approaches to sustainable manufacturing. Analytical approaches are required in order to put words and figures to the problems which may ultimately be solved by synthesis. One example of this is found in the inventory of approaches for energy efficient manufacturing at the unit process level given by Duflou et al. (2012), where data acquisition, computational models and energy assessment methods stand alongside technical solutions such as “technological change” or “waste recovery within the machine tool.” Two of the four publications go further, and state that analysis and synthesis approaches can only be effective if enabled by adapted *education* tactics. On one side of the equation, a systematic implementation of analysis and synthesis approaches in industry requires that engineers fully appreciate the sustainable manufacturing concepts and are trained in multi-objective decision-making. On the other side, the general public can only foster sustainable production if they fully appreciate the impact of their consumption patterns.

While such reviews identify different yet overlapping scopes, the sustainable manufacturing solutions they identify can be classified into four different areas, which we will call for our purposes *layers*:

- Manufacturing technologies: approaches focused on "how things are manufactured", i.e. whose object of research lies in processes and equipment, including machine-tools or facilities. Examples of such approaches are among other things: development of new or improved manufacturing processes, predictive maintenance of production equipment, determination of process resource consumption, process chain simulation, or energy-efficient facility building.
- Product lifecycles: approaches focussed on "what is to be produced", i.e. whose object of research is the product definition (where product can be understood as a good or a service). Examples of such approaches are among others: asset and product lifecycle management, intelligent product, simplified product sustainability assessment.
- Value creation networks: approaches focused on the organisational context of manufacturing activities, i.e. whose objects of research are organisations such as companies or manufacturing networks. Examples of such approaches are among others: resource efficient supply chain planning, industrial ecology.
- Global manufacturing impact: approaches focused on the transition mechanisms towards sustainable manufacturing, i.e. whose objects exceed the conventional scope of engineering. Examples of such approaches are among others: development of sustainability assessment methods, education and competence development, development of standards.

Table 1 summarizes how the four cited reviews of the field of sustainable manufacturing correspond to the four identified layers.

Table 1 Four layers of sustainable manufacturing identified in previous frameworks

Layer	Object addressed	Haapala et al. (2013)	Garetti and Taisch (2012)	Duflou et al. (2012)	Jayal et al. (2010)
Global manufacturing impact	World (society, environment, economy)	•	•		
Value creation networks	Organisations (companies and manufacturing networks)	•	•	•	•
Product lifecycles	Product definition (good and service)		•		•
Manufacturing technologies	Process and equipment (machine-tool, facility)	•	•	•	•

As a last observation, it should be noted that although these reviews define sustainable manufacturing as resulting from the consideration of the three dimensions, the specific solutions which they present remain confined to the environmental dimension (or even consider resource efficiency exclusively) and in so doing, elude the social dimension altogether. This is in accordance with the observation provided by Arena et al. in 2009 already, in their extensive state-of-the-art of industrial sustainability study: while the social dimension of sustainability is generally viewed to be worth considering, only few specific solutions have been provided to date which address these social issues. In their summary of published research on the role of manufacturing in social sustainability, Sutherland et al. (2016) state that manufacturing enterprise still lacks standardised approaches for internalising social sustainability and for outlining directions of future work in order to mitigate this situation, such as the further development of Social Life Cycle Assessment (S-LCA).

Based on these contributions and the observations made, the next section introduces a framework structuring the field of the necessary research for enabling the transition to sustainable manufacturing.

2.2 Proposed Framework

Manufacturing activities can be characterised as the interplay of five value creation factors, i.e. human, process, equipment, organisation and product, taking place in value creation modules (Seliger et al. 2011). Value creation modules are, in turn, vertically and horizontally integrated into geographically distributed value creation networks. Value creation modules generate effects on the three dimensions of sustainability that can be measured by sustainability assessment methods.

Following the value creation network model depicted in Fig. 1 and based on the findings of the previous section, sustainable manufacturing can be defined as the necessary interplay of three kinds of approaches:

- analysis approaches, i.e. methods allowing the evaluation of value creation based on the three dimensions of sustainability;
- synthesis approaches, i.e. implementation of these methods in the development of technical systems at all levels of value creation (value creation factors, modules and networks);
- approaches for systemic changes, i.e. to transform business to become standard vehicles towards sustainable processes; in other words: enabling the systematic integration of sustainability in day-to-day decision-making.

These approaches are embedded in the four concentric and sequentially including areas introduced in the previous section: manufacturing technologies, product lifecycle, value creation networks, global manufacturing impact. The interplay of analysis, synthesis and transition approaches and these four layers are

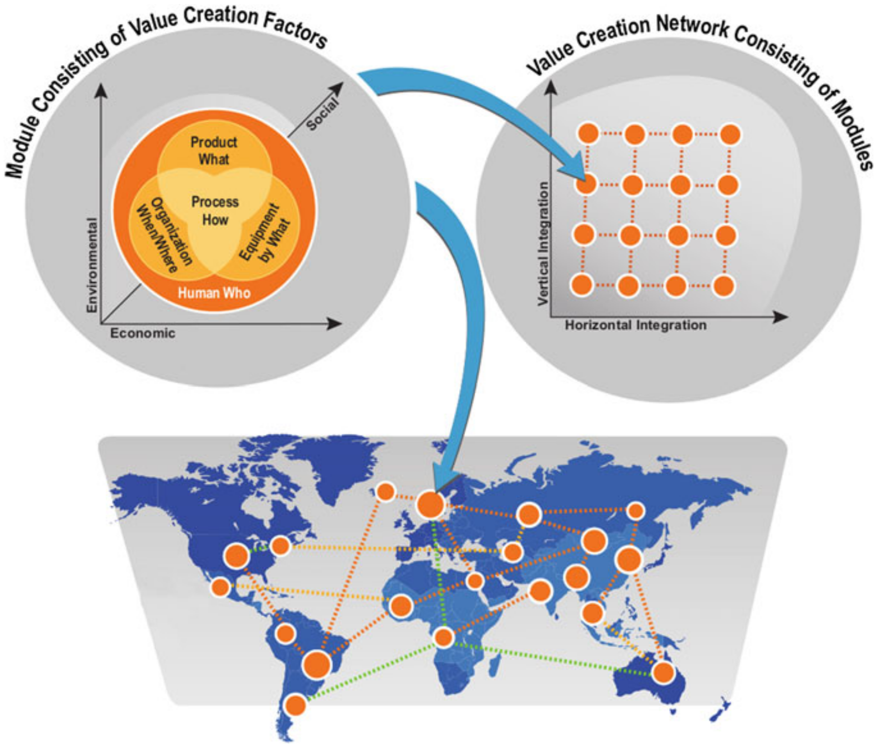

Fig. 1 Value creation network (VCN) model

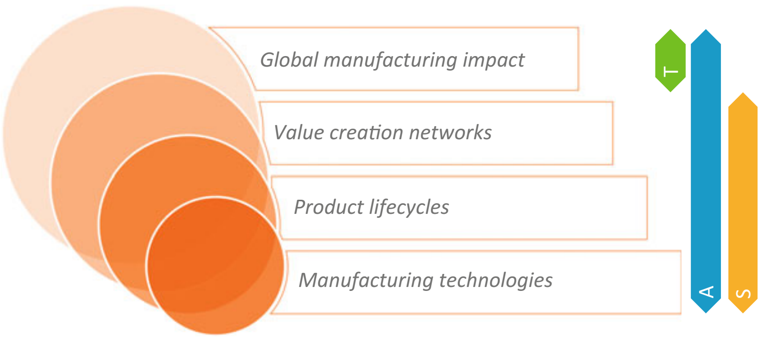

Fig. 2 Interplay of analysis, synthesis and transition approaches and the four areas of sustainable manufacturing (*T* transition; *A* analysis; *S* synthesis)

depicted in Fig. 2 while Table 2 presents their respective scientific disciplines and objects of research. Layers are depicted with more detail in the subsequent sections of this chapter.

Table 2 Objects and scientific disciplines of the four layers of sustainable manufacturing

Layer	Object addressed	Discipline concerned
Manufacturing technology	Process and equipment (machine-tool, facility)	Production engineering, factory planning, operation management
Product development	Product definition (good and service)	Engineering design
Value creation networks	Organisations (companies and manufacturing networks)	Business economics, knowledge management
Global manufacturing impact	World (society, environment, economy)	Micro and macro-economics, natural sciences, humanities, politics, education

2.3 Manufacturing Technologies

This layer specifically addresses the two factors of value creation *process* and *equipment*. It focuses on the development of production technologies, machine-tool concepts and factory management techniques ensuring that whatever has to be produced, it can be done with economy of resources which likewise uphold social standards.

This first requires determining specific indicators which enable the identification of improvement potential at the process and at the machine level. Examples of these are found in the "specific energy consumption," an empiric model developed by Kara and Li (2011) for material removal processes and based on measures on machine tools, or the "electrical deposition efficiency," an analytic model developed by Sproesser et al. (2016) for welding processes. At facility level, cyber-physical systems (Low et al. 2005) and metering techniques (Kara et al. 2011) can be employed in tandem with appropriate facility models and simulation techniques (e.g. Herrmann and Thiede 2009) in order to enable optimal steering of processes within a manufacturing system.

Regarding the development of new technologies, existing efforts encompass, for example, the improvement of welding technologies in terms of resource consumption (Sproesser et al. 2015) or the development of new internally cooled cutting processes (Uhlmann et al. 2012). At the manufacturing cell level, lifetime-extending add-ons for machine-tools (Kianinejad et al. 2016) and of automated workplaces preventing musculoskeletal strain by workers (Krüger and Nguyen 2015), can be cited as examples.

While such solutions form a necessary basis for sustainable manufacturing, macroeconomic calculations underscore that applying best available sectorial technologies in all regional industry sectors across the world would reduce CO_2 emissions to one-third (Ward et al. 2015). This shows that solutions are required beyond the manufacturing technology level in order to reach e.g. the factor 4 or 10 pinned by some authors as a necessary objective of environmental reduction of human activities (e.g. Weizsacker 1998).

This layer is specifically addressed in the part "Solutions—Sustainability-driven Development of Manufacturing Technologies" of the present book.

2.4 Product Lifecycles

This layer specifically addresses the factor of value creation *product*. It focuses on enabling the operation of product development processes systematically leading to products which achieve balance of the three dimensions of sustainability, i.e. which generate low environmental impacts while delivering socially useful functions, all available at reasonable production and purchase prices. This requires the application of methods allowing product development teams to systematically integrate sustainability criteria into their decisions.

Over the past decades, a large variety of methods of this type have been developed. As early as 2002, Baumann et al. identified more than 150 methods for "green product development", i.e. focusing strictly on the environmental dimension of sustainability, while Pigosso (2012) more recently identified 106 of them. The wide range of methods generated by the scientific community led Ernzer and Birkhofer (2002) to state that the difficulty no longer lies in developing design methods, but lies rather in selecting the relevant methods and applying them efficiently. As a matter of fact, existing methodological support for sustainable product development is often criticized for being poorly integrated into the product development process, ultimately leading to additional exertion on the part of product development engineers, and at the same time to low industry diffusion (Rosen and Kishawy 2012; Knight and Jenkins 2009).

Addressing this very issue, Pigosso et al. (2013) developed a maturity model which allows a step-by-step, guided integration of sustainable product development methods in companies. At a more operational level, Buchert et al. (2014) developed an IT-tool aimed at supporting the selection of the appropriate method for a given design problem. From the flipside of the process, some other authors have striven to reduce the diversity of tools through the development of integrated frameworks (e.g. Dufrene et al. 2013). In all cases, a key factor for effective consideration of sustainability in daily product development activities is found in the integration of methods in information systems such as Product Lifecycle Management (Stark and Pförtner 2015).

Given the high number of constraints applying to product development which limit the solution space spectrum along with the attainable level of innovation, parts of the research community have striven to reclaim degrees of freedom in their pursuits, by fostering alternative production or consumption patterns. A well-researched topic in this area is found in the concept of product service systems through which: "it is in the economic and competitive interest of the producer/provider to foster continuous innovation in reducing the environmental impacts and improving social equity and cohesion" (Vezzoli et al. 2015). Another partially overlapping field of research is found in the participative design models allowing for a deeper integration of the voice of the final user in the design process, such as user-centred design or open source design (Aitamurto et al. 2015; Bonvoisin and Boujut 2015).

This layer is specifically addressed in the part "Solutions—Sustainable Product Development" of the present book.

2.5 Value Creation Networks

This layer addresses the value creation factor *organisation* as well as the combination of value creation modules into value creation networks. It addresses the ability of the value creation networks to support sustainable production and products. How sustainable a product proves to be, may, for instance, be determined not only by its design, but also by an array of choices made in the value creation network that are not accessible to the product development team. More specifically, a given product cannot be claimed to be sustainable universally or inevitably, but in relation to a given context and associated use (Manzini and Jégou 2003). The remanufacturability of a product, furthermore, only constitutes potential that is born out of the product design itself, and can only be realized by the interplay of activities including, among other things, reverse logistics, product dismantling and testing. How sustainable a transportation system based on electric cars proves to be for a given area, for example, may depend on the density of the population and the existence of an appropriate public transportation network. Following Haapala et al. (2013) in that pursuit, then, the question lies not only in which processes are performed, but also *where* these processes are performed. This question is notably important in a world of globalized supply chains where intensive processes tend to be outsourced to emerging countries (Andersson and Lindroth 2001; Bonvoisin 2012).

Taking this into consideration, approaches are required to help ensure the development of organisational infrastructure which facilitates sustainable products and productions. Two critical aspects identified by Jayal et al. (2010) are multi-objective and integrated value creation planning. One challenge lies in moving from the coordination of independently managed organisations with individual profit maximisation behaviour, to more integrated planning. The other challenge is to go beyond profit minimisation and integrate several dimensions into the decision-making process in pursuit of connecting value creation modules.

This layer is specifically addressed in the part "Solutions—Sustainable Value Creation Networks" of the present book.

2.6 Global Manufacturing Impact

This last layer addresses the penetration rate of sustainable solutions, i.e. how far sustainable decision-making methods are implemented in practice. In order to pave the way for necessary cultural change, research which takes on the triple role of yardstick (measuring sustainability), guidepost (setting targets) and multiplier (motivating towards a direction), is what is required.

The first role requires the development of methods for measuring the actual sustainability performance of products and manufacturing activities, examining improvement potentials and identifying trade-offs between the achievement of multiple targets. As a central methodology in sustainable engineering, Life Cycle Assessment (LCA) and even more relevant, Life Cycle Sustainability Assessment (LCSA) (Finkbeiner et al. 2010), figure as essential parts of the solution. These tools however represent heavy machinery that remain too time-consuming and difficult for engineers to appreciate, and therefore hardly applicable in day-to-day decision-making. In particular, a first task lies in equipping engineers with the knowledge and framework of reference necessary to select appropriate indicators among the huge amount of indicators available. A second predicament underlined by Jaya et al. (2010) lies in the development of rapid and convenient sustainability evaluation procedures which yield results as precise as LCA.

The second role requires the development of methods for setting appropriate sustainability targets. For example, most LCA indicators (e.g. global warming potential) have been primarily developed for determining the sustainability performance of a product or process in comparative terms (i.e. in comparison with another product or process delivering the same function). Hence, they can support manufacturing that always strives to "be more sustainable than before" but cannot ensure that manufacturing is sustainable in absolute terms (Bjørn and Hauschild 2013). Yet, despite however useful they may be for comparing processes or products, these indicators need to be complemented by a sustainability analysis in more absolute terms. This includes both the setting of clear sustainability reference values/targets (e.g. maximum allowed CO_2 emissions to meet the 2° goal) and the development of methods to analyse the sustainability of products and processes with regard to these targets (as proposed by Bjørn et al. 2016, for example).

The third role involves the overall effort attached to the information transfer to industry, policymakers and the general public, in order to stimulate the necessary cultural change. One essential lever in that pursuit advocated by Haapala et al. (2013), Mihelcic et al. (2003) and Garetti and Taisch (2012) is non other than pure and simple education. On the one hand, manufacturing-related curricula should provide engineers with a broader understanding of the concept of sustainability and of the influence of their activities on societal and environmental systems. They should be able to identify improvement potential in technical systems towards sustainability, evaluate optimal solutions, and take decisions accordingly. At the same time, they should be made to appreciate the socio-technical nature of sustainable manufacturing, along with the influence of the behaviour of consumers and users on the other side of the spectrum. On the other hand, the actual transition towards sustainability not only relies on engineers, but also on the "environmental" and "technological literacy" (Mihelcic et al. 2003) of the greater citizenry, which would allow people to make enlightened and balanced consumer decisions. Considering empirical observations showing that both concepts of sustainability and manufacturing may not generally be well understood (e.g. Roeder et al. 2016), a tremendous need is present for the integration of all such concerns in education agendas, from primary school to university.

This layer is specifically addressed in the part "Implementation Perspectives" of the present book.

3 Challenges of Interdisciplinarity in Sustainability Research

The above detailed layers are not only complementary on the topics which they address, but likewise interdependent. Stock and Burton (2011) note that sustainability "necessitate[s] solutions informed by multiple backgrounds that singular disciplines seem unable to provide, and possibly, are even incapable of providing" and therein they underline the necessity for collaboration between the disciplines. They differentiate between multi- and interdisciplinarity: while multidisciplinarity is characterized by the co-existence of different scientific disciplines with parallel objectives in a common research field, interdisciplinarity seeks to bridge disciplinary gaps in perspective by involving different disciplines in the achievement of a common goal. Together with Schäfer (2013), they even advocate for transdisciplinary research, i.e. the inclusion of non-researcher stakeholders such as representatives from enterprises, administration or NGOs, end-users or citizens in the process of producing solutions of complex socio-technical problems. One argument for this is that the very concept of sustainability cannot be stated universally, but instead has to be considered within each and every specific social context. This requirement is backed by the strong observation stressed by Mihelcic et al. already in 2003 that engineering disciplines lack connective oversight of societal problems, that the public has difficulty appreciating what exactly engineers do, and that engineers tend to overlook the social dimension attached to the socio-technical problems which they invariably address. A further tendency to isolation of engineering disciplines, furthermore, generates a risk of drifting towards what has been already criticized by thinkers of the technological society such as Ellul (1964) or Illich (1982), and referred to as "second order problems" in the sustainability debate. That is, strictly technical solutions to sociotechnical problems serve to increase technicisation and generate new socio-technological problems in a headlong rush, serving ultimately to worsen the situation that is supposed to be mitigated. One typical example of the result of such processes is the often cited "rebound effect," defined for example by Hertwich (2005) in an industrial ecology perspective as "a behavioural or other systemic response to a measure taken to reduce environmental impacts that offsets the effect of the measure." The problem thus lies in the propensity of engineers to develop one-sided technological solutions, or, better said, the general tendency on the part of engineering disciplines to "generate clever solutions for problems that do not exist." Overcoming this problem thus figures hugely in the pursuit of sustainable manufacturing solutions. Specifically, bridges have to be built between disciplines well-rehearsed in asking questions (e.g. humanities) and disciplines adept in developing solutions (e.g. engineering).

Unfortunately, inter- and transdisciplinarity approaches in research remain ridden with obstacles. The major challenges of such approaches are highlighted for example by Schäfer (2013):

- Researchers should be open to broadening their horizons, i.e. acknowledging that collaboration with other disciplines gives them opportunities to address questions that are not accessible within the framework of their own discipline. For example, production technology engineers can develop cleaner production technologies with the help of environmentalists, allowing them to identify the relevant parameters. Empirical observations show that the lack of fulfilment of this basic requirement may be a significant reason for the failure of a large part of transdisciplinary projects.
- Disciplines should acknowledge the epistemic values and methods of other disciplines, which may prove to be particularly thorny between, for example, engineering and humanities—the former being generally based on positivist and the latter on constructivist epistemology.
- Considering that differentiation of technical terminology stands in the way of common understanding between disciplines, the fostering of common understanding requires the development of a common language. This requires in turn that researchers (1) acknowledge terms may have different meanings in their respective disciplines (2) consent to making the effort of identifying potential misunderstandings and defining the terms (3) avoid technical jargon in interdisciplinary exchanges.
- A barrier for openness of researchers towards inter- and transdisciplinarity might lie in the organisation of academia in highly specialized disciplines. In the context of the evaluation of research and allocation of research grants driven by discipline-related quality criteria, inter- and transdisciplinarity research may be disadvantaged.

Although the four difficulties cited here may sound trivial, experiences in major interdisciplinary research projects show that they are decisive indeed. Although convinced by the necessity of developing solutions for sustainability and by the complexity of the problem, researchers may well fail to cultivate interest in interdisciplinarity research and in broadening the focus of their activity. Literature on inter- and transdisciplinary sustainability research already gives some hints on how to address these challenges, that should indeed be more systematically taken into account in the planning and operation of research projects dealing with engineering and sustainability.

4 Conclusions

In this contribution, the current field of research in sustainable manufacturing has been screened, with a particular focus on technology and management. Based on this review, this article provides a definition of the term sustainable manufacturing as well as a structuring framework defining four complementary areas of research: manufacturing technologies ("how things are produced"), product development ("what is being produced"), value creation networks ("in which organisational context") and global manufacturing impacts ("how to make a systemic change"). These layers have been illustrated with examples from current research initiatives addressing analysis, synthesis or transition issues, while their respective principal challenges have been illuminated.

This article emphatically states the equal importance and the complementarity nature of these four layers, at the same time that we likewise underline the necessity of the interdisciplinary nature of action towards sustainable manufacturing. Since individual fields of expertise are unable to grasp the entire complexity of the challenges raised by sustainability, researchers are invited to consider the limits of the solutions they can offer, and to search for broadened perspectives beyond the frontiers of their expertise.

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Sustainability Dynamics

Rainer Stark and Kai Lindow

Abstract Value creation ensures societal prosperity. At the same time, *Sustainable Development* determines the future of global human wellbeing. Both aspects are based on profound environmental, social and economic mechanisms—and both aspects are closely linked. The *Sustainability Dynamics Model* describes the direct and indirect effects of value creation together with the three dimensions of *Sustainable Development*. This contribution introduces and defines the *Sustainability Dynamics Model*. The effects and dynamics are exemplarily shown. Eventually, the link to circular economy is drawn. In the future, the *Sustainability Dynamics Model* can be used as a control model in order to predict consequences of value creation towards environmental, social and economic sustainability.

Keywords Sustainability dynamics model · Sustainable development · Circular economy · Value creation · Consumption and production

1 Dynamics in Value Creation and Sustainable Development

Value creation is a key element for ensuring societal prosperity. In the classic sense, value creation is equated with industrial production to meet the needs of society (cp. Fry et al. 1994). Likewise, *Sustainable Development* (cp. WCED 1987) determines the future of global human wellbeing. In the year 2015, the *United Nations* defined *Sustainable Development Goals* (UN 2015) and targeted them to the year 2030 (Fig. 1).

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Fig. 1 The United Nations Sustainable Development Goals at a glance (UN 2015, *image source* http://www.un.org/sustainabledevelopment/sustainable-development-goals)

On the 25th of September 2015, 193 countries of the *United Nations General Assembly* adopted a set of sustainable development goals to end poverty, protect the planet and ensure prosperity for all as part of a new sustainable development agenda. Following the adoption, *United Nations* agencies have supported a follow-up campaign on the part of several independent entities, among them corporate institutions and international organizations. The campaign, known as Project Everyone, introduced the term global goals. Its intention is to help communicate the agreed upon *Sustainable Development Goals* to a wider constituency.

For the first time, sustainable consumption and production patterns are specifically mentioned among the seventeen goals (Fig. 2, UN 2015).

The particular claim of goal 12 is to reach out for sustainable consumption and production at "doing more and better with less." The scope ranges from macro- to microeconomic level, from society to individuals, from degradation to pollution along the whole lifecycle, while likewise increasing quality of life. It involves different stakeholders, including business, consumers, policy makers, researchers and retailers among others. Furthermore, this goal requires a systemic approach and cooperation among stakeholders in the entire supply chain, from producer to final consumer.

Ueda et al. take up the basic idea and elaborate: "in association with globalization and networking, every industry in this century is strongly required to contribute to sustainable development, but no solution can be obtained easily when considering the complexity and instability of the social systems. Additionally, maintaining sustainability often creates a dilemma between values of a whole society and values of individuals […]. Therefore, to resolve this problem, more attention must be devoted to value creation mechanisms" (Ueda et al. 2009).

In this context, both aspects of value creation and sustainable development need to be combined to form *Sustainable Value Creation*. The mechanisms included in value creation and *Sustainable Development* are highly dynamic.

Goal 12. Ensure sustainable consumption and production patterns

12.1 Implement the 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries

12.2 By 2030, achieve the sustainable management and efficient use of natural resources

12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses

12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment

12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse

12.6 Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle

12.7 Promote public procurement practices that are sustainable, in accordance with national policies and priorities

12.8 By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature

Fig. 2 Goal 12 “Ensure sustainable consumption and production patterns” among the seventeen *United Nations Sustainable Development Goals* (UN 2015)

Firstly, value creation is characterised by flows of information, resources, capital and labour among production systems. Secondly, these flows are realized within socio-economic, natural and sociotechnical systems. Thirdly, value creation runs over two major levels:

(a) The micro-economic level manages e.g. value creation in supply-chain of a product and value creation along the lifecycle of a product) and
(b) The macro-economic level manages value creation of an entire branch and value creation among countries and within regions.

The interaction and interdependencies of *Sustainable Value Creation*, therefore, lead to a high dynamic among the different systems and their linkages. Value creation activities and services follow three types of interactions as direct and indirect effects between the three major dimensions of sustainability (environment, society and economy):

1. Causal relations,
2. Magnitude and scale drivers and
3. Latency and timely duration dependencies.

Causal relations describe the determined effects between a solution and its direct and indirect impact on the three dimensions of sustainability (e.g. a new manufacturing solution and its direct impact on the economy, as well as its indirect impacts on society and environment). The direct and indirect impact is determined by the magnitude and scale of a solution's dissemination (e.g. the societal and environmental impact of a solution becomes measurable due to its increasing market share). The effects and impacts have different latencies and time durations (e.g. the societal and environmental impacts of an established solution have a delay and last a certain period of time). The evaluation and description of these dynamic effects is a scientific task and its solution has to however be practical at the same time.

2 Sustainability Dynamics Model

The *Sustainability Dynamics Model* (SDM) is an instrument for describing the direct and indirect effects of value creation solutions on the three dimensions of sustainability and vice versa. Since value creation solutions are the key elements they become the central focus of the model. The three dimensions of *Sustainable Development* (environment, society and economy) actually represent systems of their own and evolve around the value creation solution (Fig. 3).

Starting from the value creation solution, direct effects between the solution and each sustainability dimension system can be pinpointed:

- The primary effects on the environment are the use and conversion of energy, materials, greenhouse gases etc.
- The primary effect on the society are the improvement of living standards, the use of products, prosperity etc.
- The primary effects on the economy are manufacturing processes, factories, logistics etc.

The primary effects on one dimension system can cause impacts on other dimension systems. In addition to causal effects (e.g. between environment and society), the above-mentioned effects in the levels of magnitude and scale as well as latency and time duration can be observed. In this case, the root causes not only primary impacts on one dimension system but also secondary impacts on the other two dimension systems of sustainability. Mutual spiral effects between the sustainability dimension systems can, furthermore, be caused by the intended primary effects.

The effect of a value creation solution on the dimension systems of sustainability can be defined as an inside-out effect. Even so, cause and effect vary with different

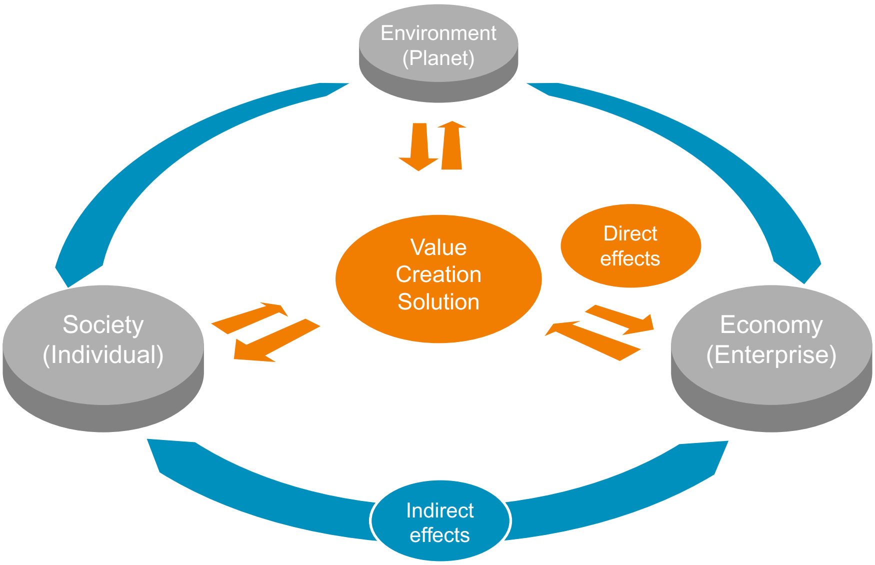

Fig. 3 Introduction of the *Sustainability Dynamics Model* (value creation solution and their direct and indirect effects on sustainable dimension systems)

value creation solutions and their impact on sustainability, among other factors. The *Sustainability Dimension Model* allows an opposite contemplation, which is called an outside-in effect. In this case, the cause can be met in any of the three sustainability dimension systems. This leads to a direct impact on the value creation solution and, additionally, to secondary effects on other sustainability dimension systems through the value creation solution.

An example of outside-in effects is found in the sub-goal 12 "Ensure sustainable consumption and production patterns" of the *United Nations Sustainable Development Goals* (UN 2015). The dynamic effects of sustainable consumption and production play a major role on a macro-economic level, especially in sustainability dimensions and the indirect effects in between. Figure 4 represents the mapping of the eight sub-goals.

In order to illustrate the dynamics in sustainability, the following exemplary goals are revealed:

- 12.2: "By 2030, achieve the sustainable management and efficient use of natural resources" (UN 2015).
- 12.4: "By 2030, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment" (UN 2015).
- 12.5: "By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse" (UN 2015).

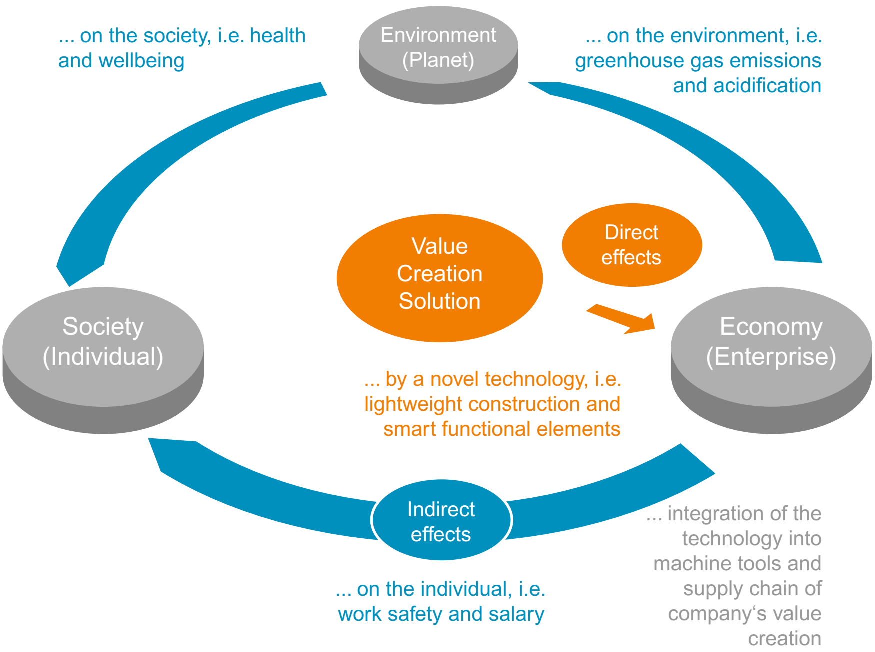

Fig. 4 Mapping of the eight sub-goals of goal 12 “Ensure sustainable production and consumption patterns” of the *United Nations Sustainable Development Goals* and the *Sustainability Dynamics Model*

Goal 12.2 focuses on the overall introduction of principles of sustainable development into country policies and programmes. Regarding the *Sustainability Dynamics Model*, its primary effect lies in the social dimension system. Actions from this dimension system have a direct causal effect on the economic dimension system. Companies within this dimension system have to fulfil sustainable policies and programme demands. That way, the indirect effect is on value creation solutions. Sustainable solutions have to be researched and they need to be applied in manufacturing companies. Depending on the magnitude and scale, an indirect effect on the environmental dimension system takes place and, in return, on the social dimension system on top of that.

Goal 12.4 directly affects the environmental dimension system. The environmentally sound management of chemicals and all wastes throughout their life cycle, along with the significantly reduction of their releases into air, water and soil, together impact both the social and the environmental dimension system at the same time. In order to minimise their impacts on human health, sustainable value creation solutions have to be implemented on a large scale and level of magnitude. These effects occur in latency and timely duration dependencies.

Goal 12.5 deals with the generation and management of waste on a micro- and macroeconomic level. It directly affects the economic dimension system. Technologies and techniques from sustainable value solutions should be applied and used in order to reduce and manage waste from industry. At the same time, products and services that are offered in this dimension system have a causal relationship with its use within the social and individual dimension system. That way, prevention, reduction, recycling and reuse solutions all have an effect on the environmental dimension system.

3 Instantiation of the Model

The direct and indirect effects along the *Sustainability Dynamics Model* can be defined as inside-out effects and outside-in effects. These effects can be either observed when the model is read from the inside (sustainable value creation) to the outside (sustainable dimension systems,) or, vice versa, from the outside the inside. In the following, these two principles are illustrated with two examples.

The first example deals with a novel sustainable manufacturing solution which is based on an innovative manufacturing technology (Fig. 5). This could be gained i.e. by lightweight construction, smart functional elements, improved working accuracy or smart interfaces. The effect on the environmental and social dimension system of the new technology itself is not yet provided. That is, a causal relationship with society and environment can only be found indirectly. However, a direct causal relationship, and in that respect, a direct effect of the new technology, are offered to the economic dimension system. The new technology has to be implemented into a machine tool and into the supply chain. This entails that, a company integrates the solution into their value creation process. Over time, the new solution is in use, indirect effects on the social and environmental dimension system can be found. On the one hand, individuals who are in charge of the new solution are affected i.e. by work safety and salary. Depending on the magnitude and scale of the new solution, the degree of impact on the environmental dimension system is defined, i.e. greenhouse gases and acidification. Furthermore, not only the individual but the whole society is indirectly affected by the environmental impact, i.e. in terms of health and well-being.

The second example deals with the growing awareness among society about sustainable products and services (Fig. 6). In this case, society and individuals demand sustainable solutions. The direct effect is the need for a sustainable value creation solution which can be either a product, a service or a *Product-Service System*. The solution should provide sustainable principles to the customer, i.e. in terms of emissions, noise, safety, costs, recyclability. The indirect effect is basically on manufacturing companies which develop, manufacture and provide the new

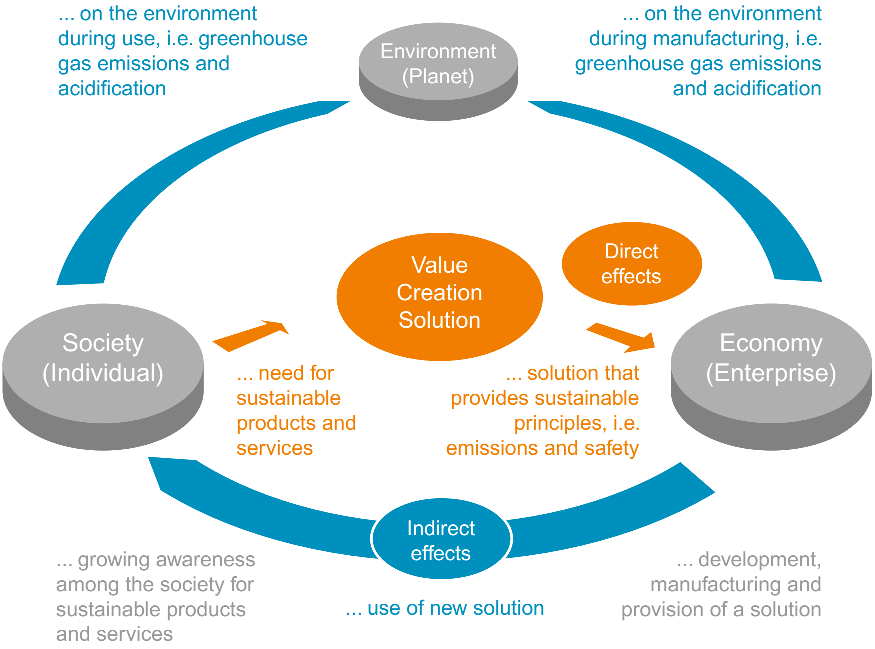

Fig. 5 Inside-out effects of an innovative value creation solution on the economic, social and environmental dimension system

solution to the individual. Depending on the magnitude and scale of the new solution, the impact on the environmental and social dimension system varies, i.e. in terms of greenhouse gas emissions and acidification by manufacturing and use of the solution.

4 Conclusion

The notion of *Sustainability Dynamics* is a new scientific approach which describes the interconnectivity between core dimensions of sustainability and their related internal systems with the system of value creation solutions. The new approach is described within this contribution as a first foundation causal model in pursuit of providing a new basis for describing cross-system sustainability behaviours and influences.

The authors have concentrated on demonstrating the principle power of the model with the help of allocating the sub-targets of goal 12 of the seventeen United Nations Sustainable Development Goals into the causal network of the *Sustainability Dynamics Model*. This goal 12 represents the only goal amongst the seventeen goals which directly addresses sustainable consumption and production patterns critical for sustainable value creation and manufacturing contributions.

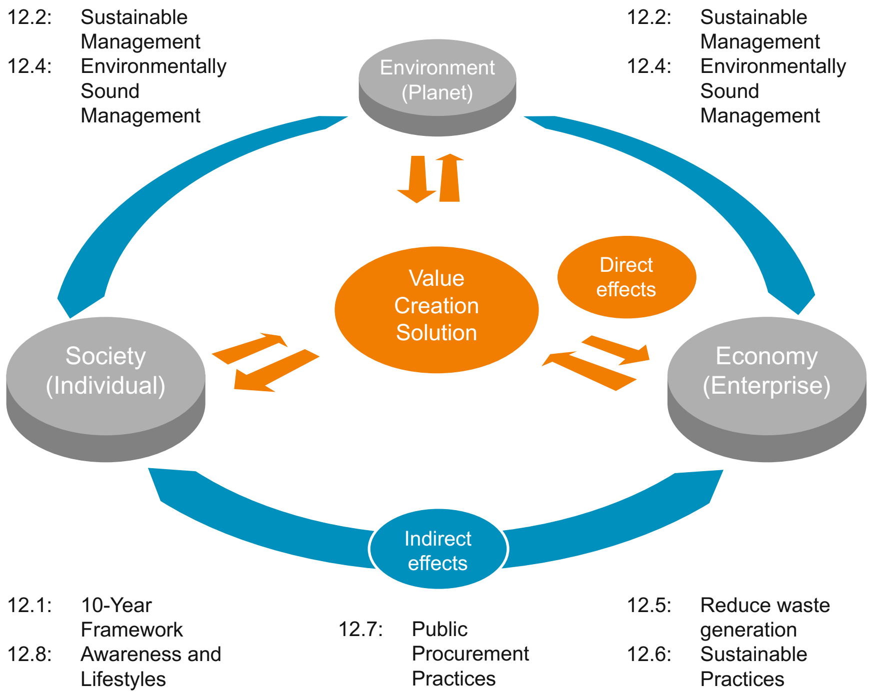

Fig. 6 Outside-in effects of a growing awareness among the society for sustainable products and services on the value creation solution and on the economic, social and environmental dimension system

The *Sustainability Dynamics Model* for the first time ever enables the visual and qualitative capabilities for showing the interdependencies and causal effects of value creation solutions (e.g. as part of sustainable product development and sustainable manufacturing) with the major systems of the three sustainability dimensions of environment (planet/earth), economy (enterprises) and society (individual). At this point, in time the *Sustainability Dynamics Model* exists at a foundational level in order to allow high level and principle trade-off discussions and qualitative reasoning.

The next level of the *Sustainability Dynamics Model* is targeted at fostering and expanding the "dynamic" dimension. That is, principles of the model theory *system dynamics* (cp. Sterman 2000) will be utilised in pursuit of quantitative prediction capability. From a knowledge and model depth point of view it will be scrutinized which type of model laws can be integrated robustly. At this point in time it is the authors' belief that the *Sustainability Dynamics Model* bears significant capability to deploy both rule-based dynamic mechanisms as well as big/smart data plug-ins, for the purpose of delivering an increasing level of consequence prediction capability for the contributions of value creation solution towards "measurable" sustainability.

5 Outlook

The major element to transform manufacturing towards “higher sustainability” with respect to global value creation is “resource productivity within a compatible environment” (cp. Bleischwitz et al. 2009). Such target state requires continuous improvements in resource discovery. At the same time, resource productivity remains hugely underexploited as a source of wealth, competitiveness and renewal.

The European Commission started to propose a circular economy strategy (EC 2015) and many business leaders have indeed embraced the circular economy as a path to increasing growth and profitability (Lovins and Braungart 2014). In this manner, the circular economy is gaining increasing attention and offers a potential way for the society to increase prosperity, while reducing dependency on primary materials and energy. In this context, the *Sustainability Dynamics Model* even now at its infancy stage serves as an enabler for explaining basic connections between value creation and circular economy against the background of sustainable development. Furthermore, correlations and coherences could be explained by direct and indirect effects in terms of causal relations, magnitude and scale drivers and latency and time duration dependencies at a micro- and macroeconomic level.

Future expansions of the *Sustainability Dynamics Model,* as depicted in Sect. 4 of this contribution, will deliver the potential to serve as one of the core control models of value creation contributions within the circular economy of the future.

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Enabling Low-Carbon Development in Poor Countries

Jan Christoph Steckel, Gregor Schwerhoff and Ottmar Edenhofer

Abstract The challenges associated with achieving sustainable development goals and stabilizing the world's climate cannot be solved without significant efforts by developing and newly-emerging countries. With respect to climate change mitigation, the main challenge for developing countries lies in avoiding future emissions and lock-ins into emission-intensive technologies, rather than reducing today's emissions. While first best policy instruments like carbon prices could prevent increasing carbonization, those policies are often rejected by developing countries out of a concern for negative repercussions on development and long-term growth. In addition, policy environments in developing countries impose particular challenges for regulatory policy aiming to incentivize climate change mitigation and sustainable development. This chapter first discusses how climate policy could potentially interact with sustainable development and economic growth. It focuses, in particular, on the role of industrial sector development. The chapter then continues by discussing how effective policy could be designed, specifically taking developing country circumstances into account.

Keywords Developing countries · Climate policy · Sustainable development

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1 Introduction

Economic development and poverty eradication (as aimed at in the Sustainable Development Goals, SDGs) have in the past gone hand in hand with the large-scale carbonization of countries' energy systems. That is, countries that have been successful in lifting people out of poverty have also dramatically increased their per-capita emissions, hence contributing significantly to climate change. This trend has recently accelerated by a global renaissance of emission-intensive coal. This renewed embrace of coal is mainly driven by countries that currently have low income, but whose economies are growing rapidly. They are investing in cheap and widely available coal to fuel their increasing energy demand and ongoing industrialization (Steckel et al. 2015). Coal-fired power plants that are currently under construction or planned would—if realized—consume one third (240 Gt of CO_2) of the carbon budget still available to achieve a 2 °C goal (roughly 800 Gt CO_2) (Edenhofer et al. 2016). Six developing or newly industrializing countries (China, India, Vietnam, South Africa, Turkey and Indonesia) are responsible for 85 % of ongoing and planned coal investments. In those countries, the relative prices of coal are usually low despite recent cost reductions of low carbon alternatives, including natural gas and renewable energy (Edenhofer et al. 2016).

Against this background, it comes as no surprise that in order to achieve ambitious climate change mitigation targets, more than half of global mitigation (compared to "business as usual" scenarios based on historic correlations between GDP and carbon emissions) will need to take place in today's low and middle-income countries (Jakob and Steckel 2014). In other words, for the Paris Agreement to be successful, these countries cannot replicate the emission- and energy-intense development pathways of the past, but will need to decouple growing GDP and greenhouse gas emissions. Providing energy by means of low carbon technologies, like renewable energy, biomass, nuclear or fossil fuels in combination with carbon-capture and storage (CCS) is thus one important element in the process of detaching emissions from economic growth (IPCC 2014).

Another way of reducing emissions entails reducing energy use, particularly in the manufacturing sectors. Today, technological differences across economic sectors (i.e. value added per energy input in specific sectors, e.g. the automobile sector) the world over can be multiple orders of magnitude, with poor countries usually employing outdated, inefficient technologies (Kim and Kim 2012). Figure 1 shows that sectoral energy intensity levels in rich countries (listed in Annex I to the UNFCCC) are usually much lower than in developing and newly industrializing countries (non-Annex I countries), with some manufacturing sectors showing differences by multiple orders of magnitude.

Ward et al. (2016) show that equalizing existing differences at least to some extent using technology available today, carries potential for global greenhouse gas (GHG) reductions in the energy sector of 10 Gt CO_2 or more. This result is obtained considering higher order effects—that is, considering the effect of changes in technology on the entire supply chain (first order effects, in contrast, only take

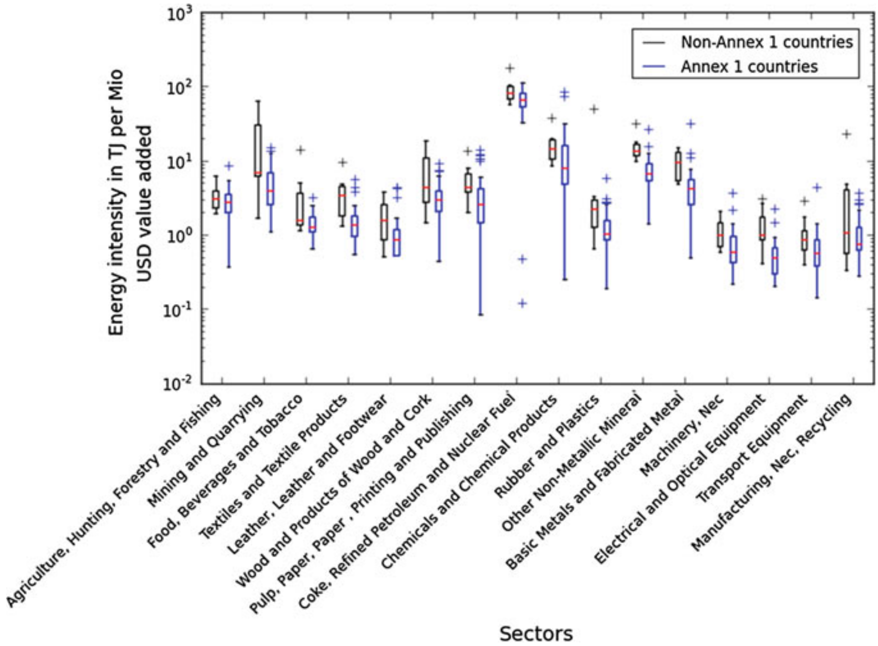

Fig. 1 Distribution of energy intensity of industrial sectors across the World Input-Output Database's (WIOD) regions. *Boxes* represent 25th–75th percentile, *red line* refers to median. *Whiskers* in each direction correspond to 1.5 times the interquartile range. *Black boxplots* represent non-Annex I regions of the UNFCCC, *blue boxplots* corresponds to Annex I regions. *Crosses* represent outliers. *Source* Ward et al. (2016)

direct suppliers into account while multiple layers of the supply chain are ignored). Equalizing existing differences and significantly enhancing energy efficiency levels furthermore likewise play an important role in global mitigation scenarios (IPCC 2014; Luderer et al. 2012).

From an economic point of view, an important question lies in how technological improvements focusing on both the demand side and the investment in low carbon energy systems on the supply side can be incentivized. In this paper we will argue that it is of particular importance to come up with such reward systems that can work in developing country frameworks. Broad agreement among economists holds that a carbon price is the most efficient ("first best") policy instrument. In developing countries, however, carbon prices are hardly ever instituted due to distributive concerns—that is, concerns that the effect of the prices will be distributed unequally amongst the population. A major distributive concern is that carbon prices have a regressive effect, wherein the poor pay proportionally more than the wealthy. Second, there is a concern that carbon prices interfere with economic growth, structural change, involving a shift in importance among different sectors in the economy and industrial development (Jakob and Steckel 2014). While this argument is frequently made by policymakers from developing counties, hardly any evidence exists on how exactly structural change and carbon pricing would actually interact.

In this chapter, we will therefore investigate the role of structural change and industrial development on economic growth. Against this background, we will then examine various policy options in developing countries. We will first look into different conceptual possibilities for carbon pricing, including taxes, subsidy removal policies and emissions trading. Second, we will discuss potential barriers specific for developing country environments. We conclude with options for enabling low carbon development in developing countries.

2 Industrialization, Economic Development and Climate Policy

In order to properly assess future developments and evaluate the impacts of envisaged climate policies for affected countries, it is crucial to have a clear picture of the role of specific economic sectors in the process of economic growth. It is particularly important to appreciate the role of energy industry sectors for development. Yet, whereas mitigation scenarios as reviewed in the IPCC (2014) display a high level of technological detail in the energy sector, they usually abstract from modelling economic sectors at a fine resolution. For this reason, some key stylized facts on energy use are not well captured by current climate scenarios. For instance, there is a clear correlation of GDP and energy use up to a certain threshold (Steckel et al. 2013; Steinberger and Roberts 2010). Compared to levels that are observed today, additional energy is undoubtedly needed for covering subsistence needs (Rao et al. 2014) as well as provision of basic infrastructure services (Steckel et al. 2013, 2015). Furthermore, the share of the industry sector in countries' energy demand increases dramatically in development processes before it eventually declines again (Schäfer 2005).

Today, most integrated assessment models (IAMs) that are assessed for the IPCC (2014) and thus constitute the backbone of analyses regarding climate change mitigation, rely on economic models which abstract from differences between sectors. These models however do not take any particular income levels or different economic structures explicitly into account. Instead, they assume that the production factors of labour, capital and (in a subset of models) also energy can be substituted with one another at a given cost. Yet this assumption partly contradicts the empirical observations mentioned above. More realistic modelling of economic growth and associated energy use patterns during industrialization could however indeed substantially affect mitigation costs in developing countries.

Early theories of economic growth focused heavily on the role of specific economic sectors and structural changes. Since the works of Hirschman (1958), the structure of an economy—the composition of economic sectors in the overall economy and how they are interlinked—is commonly conceived of as an important driver for economic growth. Yet as a result of the analytical intractability of such models, one-sector growth models à la Ramsey (1928) and Solow (1956) have become the workhorse models of both economic theory and several IAMs. Structural change has only recently re-emerged as a central topic (Hansen and Prescott 2002), and has been recognized as one of the main factors of future economic growth, in particular in African countries (McMillan et al. 2014).

This recent work shows that during the development process, the forces which drive structural changes are the changing patterns of demand due to increasing incomes and differences in sectoral (labour) productivities. Early in the development process, economies typically have large agricultural sectors and then develop first the industrial and then the service sector (Herrendorf et al. 2014). Convergence of productivities across countries only takes place in manufacturing sectors, or, in countries that have gone through basic structural changes (Rodrik 2013). Countries going through structural changes first diversify their economies (i.e. building up more complex industrial sectors) and then undertake specializing further once they have reached a certain level of affluence (Imbs and Wacziarg 2003).

Recent economic research has probed more deeply into the processes going on within the three major sectors. These authors regard the economy as a network of interconnected products or sectors. In the process of compiling this information into an aggregate index of economic complexity, it turns out that economic complexity (usually measured in the structure of exports) is predictive of economic growth (Hidalgo et al. 2007; Hidalgo and Hausmann 2009) and can even explain economic growth better than aggregated neo-classical growth models (Hausmann 2007; Hausmann and Hidalgo 2011). Some authors (e.g. Hidalgo and Hausmann 2009) moreover presume increasingly complex export structures to be explainable by means of underlying societal capabilities. Increasing complexity is hence related to the increasingly diverse interplay of ingredients that are of general importance for socio-economic development and growth. Radebach et al. (2016) find a clear community structure of economic sectors by using value-added data. Some sectors occupy a central position in the emerging network, mainly light industry sectors, such as textiles and wood products. These sectors can be deemed to be of particular relevance to economic development, as they allow a transition from an agricultural to an industrialized economy. In line with other results from the literature, this result suggests some sectors of being more important for economic growth than others (Fig. 2).

This observation seems to be especially significant considering that underlying capabilities (such as institutions and human capital) relevant for economic growth and development (e.g. Acemoğlu et al. 2005; Acemoğlu and Robinson 2000) depend on increasing complexity. If building up specific (energy- and carbon intensive) sectors enhances spillovers for general economic development and growth, then this indeed yields decisive consequences for climate policy. It follows then, that failing to go through the process of the industrial stage proves detrimental to an economy aiming at economic growth and sustainable development. Yet more central in the pursuit of sustainable development are the factors of innovation and technological development, or, *sustainable manufacturing*.

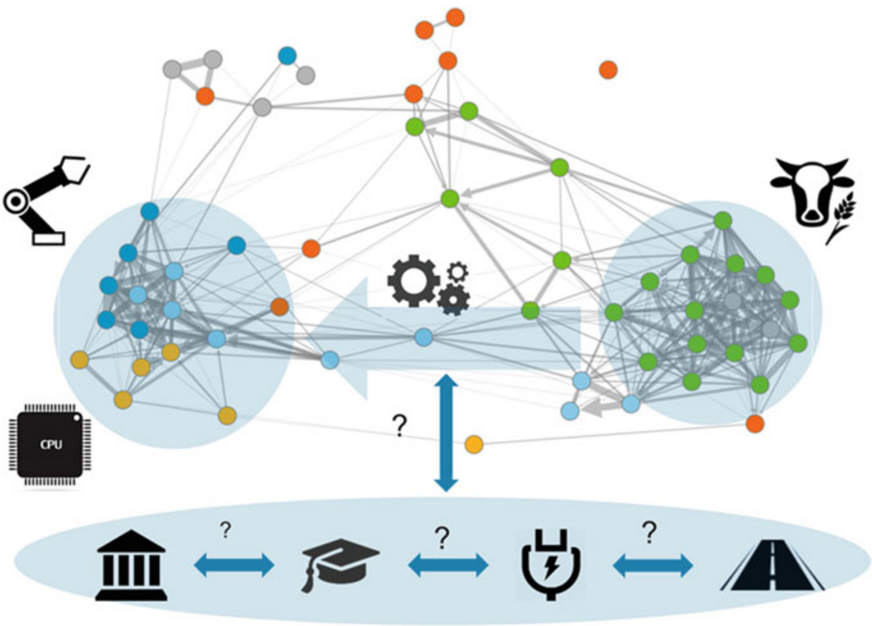

Fig. 2 Stylized representation of the role of manufacturing sectors for structural change and economic development. To the *right* (*green dots*), mainly agricultural sectors can be seen, while high-tech (*dark blue*) and service sectors (*yellow*) sectors are mainly found on the *left hand side*. Certain sectors bridge those communities (light manufacturing sectors, *light blue*), which has given rise to the hypothesis that those sectors are important for building up societal capabilities, including institutions, education, and infrastructure. Adapted from Radebach et al. (2016)

This observation thereby yields important insights for the design of policy instruments in developing countries. Climate policy that discourages investments in manufacturing sectors and decelerates structural change might therefore indeed prove harmful to development—an argument often brought forward by developing countries themselves. For example, from the very onset of the UNFCCC Conference of the Parties in Paris, India's Prime Minister Modi proceeded to highlight, while acknowledging the challenges of climate change for India, that his country will further invest in coal to fuel its energy needs and ensure its right to development.

On that token, the following section will explore the policy options for enhancing low-carbon development in developing countries in more detail.

3 Incentivizing Change—Carbon Pricing in a Developing Country Context

From an economic theory point of view, carbon pricing is the *sine qua non* of climate policy, a precept broadly agreed upon by economists (see e.g. Acemoglu et al. 2012; Stiglitz 2016; Weitzman 2014). A global price on carbon is generally believed to be a key solution for settling the climate problem, which was recently prominently reiterated by MacKay et al. (2015). Carbon prices ensure that negative implications and damages of emissions—including changes in the climate—are readily transparent and therefore taken into account by market participants, and hence incorporated into investment decisions. Applied to the entire economy, they also ensure that loopholes can be avoided and transaction costs can be kept to a minimum. Other policy instruments, like research subsidies and technology standards, furthermore, have proven quite successful in reducing the energy and carbon intensity of the targeted sectors or products, but at the same time do not prevent increasing emissions in other areas of the economy. This is an effect described as the "rebound effect" (Arvesen et al. 2011; Gillingham et al. 2016)

In this context, it is important to keep in mind that carbon prices can be implemented in a wide variety of ways. While the straightforward method is obviously imposing a tax on carbon (which again can be levied at various points of regulation, up- or downstream), a carbon price can also be applied in the form of a quantity-based instrument, i.e. an emissions trading scheme. Following the logic applied in the Kyoto Protocol, it has long been discussed as a viable means of implementing an international carbon market. In such a trading scheme, the amount of total emissions is capped, while emission allowances are allocated to countries. The allocation is often inspired by an ethical principle and results from specific negotiations between countries, e.g. equal emission rights per capita. An international carbon price would then be established on the grounds of supply and demand for emission certificates. Allocation schemes could be designed in such a way that they favour developing countries insofar as they ensure that they are compensated for the potential incremental costs attached to low-carbon technologies.

While countries are increasingly implementing carbon pricing schemes (in particular OECD countries, World Bank 2015), high fossil fuel subsidies have led to a de facto subsidy for carbon (i.e. a negative carbon price) at the global level (Coady et al. 2015). Foregoing fossil fuel subsidies is hence an important first step in incentivizing climate change mitigation, particularly in developing countries.

While affecting the relative price with carbon prices is appealing conceptually, this process runs up against copious obstacles in developing countries, some of which do not exist in this form in developed countries. First, financing costs are usually higher in developing countries. Typically, interest rates are higher and access to capital is more difficult than in developed countries, as are the political and regulatory risks incurred by investors. Both factors lead to weighted average costs of capital in developing countries being significantly higher than in OECD countries (Schmidt 2014). In this market environment, raising (or implementing) a price on carbon would increase energy prices, but not necessarily lead to investment in low-carbon and energy efficient technologies. As those are usually more capital intensive than dirty technologies (Schmidt 2014) a price on carbon can be ineffective in terms of triggering low-carbon investments and hence remains ineffective (Hirth and Steckel, under review). Additional policy instruments designed to alleviate investor risk and buy down technology costs thus might be needed in addition to carbon pricing in order to incentivize low-carbon development.

Second, a range of economic analyses on carbon pricing implicitly presume a liberalized energy market that allows for price signals to be passed through. However, this stands in stark contrast to the (generally) non-liberalized nature of energy markets in many developing countries (Goldblatt 2010; Wisuttisak 2012). Non-liberalized energy markets however indeed grossly impact the effectiveness of carbon pricing. When the government (or one of its agencies) is directly responsible for energy investments, it therefore has to take on payment of the carbon price itself. Unless government agencies, and in particular the energy utility, are made fully responsible for their individual financial performance, the carbon price is unlikely to have any strong incentive effect. This is in particularly true when the government aims to keep energy prices as low as possible, e.g. to prevent negative income effects on poor households or out of the interest in competiveness. In developing countries, where energy utilities are responsible for a large part of total emissions, this situation can mean that total emissions are hardly affected by the carbon price.

Hence, a third obstacle is rooted in distributive concerns. If carbon prices have the desired incentivizing effect, they inevitably cause higher energy prices. Low energy prices, however, are ostensibly considered to be an essential channel for supporting the poor in many countries and are often subsidized for that very reason. What's more, energy prices are considered to be a critical element in the pursuit of the competitiveness of the country's overall economy in the global marketplace. Indeed rising energy prices frequently lead to public protests and societal unrest. Yet balancing distributive issues of rising energy prices is far from impossible. Foregoing fossil fuel subsidies in Indonesia or Iran, for example, have been complemented by transfer schemes favouring poor households (Lindebjerg et al. 2015).

The quality of institutions is also relevant when considering carbon pricing options in developing countries. One frequently proposed model for implementing international carbon prices is an international carbon market, which considers equity issues by means of allowance allocation schemes that favour developing countries. Jakob et al. (2015) emphasize that related transfers could be in the form of resource rents, for example, that yielded negative implications on long-term growth in the past—often referred to as "resource curse". Under such conditions, developing countries might not be able to absorb the carbon rent in a productive way. Low institutional quality and high rates of corruption might also have proven to be pertinent in cases where a pricing instrument was in place related to administrative efforts at monitoring market participants. Even in the EU ETS, some have reported that information asymmetries between regulators and firms have led to reported cases of fraud (Nield and Pereira 2011).

4 Conclusion: Climate Policy Solutions for Developing Countries

Overall, a price on carbon is seen to have the effect of penalizing carbon emissions. To avoid paying this price, firms could reduce emissions per unit of energy by employing low-carbon technology and reducing energy use by improving energy efficiency. However, specific market environments featuring rather low institutional quality, coupled with rather high inequality, high capital costs and regulated energy markets, to mention only a few factors, need all to be taken into careful consideration when crafting the design of policy instruments. Most importantly, it needs to be acknowledged that distributional concerns, both regarding the poorest parts of countries' populations as well as decelerated economic growth (i.e. slower convergence to developed countries' income levels), likewise figure into the equation in a huge way for policy makers in developing countries.

Given this background, Jakob et al. (2016) propose using revenues from carbon pricing to finance infrastructure investment. In many countries, the revenues which a government can collect from taxing CO_2, can then be utilized to finance SDGs, e.g. access to water, sanitation or electricity. In the case of Nigeria, Dorband (2016) shows that a carbon tax deployed in this way turns out to be largely progressive, and hence can alleviate distributional concerns.

In addition, it will be necessary to institute de-risk measures for investments in low-carbon technologies. While one possibility could be to implement subsidies in addition to carbon prices, it may well be useful to offer additional securities to companies that aim to invest in developing countries. Those securities today are often granted to fossil fuels (Coady et al. 2015).

Moreover, carbon taxes can be levied downstream, for example, at the sale of the final good to the consumer, or upstream, where a fossil fuel is extracted or imported. Given issues with institutional quality, it seems that levying carbon taxes upstream is the most useful mechanism for introducing a carbon tax in developing countries. Even when markets remain regulated in this way, fossil fuel costs increase. This would also be relevant for investment decisions taken by governments themselves.

An open question however remains with regards to carbon taxes possibly ushering in a decelerating force on industrial development. As literature shows possible positive spillovers from a more complex economy, it might therefore be necessary to come up with industrial policy to complement climate policy in order to alleviate negative effects on growth and development. Future research will be needed to better appreciate the precise relationship between industrial development and climate policy.

Finally, the UNFCCC demands common but differentiated responsibility and burden sharing, implying support from developed for developing countries both for climate change adaptation and mitigation. Based on those fundamental principles, international climate finance (e.g. by the Green Climate Fund) is supposed to support the low-carbon transformation of developing countries. While international climate finance is slowly under way, it is still rather unclear how exactly it will be disbursed. It will be an interesting question for future climate negotiations to tackle how to redesign international climate finance to support structural transformations towards low-carbon development and economic leapfrogging in pursuit of climate change mitigation.

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