Part V
Implementation Perspectives

Sustainable Value Creation—From Concept Towards Implementation

Steve Evans, Lloyd Fernando and Miying Yang

Abstract Sustainability is crucial to create long-term high value in manufacturing system. Sustainable value creation requires systems thinking in order to maximise total value captured. There is a need to better understand how companies can improve sustainable value creation. Few tools or structured approaches to thinking about sustainable value are available. This chapter seeks to provide understanding of key concepts for and tools that aid practitioners in sustainable value creation in manufacturing. The chapter also provides case studies on how the tools have helped companies improve sustainability.

Keywords Sustainable value creation · System thinking · Cambridge Value Mapping Tool · Sustainable Value Analysis Tool · Business model innovation · Sustainable business models

1 Introduction

We currently live in a world of constrained resources, growing populations and exceeding planetary boundaries. There is a need for industry to change the way we make things and shift towards a more sustainable industrial system. Understanding of system transformation and value transformation are important concepts for transitioning towards a more sustainable industrial system. Senge (1990) states that the un-healthiness of the world today is indirect proportion to our inability to see it

S. Evans (✉)
Centre for Industrial Sustainability, University of Cambridge, Cambridge, UK
e-mail: se321@cam.ac.uk

L. Fernando
Expo Industrial Engineering, University of Cambridge, Cambridge, UK

M. Yang
University of Cambridge, Cambridge, UK

© The Author(s) 2017

R. Stark et al. (eds.), *Sustainable Manufacturing*, Sustainable Production, Life Cycle Engineering and Management, DOI 10.1007/978-3-319-48514-0_13

as a whole. Companies may not be fully aware of the full range of potential value outcomes. Most existing business models are mostly based on creating, delivering and capturing economic value, with limited or no attention to environmental and social value. The changing business environment, wider range of stakeholders engaging in debate over industry, resource limitations and emphasis on social responsibilities of firms has raised the need for sustainable value creation.

2 Key Concepts for Sustainable Value Creation

The industrial sustainability literature reviewed suggests system thinking and whole system design techniques as being one of the critical ways to understand sustainable value. This section presents main ideas on system thinking, whole system design, systems innovation and sustainable business models as the key concepts for sustainable value creation.

2.1 Systems Thinking

Seiffert and Loch (2005) suggest that the most important property of systems is that they are made up of several parts that are not isolated, but closely interlinked, forming a complex structure. Systemic or systems thinking, facilitates the improved understanding of these complex systems and enables the identification and utilisation of interrelationships and linkages as opposed to things.

Systems thinking is a technique for investigating entire systems, seeking to understand the relationships, the interactions, and the boundaries between parts of a system (Senge et al. 2008; Cabrera and Cabrera 2015). Systems thinking is particularly well suited to modeling highly complex open-systems where an integrated understanding is required at both the micro and macro-levels in order to predict or manage change. This contrasts with the dominant analytical approach of the physical sciences, which is based on reductionism, analysing closed-systems at the level of their constituent parts and then simplifying to draw out general conclusions. Systems thinking is a generic term that spans a range of more than 20 tools and methodologies (Reynolds and Holwell 2010).

Senge (1990) explains that systems thinking is a discipline for seeing wholes. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static snapshots. It appears that systems thinking is a way of approaching problems: rather than applying a strict linear methodology, the techniques are iterative, and designed to stimulate investigation, discussion and debate by encouraging multiple perspectives. Systems thinking does not aim to provide quantifiable answers to specific problems, but rather provides a range of options and better understanding of the implications of those options (Meadows and Wright

2009; Madrazo and Senge 2011). Manzini and Vezzoli (2003) emphasise the need for design for sustainability to move from product thinking to system thinking.

Network analysis potentially provides the scope to integrate multiple factors (economic, social and environmental). Preliminary research on analysing sustainability within industrial networks has demonstrated the use of such tools in understanding how and why networks adopt sustainability initiatives and the significance of 'focal' companies within the network (Van Bommel 2011).

It is described by authors (e.g. Senge et al. 2008) that many of the current challenges in industrial systems stem from the inability to understand and manage dynamic systems. Systems Thinking takes a birds-eye view and observes the whole picture by focusing on the relationships between the different entities of a system, rather than on isolated parts. Systems thinking is described by authors (Hawken et al. 1999; Rocky Mountain Institute 2006; Senge et al. 2008; Evans et al. 2009; Charnley et al. 2011; Cabrera and Cabrera 2015) as providing the foundation for a proactive approach to be able to design sustainable industrial systems (e.g. Systems Thinking can be a way to understand complex, non-linear, and interconnected systems of businesses, whether social, managerial, economical or environmental issues). There is lack of evidence and understanding of what abilities do companies need to improve their industrial sustainability at systems level. An ability-based view is not presented.

2.2 *Whole System Design*

Whole systems design is one approach to sustainable design offering great potential, however the processes, principles, and methods guiding the whole systems approach are not clearly defined or understood by practicing designers or design educators (Charnley et al. 2011).

Evans et al. (2009) describes whilst it is important to address the impact of each aspect of the industrial system and pursue aggressive reduction in the impact of specific activities, we must also examine the operation of the whole system. Efficiently manufacturing products that are inefficient in use, for example, is not enough. This approach can even result in substantially negative outcomes when efficiency gains or cost reductions result in increases in consumption (the so-called Rebound Effect). The greatest opportunity to reduce the impact of the industrial system on the planet arises when we consider the whole system and the optimisation of any individual component of the industrial system.

Rocky Mountain Institute-RMI (2006) define whole system design as 'optimising not just parts but the entire system … it takes ingenuity, intuition, and teamwork. Everything must be considered simultaneously and analysed to reveal mutually advantageous interactions (synergies) as well as undesirable ones'. Whole-systems thinkers see wholes instead of parts, interrelationships and patterns, rather than individual things and static snapshots. They seek solutions that simultaneously address multiple problems (Anarow et al. 2003). Lovins (2011) are among the small number of authors who suggest that understanding the dynamics of a system is integral to the whole system approach. The Rocky Mountain Institute (2004) highlights systems thinking as the method that should be utilised not only to point the way to solutions to particular resource problems, but also to reveal interconnections between problems, which often permits one solution to be leveraged to create many more. Meadows (2009) lists nine places to intervene in a system, in increasing order of impact: numbers (subsidies, taxes, standards), material stocks and flows, regulating negative feedback loops, driving positive feedback loops, information flows, the rules of the system (incentives, punishment, constraints), the power of self-organisation, the goals of the system, and the mindset or paradigm out of which the goals, rules, and feedback structures arise.

It is suggested by the authors that reframing the system with a whole systems view helps people to understand more fully the way manufacturing affects the world we live in and how we might begin to change it (i.e. redesign the industrial system). Understanding who is involved in the current system and how they interact with it can help identify more opportunities to create sustainable value. The field of whole systems design and the literature surrounding it remains limited (Coley and Lemon 2009). Evans et al. (2009) describes the evidence from the case studies implementing and shifting towards more sustainable manufacturing and demonstrates that dramatic improvements can be made at the level of sub-systems, such as factories or businesses. In parallel, however, it will be necessary to develop the understanding and capabilities necessary to enable changes in the whole industrial system. Anarow et al. (2003) state that “sustainability cannot be achieved in the absence of whole-systems thinking”, an ability that appears to be essential to improve industrial sustainability performance.

2.3 Systems Innovation

It is argued the innovations required for sustainable development need to move beyond incremental adjustments. Sustainable development requires the transformation of larger parts of production and consumption systems (Boons 2009). Incremental (product- and process-related) innovations in existing production and consumption systems may lead to further gradual improvements of sustainability performance, but in the end, incremental innovation frequently does not lead to a globally optimal system configuration in a multi-dimensional production and consumption system space (Larson 2000; Frenken et al. 2007; Vezzoli et al. 2008; Schaltegger and Wagner 2011).

While the term sustainable innovation has been widely used during the last decade, the number of definitions in the academic literature is limited (Holmes and Smart 2009; Boons and Lüdeke-Freund 2013). The review by Carrillo-Hermosilla et al. (2010) lists innovation definitions that focus on ecological sustainability, such as eco-innovation and environmental innovation. For instance, Carrillo-Hermosilla et al. (2010) introduced their own definition of eco-innovation: “innovation that improves environmental performance". Charter et al. (2008) describes that given the challenges posed by sustainable development, sustainable innovation will often be characterised by systemness and radicalness. Generally, sustainable innovations go beyond regular product and process innovations and are future-oriented. Sustainable innovation goes beyond eco-innovation because it includes social objectives and is more clearly linked to the holistic and long-term process of sustainable development for the short- and long-term objectives of sustainability. Holmes and Smart (2009) describe the need for more research in sustainability-led innovations and partnerships.

Adams et al. (2016) presents a model of (SOI) sustainability-oriented innovation onto which sustainability oriented innovation practices and processes can be mapped:

- Operational optimisation (e.g. eco-efficiency—compliance, efficiency, doing the same things better)
- Organisationtinal transformation (e.g. new market opportunities—novel products, services or business models, doing good by doing new things)
- Systems building (e.g. societal change—novel products, services or business models that are impossible to achieve alone, doing good by doing new things with others).

Adams et al. (2016) describe sustainability-oriented innovation as making intentional changes to an organisation's philosophy and values, as well as to its products, processes or practices to serve the specific purpose of creating and realising social and environmental value in addition to economic returns.

Draper (2015) in the report—'Creating the big shift: system innovation for sustainability, defines systems innovation as "a set of actions that shift a system—a city, a sector, an economy—onto a more sustainable path". It is described in this definition; being able to identify the set of actions is important, systems change usually requires multiple interventions across different areas of society, it is very rare that a single person or innovation can change a whole complex system, such as waste or energy and tackling problems that are too large for any one organisation, however powerful, to solve on its own (e.g. shift systems to make them more resilient, more equitable and able to continue into the future). Draper (2015) states that there is an "absence of necessary skills in sectors that can take the innovation to scale".

Sustainable development is argued by some authors to require radical and systemic innovations. Some authors argue these innovations can be more effectively created when building on the concept of business models. Sustainable business models provide the conceptual link between sustainable innovation and economic performance at higher system levels (Boons and Lüdeke-Freund 2013). Sustainable innovation is described by some authors to often be characterised by radicalness, some argue sustainable innovations go beyond regular product and process innovations and are future-oriented (Charter et al. 2008). Sustainable innovation is described by Charter et al. (2008) "Sustainable innovation is a process where sustainability considerations (environmental, social, and financial) are integrated into company systems from idea generation through to research and development (R&D) and commercialisation. This applies to products, services and technologies, as well as to new business and organisational models".

2.4 Sustainable Business Models

Bocken et al. (2014) states that business model innovations for sustainability are defined as: innovations that create significant positive and/or significantly reduced negative impacts for the environment and/or society, through changes in the way the organisation and its value-network create, deliver value and capture value (i.e. create economic value) or change their value propositions. It is argued in Bocken et al. (2014) that to tackle the pressing challenges of a sustainable future, innovations need to introduce change at the core of the business model to tackle unsustainability at its source rather than as an add-on to counter-act negative outcomes of business. The level of ambition of business model innovations needs to be high and focused on maximising societal and environmental benefits, rather than economic gain only. The sustainable business model innovation describing radical changes in the way companies do business has received considerable attention from both academia and practitioners (Chesbrough 2010; Zott et al. 2011). Sustainability management deals with social, environmental and economic issues in an integrated manner to transform organisations in a way that they contribute to a sustainable development of the economy and society within the limits of the ecosystem. Leaders, managers and entrepreneurs are challenged to contribute to sustainable development on the individual, organisational and societal level. Scholars and practitioners are recently increasingly exploring if and how modified and completely new business models can help maintain or even increase economic prosperity by either radically reducing negative or creating positive external effects for the natural environment and society, literature surrounding this area is scarce and still emerging.

Organisations today are challenged to contribute to sustainable development on the individual, organisational and societal level. Sustainability management refers to approaches dealing with social, environmental and economic issues in an integrated manner to transform organisations in a way that they contribute to a sustainable development of the economy and society within the limits of the ecosystem e.g. (Starik and Kanashiro 2013; Schaltegger et al. 2012; Boons and Lüdeke-Freund 2013). It appears "technological fix"—is insufficient to create the required transformation of organisations, industries and societies towards more sustainability. Researchers and practitioners are therefore increasingly exploring how completely new business models can help maintain or even increase economic prosperity by either radically reducing negative or creating positive external effects for the natural environment and society e.g. (Boons and Lüdeke-Freund 2013; Hansen et al. 2009; Schaltegger et al. 2012; Stubbs and Cocklin 2008). This perspective does not only cover existing organisations and how their business models are transformed (e.g. Sommer 2012), but also entirely new business models pioneered by entrepreneurs. The literature on sustainable business models is still emerging.

The literature presents numerous views on what constitutes a business model (e.g. Richardson 2008). Teece (2010) provides a concise definition: a business model is the design or architecture of the value creation, delivery and capture mechanism of a firm, how the firm delivers value, how it attracts customers, and how it converts this to profit (Teece 2010). Richardson proposes a summary organised around the concept of value:

- The value proposition—offering, target customer, differentiation;
- The value creation and delivery system—The value chain required, resources, assets, processes, position in the value network relative to customers, competitors and collaborators;
- The value capture system—How the firm makes money (financial model) and competitive strategy.

Evans et al. (2015) describe manufacturers are increasingly experimenting with new ways of meeting customers' needs. This includes shifting from providing products to providing services, in a way that separates the use of a product from its ownership; or circular economy models where products are designed and manufactured for continuous reuse, and value is captured from 'waste' wherever possible.

The sustainable business model literature describes the concept of value proposition and the creation of creative positive benefits to its stakeholders. There a growing volume of industrial cases on sustainable business models, but little is known on how these improvements were conceived, little is available about specific abilities and competencies (Barth et al. 2007; Segalas et al. 2009; Willard et al. 2010; Teece 2010; Bocken et al. 2014). System transformation and value transformation appear to be importance concepts to the research enquiry.

2.5 *New Concepts for Sustainable Value Creation—Negative Forms of Value*

Very few authors have contributed towards understanding the creation of new systems and generating value across the value network in the sustainable business models literature by identifying failed value exchanges. Authors such as (Rana et al. 2013; Yang et al. 2013; Bocken et al. 2014) are the few authors that have contributed

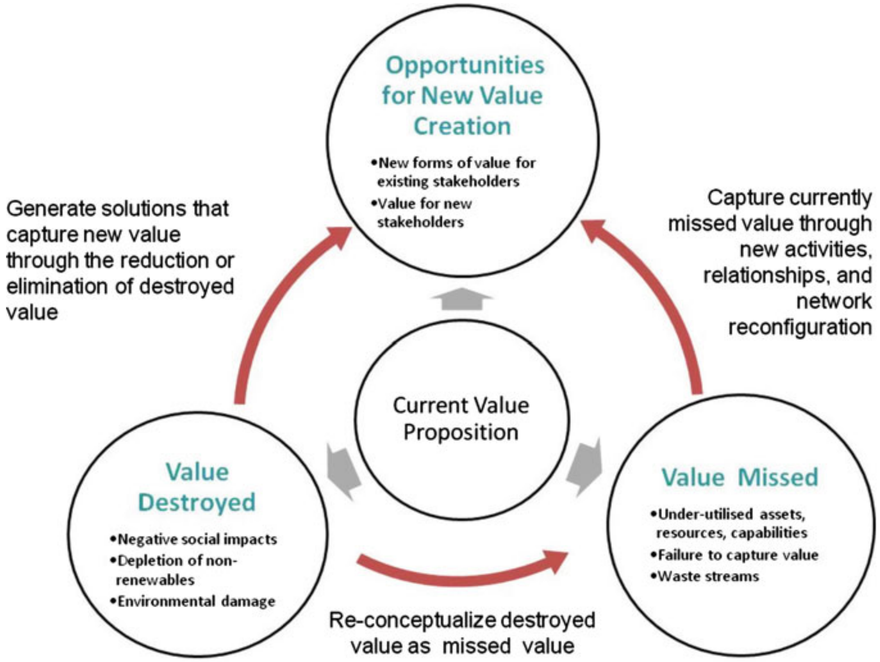


Fig. 1 Value propositions (Rana et al. 2013)

towards understanding opportunities for value creation. Yang et al. (2014) describe and define multiple forms of value (e.g. value absence, value surplus, value destroyed, value missed). Rana et al. (2013) and Bocken et al. (2014) in their research propose a framework for business model innovation for sustainability by explicitly considering value destroyed and value missed within the business model, as these often represent important opportunities for sustainability innovation. Their research provides a qualitative framework to facilitate systematic exploration of the different forms of value for each stakeholder (Fig. 1).

- Value captured—current value proposition
- Value destroyed—negative value outcomes of current model
- Value missed—value currently squandered, lost or inadequately captured by current model
- Value opportunities—new opportunities for additional value creation and capture through new activities and relationships.

Based on this, Yang et al. (2016) further propose value uncaptured as a new perspective for sustainable business model innovation. Value uncaptured is defined

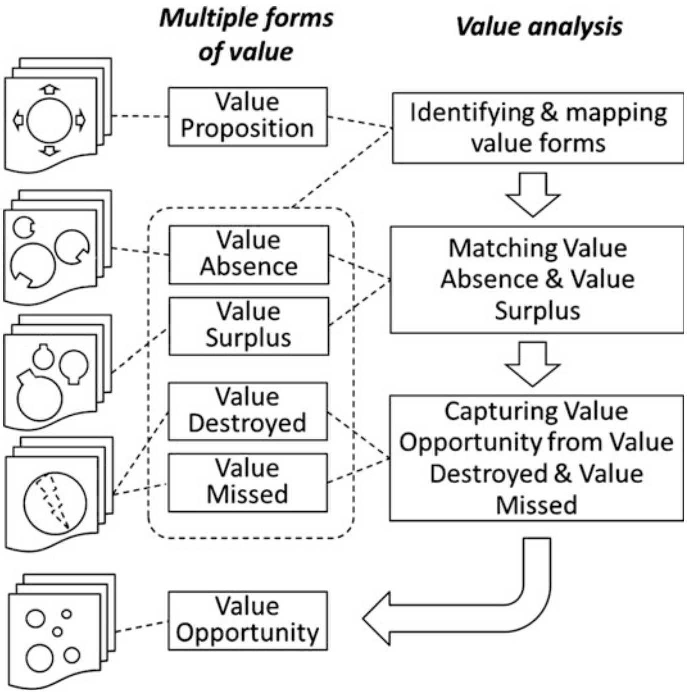


Fig. 2 Analysis of multiple forms of value (Yang et al. 2013)

as the potential value, which could be captured but has not been captured yet. Four forms of value uncaptured, i.e. value surplus, value absence, value destroyed and values missed and an approach of analysis of multiple forms of value was proposed shown in Fig. 2 (Yang et al. 2013).

Value uncaptured exists in almost all companies. Some uncaptured value is visible, e.g. waste streams in production, co-products, under-utilised resources, and reusable components of broken products; some is invisible, e.g. over capacity of labour, insufficient use of expertise and knowledge. Reducing any kind of the uncaptured value would create sustainable value. Yang et al. (2016) propose a framework of using value uncaptured for sustainable business model innovation, and claims that sustainable business model innovation can be more easily achieved by identifying the value uncaptured in current business models, and then turning this new understanding of the current business into value opportunities that can lead to new business models with higher sustainable value.

3 Tools for Sustainable Value Creation

This section describes the Cambridge Value Mapping Tool, and the Sustainable Value Analysis Tool and their strengths and weakness. The tools provide a structured way of helping companies identify opportunities for business model innovations that result in more sustainable businesses. This could assist companies maximise value among stakeholders across the system. The tools also provide new perspectives on sustainable value creation and aid transforming the businesses to deliver uncaptured and sustainable value.

3.1 Cambridge Value Mapping Tool

The Cambridge Value Mapping Tool has been developed to elicit failed value exchanges among multiple stakeholders in the network of the firm and uncover new value opportunities through a structured and visual approach. It is developed to assist manufacturing companies in identifying opportunities for sustainable value creation. The tool assists in systematically analysing various forms of value in your business and your network and stimulate innovation in sustainable value creation. The tool adopts a multi-stakeholder perspective, through which the exchange of value can be analysed and potential stakeholder conflicts identified to create positive value in the network. It provides a new perspective for practitioners to understand and create new economic, social, and environmental value from their business. The tool gives practitioners a new way to gain a deeper understanding of value and create new economic, social, and environmental benefits for their business (Fig. 3).

The Cambridge Value Mapping Tool was developed at the IfM's Centre for Industrial Sustainability by a research team led by Professor Steve Evans. Originating from the EU FP7 Sustain Value project, the tool since has gone through multiple conceptual and visual iterations. Acknowledgements for their contributions go to Dr. Padmakshi Rana, Dr. Samuel Short, Dr. Nancy Bocken, Dr. Dai Morgan, Dr. Miying Yang, Dr. Lloyd Fernando, Dr. Doroteya Vladimirova, Dr. Curie Park, Fenna Blomsma and Dr. Maria Holgado. Particular thanks to all industry collaborators who took part in the development, testing and refinement of the tool.

The Cambridge Value Mapping Tool takes you in a guided step-by-step process through the following questions:

- What is the unit of analysis e.g. product, service, company, industry?
- Who are the stakeholders for the unit of analysis?
- What is the purpose of the unit of analysis?
- What is the current value captured?

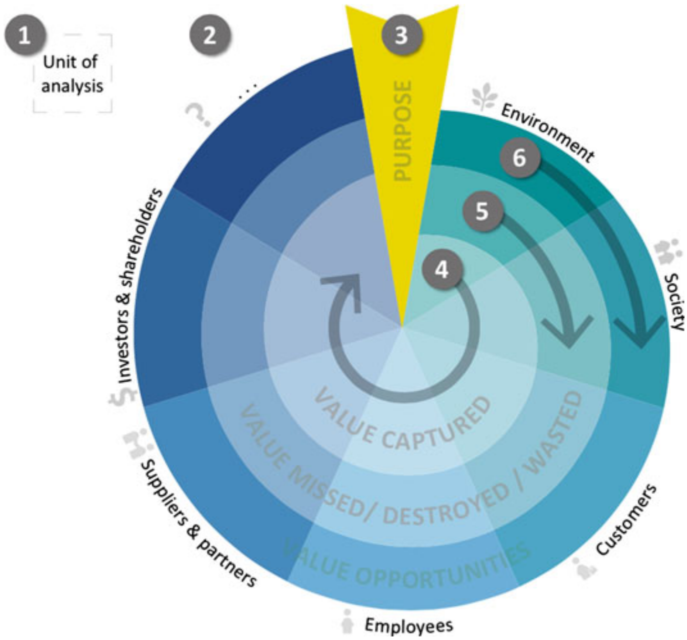


Fig. 3 Cambridge Value Mapping Tool (*Source* http://www.ifm.eng.cam.ac.uk/news/the-cambridge-value-mapping-tool/#.V8aiy5N961s)

- What is the value missed and/or destroyed?
- What is the value surplus and/or absence?
- What are the new value opportunities?

Strengths

- The tool can be used by individuals to identify opportunities to create sustainable value in their own companies.
- The tool gives practitioners a new way to gain a deeper understanding of value and create new economic, social, and environmental benefits for their business
- Designed to stimulate innovation of the business model for sustainable value
- Helps practitioners to find and create new economic, social, and environmental value from their business through a systematic analysis of various forms of value in the business and the firm's network
- Provides a structured approach to identify sustainable value opportunities

Weakness

- Does not explore the unintended consequences that can arise in other parts of the system for implementing the identified value opportunity.

3.2 Sustainable Value Analysis Tool (SVAT)

Sustainable Value Analysis Tool is built to help manufacturers identify opportunities to create sustainable value by analysing the captured and uncaptured value throughout the entire life cycle of products (Yang 2015). Identifying the value uncaptured and creating value from it is not always easy. The rationale of the tool is to use separate forms (i.e. value surplus, value absence, value destroyed and value missed) of value to inspire the identification of value uncaptured, and to further identify value opportunities by analysing the identified value uncaptured. The tool provides companies with a scheme to systematically look for each form of value uncaptured at the beginning of life (BoL), middle of life (MoL) and end of life (EoL) of the product, and with a method to turn the identified value uncaptured into value opportunities.

Sustainable Value Analysis Tool consists of a poster (see Fig. 4) and a set of cards (see Fig. 5) for an example. The poster is used for gathering insights across the different life cycle phases and the cards for guiding and inspiring the process of using the tool. As shown in Fig. 4, the tool combines the life cycle thinking and value forms analysis. The three phases of a product life cycle (BOL, MOL and EOL) could be further divided into more specific stages. For example, MOL can be further divided into distribution, use, maintenance and service. The value forms

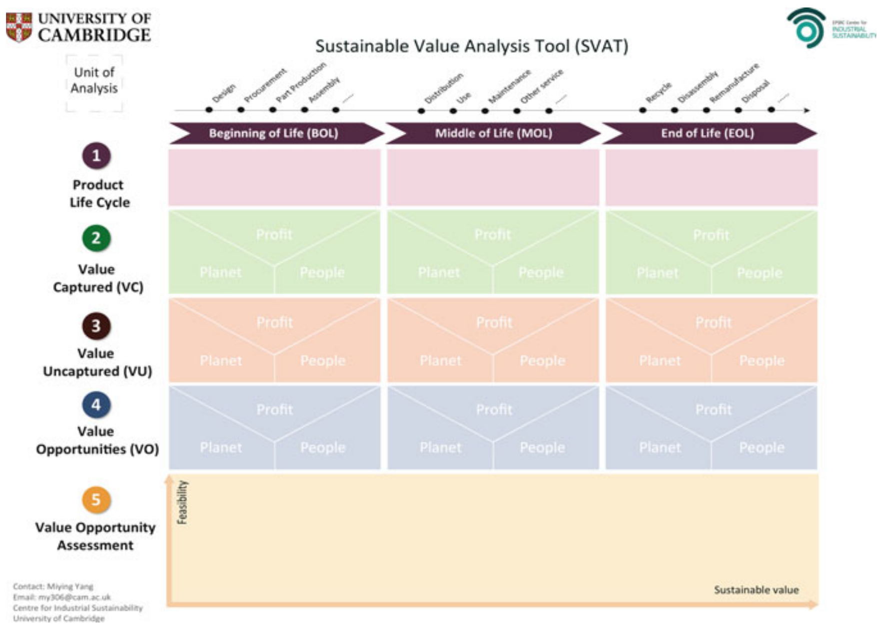


Fig. 4 Poster of Sustainable Value Analysis Tool (Yang 2015)

Fig. 5 Cards of Sustainable Value Analysis Tool (Yang 2015)

consist of value captured, value uncaptured and value opportunities. Value uncaptured could be considered from the perspectives of value destroyed, value missed, value surplus and value absence.

Sustainable Value Analysis Tool mainly consists of five steps:

- Step 1. Define the life cycle stages of a product in the company, and map the stakeholders involved in each stage of product life cycle
- Step 2. Describe what is the value captured for each stakeholder (environmental, social and economic dimensions) in each stage of the defined product life cycle
- Step 3. Identify what is the value uncaptured for each stakeholder (environmental, social and economic dimensions) in each stage of the defined product life cycle
- Step 4. Identify value opportunities, e.g. how to turn value uncaptured into value opportunities
- Step 5. Assess the feasibility and sustainability of each identified value opportunity

For each step there is a card providing step-by-step guidance including background knowledge, tasks and tips on the front and some inspirational examples on the back.

The tool can elicit value uncaptured across products life cycle, and uncover new value opportunities through a structured and visual approach.

Strengths

- Comprehensive analysis of value
- Generating business opportunities in a strategic way (by turning value uncaptured into value opportunities)

- Innovation for sustainability
- Embedding stakeholder theory and life cycle thinking
- Business model driven

Weakness

- Does not include strategic planning on how to realise the identified opportunities.

4 Case Studies: Lessons Learnt from Practice on Sustainable Value Creation

This section elaborates on the cases investigated to explore the current industrial practice in business models and identify failed value exchanged and find opportunities to capture value. For confidentiality purpose the names of the firm and the interviewees have not been revealed.

Introduction

Company A is a fast moving consumer good, Sugar manufacturer. The case studies of this company provide a generic view of value exchanges between firm and stakeholder groups.

Company A aims to transform all raw materials into sustainable products. The plant in Wissington has been operating for over 85 years and now produces over 420 kt of sugar annually for food and drinks manufacturers The company uses a culture of innovation to reduce process inputs, minimise waste and deliver its commitment to be an advanced and sustainable manufacturer. The company has been able to find ways of internalising and being very effective at it. The company converts raw beet to sugar and the byproducts are used to produce electricity, tomatoes, animal feed, and other materials. No material arriving into the company is allowed to disappear as waste (and a cost). Instead all materials are turned into valuable co-products, including the soil attached to the beet, which becomes clean soil for gardeners, these actions contribute to a very high level of efficient use of raw materials. The company has been able to bring more value under its control and link knowledge to benefit by turning everything into a valuable output.

Data

> We are the world's largest refinery producing 420,000 tonnes of Sugar annually… We been able to find opportunities in our process to produce co-products from the waste streams of the primary sugar production processes… (Symbiotic co-product lines)… We have found a broad range of additional synergistic and profitable product lines… animal feed, electricity, tomatoes, and bioethanol… More than two hundred and forty miles of piping carries hot water from the factory's Combined Heat and Power (CHP) plant around the glasshouse, to maintain the balmy temperatures, which suit tomato plants. This hot water would otherwise be destined for cooling towers, so the scheme ensures that the heat is used productively…. carbon dioxide as a by-product from the CHP boiler is pumped into the enormous glasshouse

> to be absorbed by the plants (rather than vented into the atmosphere as waste emissions)… waste carbon dioxide from the factory is used by tomatoes for photosynthesis… the site also harvests the rainwater from the giant glasshouse roof; over 115 million litres are collected annually to irrigate the plants…the horticulture business produces around 140 million 'eco-friendly' tomatoes each year…co-product generated by finding opportunities for productive, and creative use of the waste streams….The heated atmosphere of 4 times ambient levels of CO2 enables the tomatoes to grow at twice the usual rate, providing high productivity for the glasshouse investment (Interviewee 2B—Head of Engineering).

Analysis—From Concept Towards Implementation

The data suggests the company for example a leader in efficiently and sustainably manufacturing sugar beet, over the past three decades has been able to systematically find failed value exchanges in their system. The company described, "We routinely seek innovative ways to minimise waste and maximise value". The company has been able to see 'carbon emissions' and 'low-grade heat' escaping from its processes into the atmosphere as a failed value (a by-product from the CHP boiler). The company described, "this hot water would otherwise be destined for cooling towers… we identified that our supply of carbon dioxide, heat and water could be better exploited if we used it again." The company has been able to identify the waste streams (i.e. carbon dioxide, heat) that had value that is not being captured and destroyed in its system (i.e. failed value).

The data suggests that company for example has been able to turn waste streams (i.e. failed value) and emissions from their core production processes into useful and positive inputs to new product lines. No material arriving into the company is allowed to disappear as waste (and a cost). Instead all materials are turned into valuable co-products. The data suggests that the company has been able to firstly identify failed values and then bring more value under its control by using and linking its knowledge to turn waste streams in its current systems into a valuable output and create positive value. The company has been able to see the combustion gases from the power station and low-grade heat as failed value lost to the atmosphere. The company described how it has been able to find away to capture the two waste streams and transform it to create new positive value (i.e. grow tomatoes) and deliberately bring it into the business model. By seeing failed value and bringing it into the business model, the company has been able to make productive use of waste carbon dioxide and heat from the sugar factory, which tomatoes (new co-product) use during photosynthesis. It is described the carbon dioxide (a by-product from the CHP boiler) is pumped into the enormous glasshouse to be absorbed by the plants, rather than vented into the atmosphere as waste emissions. It is observed the company has firstly been able to see the failed value exchange, and then figure out what to do with it to form positive value, and come up with a solution using its knowledge and control.

5 Conclusion

This chapter provides key concepts for increasing sustainable value creation in manufacturing, and presents the tools which can help companies using the concepts in practice. Sustainable value creation requires companies to have systems thinking when making business decisions. Companies need to consider the value creation for multi-stakeholders, including customers, suppliers, employees, society and planet. The concept of failed value exchange is identified to be helpful for companies to identify opportunities for sustainable value creation. The evidence suggests that by looking at what value exchanges are failing across the multiple stakeholders, organisations are found to be able to see a lot of value opportunities. The system transformation that industry needs requires more cross-business system collaboration. A case study of sugar manufacturer is provided to illustrate how these concepts are implemented in industries.

References

Adams, R., S. Jeanrenaud, J. Bessant, D. Denyer, and P. Overy. 2016. Sustainability-oriented innovation: A systematic review. *International Journal of Management Reviews* 18: 180–205.

Anarow, B., C. Greener, V. Gupta, M. Kinsley, J. Henderson, C. Page, and K. Parrot. 2003. Whole-systems framework for sustainable consumption and production. *Report for Danish Ministry of the Environment, Denmark* 807: 1–51.

Barth, M., J. Godemann, M. Rieckman, and U. Stoltenberg. 2007. Developing key competences for sustainable development in higher education. *International Journal of Sustainable Higher Education* 8: 416–430.

Bocken, N., S.W. Short, and S. Evans. 2014. A literature and practice review to develop sustainable business model archetypes. *Journal of Cleaner Production* 65: 42–56.

Boons, F. 2009. *Creating ecological value. An evolutionary approach to business strategies and the natural environment*. Cheltenham: Edward Elgar.

Boons, F., and F. Lüdeke-Freund. 2013. Business models for sustainable innovation: state-of-the-art and steps towards a research agenda. *Journal of Cleaner Production* 45: 9–19.

Cabrera, D., and L. Cabrera. 2015. *Systems thinking made simple: New hope for solving wicked problems*. Ithaca, NY: Odyssean.

Carrillo-Hermosilla, J., P. del Río, and T. Könnölä. 2010. Diversity of eco-innovations: Reflections from selected case studies. *Journal of Cleaner Production* 18: 1073–1083.

Charnley, F., M. Lemon, and S. Evans. 2011. Exploring the process of whole system design. *Design Studies* 32(2): 156–179.

Charter, M., C. Gray, T. Clark, and T. Woolman. 2008. Review: The role of business in realising sustainable consumption and production. *System Innovation for Sustainability: Perspectives on Radical Changes to Sustainable Consumption and Production* 46–69.

Chesbrough, H.W. 2010. Business model innovation: Opportunities and barriers. *Long Range Planning* 43(2): 354–363.

Coley, F., and M. Lemon. 2009. Exploring the uncertainty surrounding the design and perceived benefit of sustainable solutions. *Journal of Engineering Design* 20: 543–554.

Draper, S. 2015. Creating the big shift: System innovation for sustainability. The Forum for the Future, London. http://www.forumforthefuture.org. Accessed 9 October 15.

Evans, S., M.N. Bergendahl, M. Gregory, and C. Ryan. 2009. Towards a sustainable industrial system. In *International Manufacturing Professors' Symposium in Cambridge, UK.*

Evans, S., T. Moore, and M. Folkerson. 2015. *Industrial evolution: Making British manufacturing sustainable*. CAN Mezzanine, UK: Policy Connect.

Frenken, K., M. Schwoon, F. Alkemade, and M. Hekkert. 2007. A complex systems methodology to transition management. In *DRUID Summer Conference 2007, Copenhagen, CBS,* 18–20.

Hansen, E.G., F. Grobe-Dunker, and R. Reichwald. 2009. Sustainability innovation cube. A framework to evaluate sustainability-oriented innovations. *International Journal of Innovation Management* 13(4): 683–713.

Hawken, P., A.B. Lovins, and L.H. Lovins. 1999. *Natural capitalism: Creating the next industrial revolution*. Little, Brown and Co: Array Boston.

Holmes, S., and P. Smart. 2009. Exploring open innovation practice in firm-nonprofit engagements: A corporate social responsibility perspective. *R&D Management* 39(4): 395–409.

Larson, A.L. 2000. Sustainable innovation through an entrepreneurship lens. *Business Strategy and the Environment* 9: 304–317.

Lovins, A.B. 2011. *Reinventing fire: Bold business solutions for the new energy era*. White River Junction, VT: Chelsea Green Publishing.

Madrazo, C., and P. Senge. 2011. *Building communities of collaboration and co-inspiration*. Academy for Systemic Change.

Manzini, E., and C. Vezzoli. 2003. A strategic design approach to develop sustainable product service systems: Examples taken from the environmentally friendly innovation Italian prize. *Journal of Cleaner Production* 11(8): 851–857.

Meadows, D.H., and D. Wright. 2009. *Thinking in systems: A primer*, 1st ed. London: Earthscan Ltd.

Rana, P., S.W. Short, N. Bocken, and S. Evans. 2013. Towards a sustainable business form: A business modelling process and tools. In *Sustainable Consumption Research and Action Initiative (SCORAI) Conference: The Future of Consumerism and Well-Being in a World of Ecological Constraints, 12–14 June, Clark University, Worcester, USA*.

Reynolds, M., and S. Holwell. 2010. *Systems approaches to managing change: A practical guide*, 1st ed. London: Springer.

Richardson, J. 2008. The business model: an integrative framework for strategy execution. *Strategic Change* 17(5): 133–144.

Rocky Mountain Institute. 2004. Whole system design. http://www.rmi.org/. Accessed 20 August 2015.

Rocky Mountain Institute. 2006. Hypercar design and technology. https://old.rmi.org. Accessed 13 October 2015.

Schaltegger, S., F. Lüdeke, and E. Hansen. 2012. Business cases for sustainability: The role of business model innovation for corporate sustainability. *International Journal Innovation Sustainable Development* 6(2): 95–119.

Schaltegger, S., and M. Wagner. 2011. Sustainable entrepreneurship and sustainability innovation: Categories and interactions. *Business Strategy and the Environment* 20(4): 222–237.

Segalas, J., D. Ferrer-Balas, M. Svanstrom, U. Lundqvist, and K.F. Mulder. 2009. What has to be learnt for sustainability? A comparison of bachelor engineering education competencies at three European Universities. *Sustainability Science* 4(1): 17–27.

Seiffert, M., and C. Loch. 2005. Systemic thinking in environmental management: Support for sustainable development. *Journal of Cleaner Production* 13(12): 1197–1202.

Senge, P. 1990. *The fifth discipline: Mastering the five practices of the learning organization*. New York: Doubleday.

Senge, P.M., B. Smith, and N. Kruschwitz. 2008. *The necessary revolution: How individuals and organisations are working together to create a sustainable world*. New York: Doubleday.

Sommer, A. 2012. *Managing green business model transformations*. Heidelberg: Springer.

Starik, M., and P. Kanashiro. 2013. Toward a theory of sustainability management: Uncovering and integrating the nearly obvious. *Organization & Environment* 26(1): 7–30.

Stubbs, W., and C. Cocklin. 2008. Conceptualizing a sustainability business model. *Organization & Environment* 21(2): 103–127.

Teece, D.J. 2010. Business models, business strategy and innovation. *Long Range Planning* 43(2): 172–194.

Van Bommel, H.W.M. 2011. A conceptual framework for analyzing sustainability strategies in industrial supply networks from an innovation perspective. *Journal of Cleaner Production* 19 (8): 895–904.

Willard, M., C. Wiedmeyer, R.W. Flint, J.S. Weedon, R. Woodward, I. Feldmand, and M. Edwards. 2010. *The sustainability professional: 2010 competency survey report*. International Society of Sustainability Professionals.

Yang, M., P. Rana, and S. Evans. 2013. Product service system (PSS) life cycle value analysis for sustainability. In *Proceedings of the 6th conference on Design and Manufacture for Sustainable Development (ISBN: 978-1-84919-709-0), Zhejiang University, Hangzhou, China*.

Yang, M., D. Vladimirova, P. Rana, and S. Evans. 2014. Sustainable Value Analysis Tool for value creation. *Asian Journal of Management Science and Applications* 1(4): 312–332.

Yang, M. 2015. *Sustainable value creation for product-service systems (PSS)*. University of Cambridge.

Yang, M., S. Evans, D. Vladimirova, and P. Rana. 2016. Value uncaptured perspective for sustainable business model innovation. *Journal of Cleaner Production*. doi:10.1016/j.jclepro.2016.07.102.

Zott, C., R. Amit, and L. Massa. 2011. The business model: Recent developments and future research. *Journal of Management* 37(4): 1019–1042.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the book's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the book's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

Life Cycle Sustainability Assessment Approaches for Manufacturing

Ya-Ju Chang, Sabrina Neugebauer, Annekatrin Lehmann, René Scheumann and Matthias Finkbeiner

Abstract Sustainability assessments considering the three dimensions environment, economy, and society are needed to evaluate manufacturing processes and products with regard to their sustainability performance. This chapter focuses on Life Cycle Sustainability Assessment (LCSA), which considers all three sustainability dimensions by combining the three methods Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA). Existing LCSA approaches as well as selected ongoing work are introduced, both regarding the individual approaches as well as the combined LCSA approach. This includes, for instance, the Tiered Approach. This approach facilitates the implementation of LCSA, for instance, within the manufacturing sector, by providing a category hierarchy and guiding practitioners through the various impact and cost categories proposed for the three methods. Furthermore, ongoing developments in LCC and SLCA are presented, such as the definition of first economic and social impact pathways (linking fair wage and level of education to social damage levels) for addressing the current challenges of missing impact pathways for economic and social aspects. In addition, the Sustainability Safeguard Star suggests a new scheme for addressing the inter-linkages between the three sustainability dimensions. These approaches foster the application and implementation of LCSA and thus contribute to developing sustainable processes and products.

Keywords Life Cycle Sustainability Assessment (LCSA) · Sustainability assessment · Tiered approach · Life Cycle Assessment (LCA) · Life Cycle Costing (LCC) · Social Life Cycle Assessment (SLCA)

Y.-J. Chang (✉) · S. Neugebauer · A. Lehmann · R. Scheumann · M. Finkbeiner
Department of Environmental Technology, Technische Universität Berlin, Berlin, Germany
e-mail: ya-ju.chang@tu-berlin.de

© The Author(s) 2017

R. Stark et al. (eds.), *Sustainable Manufacturing*, Sustainable Production, Life Cycle Engineering and Management, DOI 10.1007/978-3-319-48514-0_14

1 Introduction

Sustainability and sustainable manufacturing are relevant topics for governments and industries worldwide. In that pursuit, various concepts for sustainability exist and approaches for sustainability assessment have already been introduced. Nevertheless evaluating the sustainability performance at the product level remains a challenge. One of the most widespread concepts of sustainability lies in the triple-bottom-line theory, which considers environmental, economic and social aspects (Finkbeiner et al. 2010; Remmen et al. 2007; Elkington 1998). Moreover, with regard to assessing the sustainability performance of products and processes, life cycle thinking approaches which include the whole life cycle from "cradle to grave," are increasingly gaining in importance. By employing such approaches, a shifting of impact between the different life stages and sustainability dimensions can be identified and avoided (Finkbeiner et al. 2010).

By combining both the triple-bottom line theory and life cycle thinking approaches, the Life Cycle Sustainability Assessment (LCSA) framework has been proposed as a mean of evaluating the sustainability performance of products. LCSA analyses environmental, economic and social sustainability aspects by combining the methods Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA). The LCSA framework has been initiated with the development of the "Product Portfolio Analysis" (PROSA; German: Produktlinienanalyse) (Öko-Institut 1987; Rainer Grießhammer et al. 2007) and was further developed and formulated by Klöpffer and Finkbeiner (Klöpffer 2008; Finkbeiner et al. 2010). LCSA has so far been identified and promoted as a feasible framework for measuring the performance of products in the three sustainability dimensions (UNEP 2012; Valdivia et al. 2012).

Yet, challenges in LCSA's applicability, scientific robustness, comprehensiveness, interpretation and practical implementation persist (Valdivia et al. 2012; Lehmann 2013; Neugebauer et al. 2015). These challenges mainly relate to the different maturity levels of the three methods considered. LCA is widely accepted and used in practice for assessing a variety of products and services (including e.g. technologies). Although LCA still contains some challenges (Finkbeiner et al. 2014), its general application and implementation stand unhindered. Yet, to date, SLCA and LCC have not yet reached a mature level of assessment. Their main methodological difficulties lie in insufficient guidance on indicator selection, missing sets of defined impact categories and areas of protection (AoPs, also called safeguard subjects), as well as missing links between indicators, impacts and AoPs (Valdivia et al. 2012; Lehmann 2013; Neugebauer et al. 2015, 2016). To overcome these challenges, new approaches have been proposed. One of them is the Tiered Approach, which provides a category hierarchy to facilitate the implementation of LCSA, for instance, in the manufacturing sector. Furthermore, social impact pathways (e.g. fair wage) have been defined and a new LCC approach (the economic LCA framework) has been proposed, addressing some of the methodological challenges associated with LCSA.

The following subsections present the three underlying methods of LCSA in detail, including state-of-the-art, research needs and outlook, elaboration on the application of LCSA in manufacturing (e.g. by using the Tiered approach), followed by an introduction to selected developments for improving on the LCSA framework.

2 Life Cycle Sustainability Assessment (LCSA)

As aforementioned, the LCSA framework consists of the three methods Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA), and thus considers positive and negative environmental, social and economic impacts. This combination of different life cycle methods is illustrated by the following Eq. (1) (Klöpffer 2008), which provide helpful guidance in the decision-making processes towards more sustainable products (UNEP/SETAC Life Cycle Initiative 2011).

$$\mathrm{LCSA} = \mathrm{LCA} + \mathrm{LCC} + \mathrm{SLCA} \tag{1}$$

In the following sections, the state-of-the-art of the three methods within LCSA as well as their contribution to sustainable manufacturing are introduced. In addition further research needs and outlook are described.

2.1 Life Cycle Assessment (LCA)

LCA analyses the potential environmental impacts of products and processes from a life cycle perspective. The current development of LCA, and the research needs and outlook are introduced in the following sections.

2.1.1 State-of-the-Art

According to the European Commission (2015), LCA is the best available tool for evaluating the potential environmental impacts of manufacturing processes or products from cradle-to-grave. LCA is an ISO-standardised (ISO 2006a, b) method and structured into four phases: (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) interpretation. Based on the standardised phases, environmental impact can be assessed in an iterative process.

The relation between inventory results, midpoint and endpoint impact categories and AoPs is determined through impact pathways, as displayed in Fig. 1. Inventory

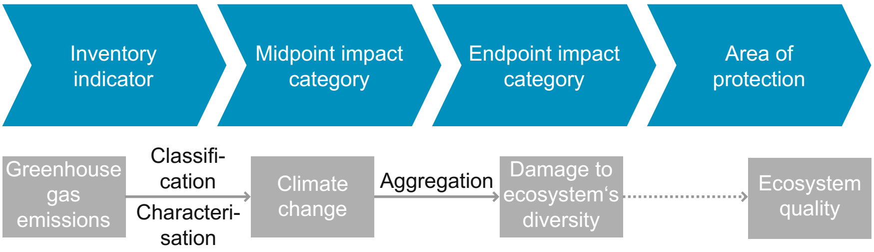


Fig. 1 Relation of inventory indicators, indicators on midpoint and endpoint impact category levels, and AoPs (exemplary illustration for greenhouse gas emissions)

indicators (e.g. greenhouse gas emissions) are classified into impact categories and characterised[1] at the midpoint level (e.g. climate change). The category indicator results achieved at the midpoint level can then be aggregated into impact categories at the endpoint level (e.g. damage to ecosystem's diversity). Those endpoint damage levels are then linked to AoPs (e.g. ecosystem quality).

After decades of method, database and software development, various case studies as well as international standardisation processes have emerged, so that one can now safely say that LCA has reached a mature stage and is robust enough to be applied in decision-making in both private organisations and governments (Finkbeiner et al. 2014).

2.1.2 Research Needs and Outlook

Although LCA has reached a mature level in implementation and has been internationally standardised, LCA still faces some challenges. Finkbeiner et al. (2014) identified 34 challenges with regard to inventory (e.g. dealing with allocation and delayed emissions), impact assessment (e.g. analysing impacts such as land use and odour), generic aspects (e.g. handling weighting and data quality analysis) and evolving aspects (e.g. considering littering, animal well-being or positive impacts), which have not been comprehensively addressed in the current literature and practice. Moreover, collecting relevant and robust data stands as an overall obstacle in carrying out LCA. Although several databases covering numerous different products and processes exist, specific applications (e.g. production of electronics) have so far been insufficiently contemplated. Work is currently ongoing to address some of the challenges, such as improving impact assessment methods (e.g. Bach and Finkbeiner 2016). Until challenges are resolved, practitioners should carefully

[1]The individual contribution of the emissions to the impact is calculated by multiplying the amount of each emission with a characterisation factor (for example, CH_4 has a 28 times higher contribution to global warming than CO_2).

check if the challenges identified limit the conclusions of LCA case studies (Finkbeiner et al. 2014).

2.2 Life Cycle Costing (LCC)

LCC evaluates different costs along the life cycle of a product or process in order to reflect the economic sustainability monetarily. Meanwhile, the current developments of LCC, the research needs in the context of LCSA, along with the overall outlook, are all introduced in the following sections.

2.2.1 State-of-the-Art

LCC appeared in the mid-1960s. Originally, it was used to rank different investment alternatives, but for a long time failed to consider operating costs occurring during the product's lifetime (Glucha and Baumann 2004). A first international standard was published in 2008 with ISO 15686-5 focusing on buildings and construction assets. Therein, LCC is defined as a tool that enables comparative cost assessments (in terms of initial costs and future operational costs) over a specified period of time (ISO 2008).

A similar approach was adopted by Hunkeler et al. (2008), who include producers, suppliers, consumers and end of life actors in the assessment for reflecting costs associated with a product's life cycle. They furthermore differentiate LCC into three types—conventional LCC, environmental LCC, and societal LCC. Conventional LCC focuses on internal costs directly associated with a product's life cycle. Environmental LCC goes beyond that scope and includes external costs likely to be internalised in the decision-relevant future, such as environmental taxes and subsidies (Hunkeler et al. 2008). Societal LCC even includes costs emerging from the side-effects of production which manifest in people's lives and society, whether today or in the long-term. Within the realm of LCSA, it is normally referred to as environmental LCC in the interest of avoiding overlap with the other two dimensions.

2.2.2 Research Needs and Outlook

Several challenges however hinder LCC's methodology development and thus implementation within the LCSA framework. They are, for example, oversimplifying the economic dimension down to a matter of costs, ignoring causalities, or unreliable data in connection with conceptual confusions (Neugebauer et al. 2016). To date, LCC in the context of LSCA is still not commonly implemented in industry, due to methodological confusion with other similar concepts, such as "total cost accounting" (Glucha and Baumann 2004). Furthermore, the limitation attached to costs has often been criticised especially in the context of LCSA. In contrast to LCA, LCC does not contain impact pathways following a cause-effect-chain. Consequently, several authors discuss whether LCC can sufficiently measure and represent economic sustainability within the LCSA framework (Jørgensen et al. 2010; Heijungs et al. 2013). The debate is associated with the question of whether or not LCC should stay at the cost level, or if the classical LCC framework should be extended to implement a broader economic perspective, e.g. by connecting costs on the microeconomic level to impact on the macroeconomic level. To mitigate this situation, May and Brennan (2006) suggested including value added (VA) as an economic indicator and relating it to wealth generation. Wood and Hertwich (2012) went even further by linking VA to gross domestic product through input-output modelling.

Furthermore, to bridge the gap in pursuit of aligning the economic dimension involved in LCSA with LCA, Neugebauer et al. (2016) proposed the concept of economic LCA (EcLCA), and defined midpoint and endpoint impact categories as well as AoPs for the economic dimension. This approach is further described in Sect. 4.1.2. Further research should focus on the definition of impact pathways as well as provision of concrete quantified measures for impact pathways.

2.3 *Social Life Cycle Assessment (SLCA)*

SLCA aims at analysing the social and socioeconomic impact of products and processes. In the following sections, the state-of-the-art, research needs and outlook for developing SLCA are presented.

2.3.1 State-of-the-Art

SLCA investigates the positive and negative social and socio-economic impact of products or processes along their life cycle. According to the 'Guidelines for SLCA of products' (UNEP/SETAC 2009), the impacts may affect the concerned stakeholder groups: workers, consumers, local communities, value chain actors and the society, and may be linked to the company's behaviour. Complying with the guidelines, the 'Methodological Sheets for Subcategories in SLCA' was published and provided practical guidance on the subcategories and potential indicators for conducting SLCA case studies (Benoît et al. 2013).

2.3.2 Research Needs and Outlook

Several deficiencies persist with the SLCA methodology and therefore impede its implementation in practice, e.g. in industry. Although the methodological sheets provided indicator sets related to relevant stakeholder groups, no widely agreed approach for selecting indicators, relevant social issues, and involved stakeholders exists (Lehmann et al. 2013; Martínez-Blanco et al. 2014; Andreas Jørgensen et al. 2009). In addition, since social impacts are usually associated with organisations' behaviour (Dreyer et al. 2006; Andreas Jørgensen et al. 2009), allocating social impact to a specific product is not straightforward and thus often hinders the implementation and meaningfulness of SLCA (Andreas Jørgensen 2013; Lehmann et al. 2013). Another big challenge lies in linking social indicators to impact categories and AoPs via social impact pathways (Lehmann et al. 2013; Neugebauer et al. 2014). Without such impact pathways, i.e. proper impact pathways and AoPs, a complete picture of potential social impacts cannot be fully anticipated. One of the first approaches for an impact pathway was developed by Jørgensen et al. (2010a, b), who developed impact pathways for child labour and also highlighted the difficulties in measuring the potential girth of the impact.

A more recent approach for impact pathways was provided by Neugebauer et al. (2014), proposing impact pathways for fair wage and the level of education. This approach is presented in more detail in Sect. 4.1.1. Further research is geared to focus on the development of databases and more impact pathways addressing social aspects beyond child labour, wage and education as well as regarding the concretisation of the impact pathways by providing e.g. concrete quantified impact pathways.

3 Application of LCSA in Manufacturing: Tiered Approach

So far, environmental indicators resulting from LCA or simplified LCA (e.g. carbon footprint) are widely employed in manufacturing sectors in order to evaluate the environmental performance of products or processes. Yet, economic and social indicators are currently just randomly considered in product or process assessments due to the methodological challenges associated with LCC and SLCA. Consequently, valid indicator sets for a holistic LCSA are currently lacking and thus hinder the implementation of LCSA in manufacturing sectors. A first attempt to foster application of LCSA is the Tiered Approach, which provides a step-by-step procedure going from a simplified LCSA to a comprehensive one (Neugebauer et al. 2015).

3.1 Framework of the Tiered Approach

The Tiered Approach is a "step-by-step" guidance for applying and implementing LCSA in practice (see Fig. 2). It provides an impact and cost categories hierarchy, which supports LCSA practitioners in selecting suitable indicators, and indicates potential directions of future development in LCSA. The categories proposed have been chosen from selected sources, e.g. the ILCD Handbook of LCA (JRC 2011), the Guidelines for SLCA of products (UNEP/SETAC 2009), and the Code of Practice for LCC (Swarr et al. 2011) based on three criteria (relevance, robustness of the methods, and practicality). For LCA, impact categories at midpoint level are selected since the midpoint results have more consensus characterisation methods and lower statistical uncertainty than the endpoint results (Bare et al. 2000).

Three tiers are recommended in the Tiered Approach: Tier 1, namely Sustainability Footprint, represents a "low entry-level" LCSA, where only few categories are considered (e.g. climate change, production costs and fair wages). Hence, Tier 1 provides a basis for aligning the different maturity levels of LCA, SLCA and LCC and allows for a screening assessment of all three dimensions of sustainability. Meanwhile, it lowers the entry barrier to implementing basics of LCSA in industry and communicating with non-expert practitioners.

Tier 2 represents a "best practice" of LCSA considering additional categories (e.g. the common used ones currently considered in the ILCD Handbook (JRC 2010b) of LCA and categories for SLCA and LCC, which have been ranked as important. Hence, additional impact categories for LCA, for example ozone depletion, eutrophication, photochemical oxidant formation, acidification, have been chosen. For LCC, consumer costs (e.g. purchase price, maintenance costs and energy costs) are included. For SLCA, health (including workers, consumers and local communities) and working conditions are taken into account. Thus, Tier 2 provides a broader range of environmental and economic aspects, and includes social topics beyond the stakeholder group workers.

The most advanced step, Tier 3, represents a comprehensive level of LCSA considering a broad set of categories (e.g. for potential new LCA impact categories like water footprint methods and land use). For LCC, production and consumer

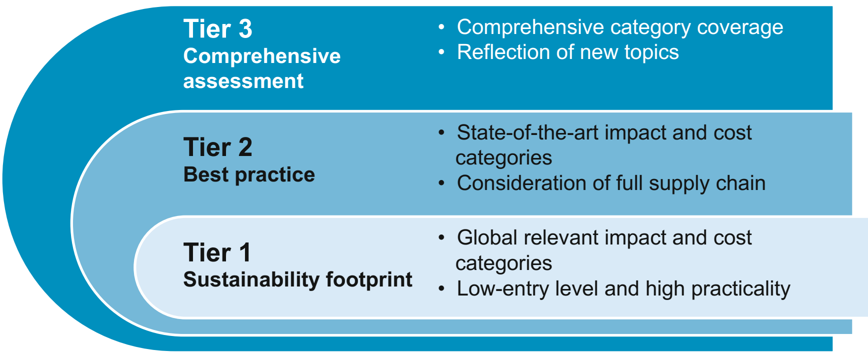


Fig. 2 Structure of the Tiered Approach—3 tiers reflecting different levels of comprehensiveness of LCSA (Neugebauer et al. 2015)

costs related to further operation, accidents, and environmental damage (if not considered within LCA and SLCA) are considered. For SLCA, the topics education, human rights, and cultural heritage are addressed.

The Tiered Approach supports a holistic sustainability assessment, as all three dimensions of sustainability are considered. In addition, it ensures practicality through its impact and cost categories hierarchy, reflecting different levels of comprehensiveness and different phases of LCSA's development.

3.2 Implementation in Manufacturing

The practicality of the Tiered Approach has been proven by first case studies on manufacturing technologies and products, e.g. modular machine tool frames and wireless micro systems (Peukert et al. 2015; Benecke et al. 2015), turning technologies as well as bicycles and pedal electric cycles (Neugebauer et al. 2013; Buchert et al. 2015). The case studies mainly focused on the Tier 1, i.e. the categories climate change, production costs and fair wages. They revealed environmental hotspots, described first selected social topics (e.g. wages) and first economic issues (e.g. production costs), and identified improvement potential for these technologies and products.

Meanwhile, by carrying out these case studies, knowledge and experience with regard to practical implementation were gained from the identification of hotspots and the interpretation of life cycle impacts of the three sustainability dimensions. Specific social aspects for example, fair wages and health, were mapped and thus compared for different countries involved in the production of smart modular machine tool frames, e.g. Germany, Brazil, and China (Peukert et al. 2015). Based on the results, recommendations could be given for advantageous material usage, supplier management and further technology improvements.

Moreover, trade-offs between the three sustainability dimensions were identified, e.g. a technology which performs better from an environmental perspective, could however lead to higher social risks. For instance, the switch from wet machined turning processes to inner-cooled ones showed potential environmental benefits (e.g. recycling of titanium chips), but at the same time increased the social risk due to the African workers involved in the inlay production being potentially paid below the poverty line.

3.3 Research Needs and Outlook

The Tiered Approach is a first step with regard to fostering LCSA in practice. However, challenges remain as comprehensive category sets as well as well-defined impact pathways for all three tiers are missing in the case of both SLCA and LCC. Moreover, at the interpretation phase, challenges occur due to the potential trade-off of the results between and within the three sustainability dimensions (Zamagni et al. 2013; Arcese et al. 2013). In the case studies described above, those trade-offs were displayed transparently for each dimension in the Tiered Approach without giving weights.

The next steps will focus on updating the selected categories and the hierarchy of the Tiered Approach, and on developing impact pathways for social and economic aspects suitable for LCSA with regard to production technologies.

4 Selected Ongoing LCSA Work

Currently, many studies have been carried out in pursuit of enhancing implementation, scientific robustness, and comprehensiveness of the three methods with LCSA. In this section, some ongoing work has been selected to show the recent research progress and direction of LCSA development particularly with regard to SLCA and LCC.

4.1 Proposals of Impact Pathways for SLCA and LCC

As described in the previous sections, SLCA and LCC face numerous challenges, particularly with regard to the impact assessment stage, which hinder the implementation and methodological robustness of LCSA. This includes missing concrete impact category definitions of SLCA and LCC, missing detailed impact pathways, as well as insufficient description of the relationship between impact categories and AoPs (Bocoum et al. 2015; Chhipi-Shrestha et al. 2015; Andreas Jørgensen et al. 2008; Neugebauer et al. 2014). First steps to address these gaps were done by establishing first impact pathways for the social dimension, describing the relation between indicators and impact categories with a focus on fair wage and level of education (Neugebauer et al. 2014), and by proposing AoPs for the social and the economic dimension, such as social justice and economic stability (Neugebauer et al. 2016; Neugebauer et al. 2014). The development of the impact pathways is introduced in the following section.

4.1.1 Proposal of Social Impact Pathways: Fair Wage and Level of Education

In order to enhance SLCA and thus LCSA, impact categories need to be clearly defined. Furthermore, impact pathways linking indicators to impact categories and AoPs need to be developed.

To that end, Neugebauer et al. (2014) defined two impact categories at a midpoint level and developed social impact pathways for them. The two topics are recognised as essential aspects for Sustainable Development Goals (United Nations 2016) for mitigating poverty and enabling the achievement of higher prosperity levels. In manufacturing, fair wage is treated as an essential aspect of worker's overall living situation and well-being. Education reflects country-specific equality aspects, and measures worker's qualifications for specific sectors and countries. With the development of the two midpoint categories, three related endpoint categories (environmental stability, damage to human health, and economic welfare) and two AoPs (social well-being and social justice) were proposed to complete the impact pathways. Interrelations along the defined pathways have been introduced, e.g. the inventory indicator lowest/highest gross income affects the AoPs social justice and social well-being through the midpoint impact category fair wage and the endpoint impact categories economic welfare and damage to human health. Similar to the impact pathway for fair wage, the relation of the inventory indicators, such as access barriers to schools, to the midpoint impact level of education, was investigated.

The proposal of potential impact pathways of fair wage and level of education, serves to facilitate a more consistent and transparent assessment of social impact. However, the characterisation factors stay at a qualitative level. The next step for refining the impact pathways focuses on the identification of quantitative characterisation factors instead of purely on qualitative descriptions. Further aspects like the interpretation of social impacts have been investigated in tandem.

4.1.2 Introduction of the New Economic Life Cycle Assessment Framework

As pointed out in Sect. 2.2, LCC so far includes pure cost assessment without considering clearly defined AoPs, impact categories and corresponding causalities described in impact pathways. For this reason, some authors discuss whether LCC can actually adequately measure the economic sustainability dimension within the LCSA framework (Jørgensen et al. 2010; Heijungs et al. 2013).

Taking into account this discussion, Neugebauer et al. (2016) proposed the new Economic LCA (EcLCA) framework, which broadens the scope of the current LCC by including the impact assessment stage. As a result, two AoPs (economic stability and wealth generation), two endpoint impact categories (economic prosperity and economic resilience), and five midpoint impact categories (profitability, productivity, consumer satisfaction, business diversity, and long-term investment) are suggested and defined. The proposed midpoint impact categories can be directly linked to manufacturing. For example, profitability considers costs regarding actual economic benefits for the firms via added values instead of purely summing up costs. Furthermore, productivity is associated with human capital aspects through the whole value chains, and consumer satisfaction influences the markets and product management expenses, etc.

The suggested EcLCA framework better meets the requirements of ISO 14040 (ISO 2006a) and 14044 (ISO 2006b) adopted within the LCSA framework and describes economic aspects targeting sustainability. The next steps would be to establish measurable linkages (i.e. quantitative relation) between inventory and impact levels as well as AoPs. Moreover, trials for testing application of the new framework will constitute part of future work.

4.2 Sustainability Safeguard Star

LCSA considers the three dimensions of sustainability by combining the methods LCA, LCC and SLCA. However, there is a risk that social, environmental and economic aspects are only interpreted individually, without considering potential interlinkages between the sustainability dimensions. For instance, climate change impacts influence AoPs in both SLCA and LCA, i.e. social well-being (e.g. by affecting human health) and ecosystem quality. To address this challenge, the Sustainability Safeguard Star was designed to structure existing AoPs used in LCA into a new scheme by addressing the inter-linkages in between the three sustainability dimensions and by including additional topics of sustainability, such as social justice (Schmidtz 2006; Neugebauer et al. 2014) and economic stability (Neugebauer et al. 2016). The proposed framework is introduced in the following section.

4.2.1 Conceptual Framework of Sustainability Safeguard Star

The Sustainability Safeguard Star goes beyond the three broadly accepted AoPs from the classical (environmental) LCA human health, resource availability, and ecosystem quality (JRC 2010a), with the goal of defining common AoPs for the LCSA framework. This means that the Sustainability Safeguard Star additionally considers three complementary AoPs (i.e. safeguard subjects), which then reflect the social and economic dimension of sustainability: man-made environment, social justice, and economic stability. The six AoPs proposed for LCSA are displayed in Fig. 3.

The AoP man-made environment, which was already proposed by de Haes et al. (1999), stands for cultural value and addresses technical infrastructure, such as energy and communication networks, and the drinking water supply, indicating the living contexts of society. The AoP is, for example, concerned with the damage resulting from acidifying substances to buildings. The other AoP, social justice, takes equal opportunities and justice as core principles, like security of freedom based on a social contract (individual vs. societal). It is of high relevance to address social justice (Nussbaum 2004) issues in order to eliminate inequality, foster human rights and intergenerational equity defined as fundamental to sustainable development pursuits as defined by the Brundtland report (United Nations 1987). Last but not least, another AoP, economic stability, aims at avoiding economic crisis and promoting economic growth and employment (European Commission 2014). It is also connected to industrial diversity and multilateral trade concerns for addressing economic vulnerability (Neugebauer et al. 2016). The AoPs defined combine different aspects to consider interlinkages between the sustainability dimensions. The AoP economic stability, for example, addresses unemployment and economic prosperity, which are associated with both social and economic perspectives.

Fig. 3 Sustainability Safeguard Star: conceptual framework and relation to LCSA

Moreover, Fig. 3 shows the general conceptual framework for the potential links between micro- and macroeconomic level. The proposed AoPs reflect sustainability goals at a macroeconomic level (e.g. from sustainable development goals or strategies defined by United Nations (2016) and European Commission (2010)). These goals, for example, reducing inequality, can be assessed by defined criteria (e.g. equal access to all levels of education). With the inclusion of the proposed AoPs and their impact pathways addressing the defined criteria, LCSA can deliver the results at the microeconomic level.

4.2.2 Research Needs and Outlook

The Sustainability Safeguard Star abolishes the presumed separation of AoPs defined in three underlying life cycle methods of LCSA and in their place, suggests six common AoPs which address the inter-linkages in between the three sustainability dimensions.

Further research should focus on establishing impact pathways between defined impact categories and the proposed AoPs (see also Sects. 4.1.1 and 4.1.2) and tested in case studies. With regard to sustainable manufacturing, the newly defined AoPs of economic stability and man-made environment, can be of relevance for the purpose of reflecting the business situation of firms with the background of different production locations.

5 Conclusion

The Life Cycle Sustainability Assessment (LCSA) framework is applied to assess the sustainability performances of manufacturing products and processes. Application of LCSA can lead to the identification of product and process hotspots, and support decision-making in production development. In favour of implementation of LCSA in practice, the Tiered Approach was proposed to provide an impact and cost category hierarchy, particularly for offering guidance to practitioners in industry. This approach has already been applied in first case studies on manufacturing technologies and products, e.g. turning technologies and pedal electric cycles, and has proven its validity. Ongoing work such as the development of impact pathways for SLCA, the suggested Economic LCA, and the Sustainability Safeguard Star, serve to enhance the robustness and applicability of the LCSA. To continue enhancing currently proposed methods, future work need to focus on developing the impact pathways of economic and social aspects in the context of LCSA, and further providing quantitative measures of the pathways.

References

Andreas Jørgensen, 2013. Social LCA—a way ahead? *International Journal of Life Cycle Assessment* 18(2): 296–299. doi:10.1007/s11367-012-0517-5.

Andreas Jørgensen, Agathe Le Bocq, Liudmila Nazarkina, and Michael Hauschild. 2008. Methodologies for social life cycle assessment. *International Journal of Life Cycle Assessment* 2: 96–103. http://www.me.mtu.edu/~jwsuther/colloquium/Nesbitt_MethodolgiesforSLCA.pdf.

Andreas Jørgensen, Lufanna C.H. Lai, and Michael Z. Hauschild. 2010. Assessing the validity of impact pathways for child labour and well-being in social life cycle assessment. *International Journal of Life Cycle Assessment* 15: 5–16. doi:10.1007/s11367-009-0131-3.

Andreas Jørgensen, Michael Z. Hauschild, Michael S. Jørgensen, and Arne Wangel. 2009. Relevance and feasibility of social life cycle assessment from a company perspective. *International Journal of Life Cycle Assessment* 14(3): 201–214. doi:10.1007/s11367-009-0073-9.

Arcese, Gabriella, Roberto Merli, and Maria Claudia Lucchetti. 2013. Life cycle approach : A critical review in the tourism sector. In *The 3rd World Sustainability Forum*, 1–10.

Bach, Vanessa, and Matthias Finkbeiner. 2016. Approach to qualify decision support maturity of new versus established impact assessment methods—demonstrated for the categories acidification and eutrophication. *International Journal of Life Cycle Assessment* (accepted). *The International Journal of Life Cycle Assessment*. doi:10.1007/s11367-016-1164-z.

Bare, Jane C., Patrick Hofstetter, David W. Pennington, and Helias a. Udo Haes. 2000. Midpoints versus endpoints: The sacrifices and benefits. *International Journal of Life Cycle Assessment* 5(6): 319–326. doi:10.1007/BF02978665.

Benecke, Stephan, Sabrina Neugebauer, Bernd Peukert, and et al. 2015. Sustainability assessment of wireless micro systems in smart manufacturing environments. EcoDesign 2015. Tokyo, Japan. (Siehe Anhang). In *EcoDesign 2015, Tokyo, Japan*.

Benoît, Catherine, Marzia Traverso, Sonia Valdivia, Gina Vickery-Niederman, Juliane Franze, Lina Azuero, Andreas Ciroth, Bernard Mazijn, and Deana Aulisio. 2013. The methodological sheets for sub-categories in social life cycle assessment (S-LCA).

Bocoum, Ibrahima, Catherine Macombe, and Jean-Pierre Revéret. 2015. Anticipating impacts on health based on changes in income inequality caused by life cycles. *International Journal of Life Cycle Assessment* 20(3): 405–417. doi:10.1007/s11367-014-0835-x.

Buchert, Tom, Jón Garðar Steingrímsson, Sabrina Neugebauer, The Duy Nguyend, Mila Galeitzkeb, Nicole Oertwig, Johannes Seidel, et al. 2015. Design and manufacturing of a sustainable pedelec. In *The 22nd CIRP Conference on Life Cycle Engineering, Procedia CIRP* 29: 579–84.

Chhipi-Shrestha, Gyan Kumar, and Rehan Sadiq Kasun Hewage. 2015. 'Socializing' sustainability: A critical review on current development status of social life cycle impact assessment method. *Clean Technologies and Environmental Policy* 17(3): 579–596. doi:10.1007/s10098-014-0841-5.

Dreyer, Louise Camilla, Michael Z. Hauschild, and Jens Schierbeck. 2006. A framework for social life cycle impact assessment. *International Journal of Life Cycle Assessment* 11(2): 88–97. doi:10.1065/lca2005.08.223.

Elkington, John. 1998. *Cannibals with forks: The triple bottom line of 21st century business*. Gabriola Island: New Society Publishers.

European Commission. 2010. EUROPE 2020—a strategy for smart, sustainable and inclusive growth. Brussels, Belgium. doi:10.1016/j.resconrec.2010.03.010.

European Commission. 2014. Economic stability and growth. *European Commission*. http://ec.europa.eu/economy_finance/euro/why/stability_growth/index_en.htm.

European Commission. 2015. European platform on life cycle assessment (LCA).

Finkbeiner, Matthias, Erwin M. Schau, Annekatrin Lehmann, and Marzia Traverso. 2010. towards life cycle sustainability assessment. *Sustainability* 2: 3309–3322. www.mdpi.com/2071-1050/2/10/3309/pdf.

Finkbeiner, Matthias, Robert Ackermann, Vanessa Bach, Markus Berger, Gerhard Brankatschk, Ya-Ju Chang, Marina Grinberg, et al. 2014. Challenges in life cycle assessment: An overview of current gaps and research needs. In *Background and future prospects in life cycle assessment*, ed. Walter Klöpffer, 207–58. Springer. doi:10.1007/978-94-017-8697-3_7.

Glucha, Pernilla, and Henrikke Baumann. 2004. The life cycle costing (LCC) approach: A conceptual discussion of its usefulness for environmental decision-making. *Building and Environment* 39(5): 571–580. doi:10.1016/j.buildenv.2003.10.008.

Heijungs, Reinout, Ettore Settanni, and Jeroen Guinée. 2013. Toward a computational structure for life cycle sustainability analysis: Unifying LCA and LCC. *International Journal of Life Cycle Assessment* 18(9): 1722–1733. doi:10.1007/s11367-012-0461-4.

Hunkeler, David, Kerstin Lichtenvort, and Gerald Rebitzer. 2008. *Environmental life cycle costing*. Boca Raton, USA: CRC Press.

ISO. 2006a. ISO 14040:2006 environmental management—life cycle assessment—principles and framework. Geneva (Switzerland): ISO.

ISO. 2006b. ISO 14044:2006 environmental management—life cycle assessment—requirements and guidelines. Geneva (Switzerland): ISO.

ISO. 2008. ISO 15686-5:2008. Buildings and constructed assets—service-life planning—Life Cycle costing. Geneva (Switzerland): ISO.

Jørgensen, Andreas, Ivan T. Hermann, and Jørgen Birk Mortensen. 2010. Is LCC relevant in a sustainability assessment? *International Journal of Life Cycle Assessment* 15(6): 531–532. doi:10.1007/s11367-010-0185-2.

JRC. 2010a. ILCD handbook—framework and requirements for LCIA models and indicators. *Luxembourg*. doi:10.2788/38719.

JRC. 2010b. ILCD handbook—general guide for life cycle assessment—detailed guidance. *Luxembourg*. doi:10.2788/38479.

JRC. 2011. ILCD handbook—recommendations for life cycle impact assessment in the European context. First. *Ispra: European Commission*. doi:10.278/33030.

Klöpffer, Walter. 2008. Life cycle sustainability assessment of products. *International Journal of Life Cycle Assessment* 13(2): 89–95. doi:10.1065/lca2008.02.376.

Lehmann, Annekatrin. 2013. Lebenszyklusbasierte Nachhaltigkeitsanalyse von Technologien: Am Beispiel Eines Projekts Zum Integrierten Wasserressourcenmanagement. Ph.D. Dissertation, Technische Universität Berlin.

Lehmann, Annekatrin, Eva Zschieschang, Marzia Traverso, Matthias Finkbeiner, and Liselotte Schebek. 2013. Social aspects for sustainability assessment of technologies—challenges for social life cycle assessment (SLCA). *International Journal of Life Cycle Assessment* 18(8): 1581–1592. doi:10.1007/s11367-013-0594-0.

Martínez-Blanco, Julia, Annekatrin Lehmann, Pere Muñoz, Assumpció Antón, Marzia Traverso, Joan Rieradevall, and Matthias Finkbeiner. 2014. Application challenges for the social LCA of fertilizers within life cycle sustainability assessment. *Journal of Cleaner Production, January.*. doi:10.1016/j.jclepro.2014.01.044.

May, J.R., and D.J. Brennan. 2006. Sustainability assessment of australian electricity generation. *Process Safety and Environmental Protection* 84(2): 131–142. doi:10.1205/psep.04265.

Neugebauer, Sabrina, Ya-Ju Chang, Markus Maliszewski, Kai Lindow, Rainer Stark, and Matthias Finkbeiner. 2013. Life cycle sustainability assessment & sustainable product development: A case study on pedal electric cycles (Pedelec). In *Proceedings of 11th global conference on sustainable manufacturing, September 23-25, Berlin, Germany*. ISBN: 978-3-7983-2608-8.

Neugebauer, Sabrina, Silvia Forin, and Matthias Finkbeiner. 2016. From life cycle costing to economic life cycle assessment—introducing an economic impact pathway. *Sustainability* 8(5): 1–23. doi:10.3390/su8050428.

Neugebauer, Sabrina, Julia Martinez-blanco, René Scheumann, and Matthias Finkbeiner. 2015. Enhancing the practical implementation of life cycle sustainability assessment—proposal of a tiered approach. *Journal of Cleaner Production* 102: 165–176. doi:10.1016/j.jclepro.2015.04.053.

Neugebauer, Sabrina, Marzia Traverso, René Scheumann, Ya-ju Chang, Kirana Wolf, and Matthias Finkbeiner. 2014. Impact pathways to address social well-being and social justice in SLCA—fair wage and level of education. *Sustainability* 6(8): 4839–4857. doi:10.3390/su6084839.

Nussbaum, Martha C. 2004. Beyond the social contract: Capabilities and global justice. *Oxford Development Studies* 32(1): 3–18. doi:10.1080/1360081042000184093.

Öko-Institut. 1987. Product portfolio analysis—needs, products and consequences (Produktlinienanalyse - Bedürfnisse, Produkte Und Ihre Folgen). Kölner Volksblatt Verlag.

Peukert, Bernd, Stephan Benecke, Janire Clavell, Sabrina Neugebauer, Nils F. Nissen, Eckart Uhlmann, Klaus-Dieter Lang, and Matthias Finkbeiner. 2015. Addressing sustainability and flexibility in manufacturing via smart modular machine tool frames to support sustainable value creation. In *The 22nd CIRP conference on life cycle engineering, Procedia CIRP* 29: 514–19.

Rainer Grießhammer, Matthias Buchert, Carl-Otto Gensch, Christian Hochfeld, Andreas Manhart, and Ina Rüdenauer. 2007. *PROSA—product sustainability assessment.* Öko-Institut e.V.

Remmen, Arne, Allan Astrup, and Jeppe Frydendal. 2007. *Life cycle management—a business guide to sustainability*. UNEP/SETAC Life Cycle Initiative.

Wood, Richard, and Edgar G. Hertwich. 2012. Economic modelling and indicators in life cycle sustainability assessment. *International Journal of Life Cycle Assessment*.

Schmidtz, David. 2006. *The elements of justice*. Cambridge, UK: Cambridge University Press.

Swarr, T., D. Hunkeler, W. Kloepffer, H.L. Pesonen, A. Ciroth, C. Brent, and R. Pagan. 2011. *Environmental life cycle costing: A code of practice.*

de Haes, Udo, A. Helias, Olivier Jolliet, Göran Finnveden, Michael Hauschild, Wolfram Krewitt, and Ruedi Miiller-Wenk. 1999. Best available practice regarding impact categories and category indicators in life cycle impact assessment. *The International Journal of Life Cycle Assessment* 4(3): 167–174. doi:10.1007/BF02979453.

UNEP. 2012. *Greening the economy—through life cycle thinking*. Paris: UNEP.

UNEP/SETAC. 2009. *Guidelines for social life cycle assessment of products*. Belgium: In de Weer.

UNEP/SETAC Life Cycle Initiative. 2011. *Towards a life cycle sustainability assessment—making informed choices on products*. Paris: United Nations Environment Programme.

United Nations. 1987. Report of the World Commission on Environment and Development: Our common future. United Nations. http://www.un-documents.net/wced-ocf.htm.

United Nations. 2016. Sustainable development goals. https://sustainabledevelopment.un.org/sdgs.

Valdivia, Sonia, Cassia M.L. Ugaya, Jutta Hildenbrand, Marzia Traverso, Bernard Mazijn, and Guido Sonnemann. 2012. A UNEP/SETAC approach towards a life cycle sustainability assessment—our contribution to Rio + 20. *International Journal of Life Cycle Assessment* 18 (9): 1673–1685. doi:10.1007/s11367-012-0529-1.

Zamagni, Alessandra, Hanna-Leena Pesonen, and Thomas Swarr. 2013. From LCA to life cycle sustainability assessment: Concept, practice and future directions. *International Journal of Life Cycle Assessment* 18(9): 1637–1641. doi:10.1007/s11367-013-0648-3.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the book's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the book's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

Optimisation Methods in Sustainable Manufacturing

Sebastian Schenker, Ingmar Vierhaus, Ralf Borndörfer, Armin Fügenschuh and Martin Skutella

1 Introduction

Sustainable manufacturing is driven by the insight that the focus on the economic dimension in current businesses and lifestyles has to be broadened to cover all three pillars of sustainability: economic development, social development, and environmental protection. In this chapter, we present two state-of-the-art approaches of mathematical optimisation and how they can be used to solve problems in sustainable manufacturing.

The multi-criteria perspective considers areas of sustainability as independent functions that are to be optimised however with divergent objectives simultaneously. Accordingly, computed outcomes that cannot be improved upon (on at least one objective without getting worse at another) are considered to be superior to outcomes that can be improved upon. A decision maker will only be interested in the first set of outcomes in order to be able to form an educated opinion with respect to his/her sustainability goal.

The system dynamics perspective on the other hand focuses on the time-dependent (or dynamic) aspects of systems that are influenced by sustainable manufacturing practices. If, for instance, a production technology was identified

S. Schenker (✉) · I. Vierhaus · R. Borndörfer
Zuse Institute Berlin, Takustr. 7, 14195 Berlin, Germany
e-mail: schenker@zib.de

A. Fügenschuh
Helmut-Schmidt-University, Holstenhofweg 85, 22043 Hamburg, Germany

M. Skutella
TU Berlin, Str. des 17. Juni 136, 10623 Berlin, Germany

© The Author(s) 2017

R. Stark et al. (eds.), *Sustainable Manufacturing*, Sustainable Production, Life Cycle Engineering and Management, DOI 10.1007/978-3-319-48514-0_15

that cannot be improved in either of the sustainability dimensions, the question then arises as to how this technology can be used in an optimal way using only limited resources. How can the impact on society and economy be steered in the direction of allowing the technology to be as beneficial as possible?

2 Multi-criteria Optimisation

Mathematical optimisation and mathematical programming is concerned with finding good solutions from a set of available alternatives. The abstract nature of mathematical optimisation allows the user to model a wide range of different problems and different objectives using the same theoretical insights and practical tools. Problems in sustainability and sustainable manufacturing have in common that there is not only one objective to be considered but several conflicting ones. This is mathematically reflected by considering several objective functions simultaneously. The set of available alternatives and the structure of the considered objective functions can generally be modelled in different ways. The focus in the following section is put on the well-studied and fruitful field of linear optimisation involving linear objective functions and linear constraints allowing the user to model as well as to efficiently solve a wide range of quantitative problems.

2.1 Multi-criteria Problem Formulation

In a *general* multi-criteria linear optimisation problem, one is given a set of k cost vectors $c_1, \ldots, c_k \in \mathbb{R}^n$ and seeks to minimize all linear cost functions $c_i \cdot x = \sum_{j=1}^{n} c_{i_j} x_j$, for $i = 1, \ldots, k$, simultaneously over all n-dimensional vectors $x = (x_1, \ldots, x_n)$ subject to a set of linear inequality and integer constraints. In particular, let M be some finite index set and suppose that for every $i \in M$, we are given an n-dimensional vector a_i and a scalar b_i. Let N_1, N_2 and N_3 be subsets of $\{1, \ldots, n\}$ that indicate which variables x_j are constrained to be non-negative, binary or integer, respectively. We then consider the problem

$$\begin{aligned} & \min(c_1 \cdot x, \ldots, c_k \cdot x) \\ \text{s.t. } & a_i \cdot x \leq b_i, && i \in M, \\ & x_j \geq 0, && j \in N_1, \\ & x_j \in \{0, 1\}, && j \in N_2, \\ & x_j \in \mathbb{Z}, && j \in N_3. \end{aligned} \tag{1}$$

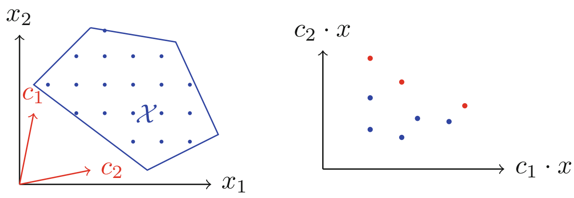


Fig. 1 Feasible space of a bi-criteria integer maximization problem and corresponding set in objective space with non-dominated points (*red*)

The variables $x_1, \ldots, x_n$ are called *decision variables* and a vector x satisfying all of the constraints is called a *feasible solution*. The set of all feasible solutions is called *feasible set* and will be denoted by $\mathcal{X}$. The image $y = (c_1 \cdot x, \ldots, c_k \cdot x)$ of a feasible solution x is called a *feasible point* and the set of all feasible points is called objective set and will be denoted by $\mathcal{Y}$. If N_1 coincides with $\{1, \ldots, n\}$ (implying $N_2 = N_3 = \emptyset$), then (1) is considered a *linear* programming problem. If $N_2 = \{1, \ldots, n\}$ or $N_3 = \{1, \ldots, n\}$, then we refer to (1) as a *binary* or *integer* programming problem, respectively. In case of $\emptyset \subsetneq N_1 \subsetneq \{1, \ldots, n\}$, (1) is considered a *mixed-integer* programming problem. The earliest investigations of multicriteria mathematical optimisation go back to the 1950s when the simplex method coined by Dantzig opened up a wide range of applications and prepared the ground for the huge success of linear programming (Dantzig 1963). If $k = 1$, then we refer to (1) as a single-objective problem and the notion of optimality is unambiguous. For a multi-criteria optimisation problem (with number of objectives $k \geq 2$) we cannot expect to find a solution that optimizes all objectives simultaneously leading to several possible notions of optimality in the multi-criteria case (Ehrgott 2005). A widely accepted (and in the following considered) one is the notion of *efficiency*. A solution $x^* \in \mathcal{X}$ is considered *efficient* if there is no other solution $x \in \mathcal{X}$ that achieves objective values at least as good with a strictly better value in at least one objective, i.e., there is no $x \in \mathcal{X}$ with $c_i \cdot x \leq c_i \cdot x^*$ for $i = 1, \ldots, n$ and $c_i \cdot x < c_i \cdot x^*$ for at least one $i \in \{1, \ldots, n\}$. The image of an efficient solution is called *non-dominated*. The challenge for a multi-criteria optimisation problem is then to compute all different non-dominated points (Figs. 1 and 2).

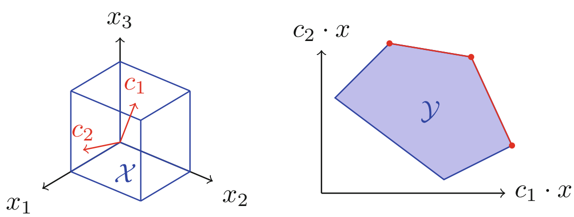


Fig. 2 Feasible space of a bi-criteria linear maximization problem and corresponding set in objective space with non-dominated points (*red*)

2.2 Manufacturing and Scheduling

Production problems, scheduling problems and similar decision problems are a fruitful domain for (mixed) integer programming. Binary variables might represent on-off decisions and linear or integer variables, respectively, might represent production quantities. In the following we will shortly present how multi-criteria integer programming could be used to model a scheduling problem that accounts for production costs, electricity consumption and worker satisfaction. Lets $[M] = \{1, \ldots, M\}$ be a finite set representing a set of different machines and let $[J] = \{1, \ldots, J\}$ be a finite set representing a set of jobs. We will consider a time horizon for the entire production process and let s and e be the start and end time of it. Introduce variables $x_{jmt} \in \{0, 1\}$ where $j \in [J]$, $m \in [M]$ and $t \in \{s, \ldots, e\}$. We set $x_{jmt} = 1$ if and only if starting time of job j on machine m is set to t. In order to model the constraint that every job needs to run on every machine before end time e, let $dur(m)$ the duration on machine m, i.e., the time that a job spends on machine m. Then,

$$\sum_{t=s}^{e-dur(m)} x_{jmt} = 1 \, \forall j \in [J] \wedge \forall m \in [M] \tag{2}$$

models the above fulfilment constraint. Furthermore, the constraint that job j is only allowed to run on machine $m+1$ if it is finished on machine m can be modelled via

$$\sum_{t=s}^{e} t \cdot x_{jmt} + dur(m) \leq \sum_{t=s}^{e} t \cdot x_{jm+1t} \forall j \in J \wedge \forall m \in [M-1] \tag{3}$$

Furthermore, it is very reasonable to assume that a new job can only be started on machine m if the previous job on machine m was finished. This constraint could be modelled via

$$\sum_{t=s}^{e} t \cdot x_{jmt} + dur(m) \leq \sum_{t=s}^{e} t \cdot x_{j+1mt} \forall j \in [J-1] \wedge \forall m \in [M] \tag{4}$$

2.3 Solving Multi-criteria Optimisation Problems

For the single-objective case there are several commercial solvers and software packages (CPLEX 2016; Xpress 2016; Gurobi 2016) and non-commercial ones (Achterberg 2009). One could have expected that the exponential growth in computing power and the even larger algorithmic speed-ups in mixed integer programming during the last decade (Bixby 2002) would automatically lead to multi-criteria extensions. But the situation is contrary: none of the available

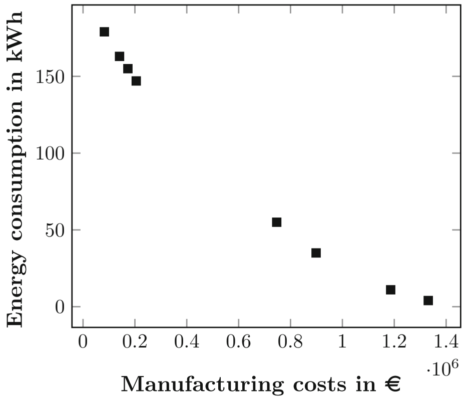


Fig. 3 Front of non-dominated points for a bi-criteria bicycle manufacturing problem

commercial solvers supports multi-criteria problems and there are only a few, recently developed non-commercial solvers available: BENSOLVE (Löhne and Weiing 2014) and inner (Csirmaz 2016) handle multi-criteria linear programming problems, SYMPHONY (Ladanyi et al. 2016) supports bi-criteria mixed integer problems and PolySCIP (Schenker et al. 2016) supports multi-criteria linear and integer problems.

PolySCIP reads problems of the above form (1) via its MOP file format which is based on the widely used MPS file format (MPS-Format 2016) and allows the user to model constraints like (2), (3), (4) easily via an algebraic modelling language (Koch 2004). It can handle an arbitrary number of objectives and thousands of variables and constraints (Fig. 3).

3 System Dynamics Optimisation

In this book, many technologies and approaches developed in the context of sustainable manufacturing are discussed. In this section, we will consider the global environment in which these technologies must be disseminated and implemented, in order to realise their positive potential.

The economy, the environment, and the society constitute complex entities and can be seen as finely balanced networks of mutual dependencies. Almost all components influence each other that have either supporting or weakening effects. Such dynamical systems can demonstrate counterintuitive behaviour. However, in order to bring about a change from the conventional production paradigm in the direction of a paradigm of sustainability, it is essential to appreciate the complex interdependencies of the systems involved.

We observe that the transition, i.e., the setup of many value creation modules and networks, constitutes a dynamic process over time that will span several years or decades. During this period, an array of interactions between the stakeholders need to be taken into account. Moreover, the transition does not take place by itself. It will only happen by means of deliberate influence on the system. A bundle of individual measures are necessary in this process.

To this end, the system dynamics (SD) approach provides the appropriate framework. It is an approach for the modelling and simulation of dynamical systems with a long history rooted in the understanding and teaching of dynamical systems in general, as well as in the field of sustainability.

After introducing system dynamics as a tool for simulation, we will formulate optimal control problems based on system dynamics models.

3.1 System Dynamics

In this section, we will introduce system dynamics as a modelling methodology as well as the most important modelling rules and characteristics of system dynamics models.

System dynamics was introduced by Jay Forrester in the 1950s as a method of describing and simulating time-dependent effects of complex influence networks with feedback loops (Forrester 1961). Such networks are characterized by non-linear, often surprising behaviour. In fact, a forecast of their future development, and thus their control, represents a difficult mathematical problem.

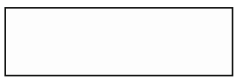
One of the strengths of the system dynamics approach lies in its visual representation of complex systems. This visual approach is essential in the system dynamics modelling process, and simplifies access for beginners and users who lack experience with systems of differential equations.

The main objects of system dynamics models are *stocks* and *flows*. The stocks contain the state information of the system. By convention, each stock has two flows, one flowing into the stock, and one flowing out of the stock. Figures 4 and 5 show visual representations of a stock and a flow respectively. As a third component, *auxiliary variables* are often introduced to structure a diagram. Lastly, the existence of functional dependencies between stocks, flows and variables is indicated by arrows. Figure 6 shows an example.

Using this visual representation, a systematic modelling process could be structured as follows:

- Definition of the modelling goal,
- Definition of the system limits,
- Definition of the system components,
- Definition of the direct relations between system components and the type of causal links (positive or negative),
- Design of an influence diagram to summarize components and their relations,

Fig. 4 Visual representation of a stock



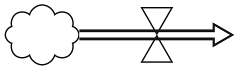


Fig. 5 Visual representation of a flow. The origin of the flow is outside of the limits of the system, as indicated by the *cloud symbol*. The *arrow* is decorated by an hourglass to indicate time dependency

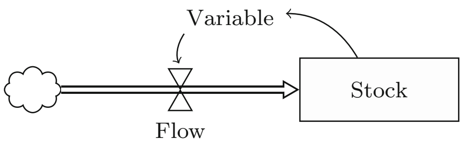


Fig. 6 Visual representation of a small model with one stock, one flow and one variable. The value of the flow depends on the value of the variable, which in turn depends on the value of the stock

- Creation of a system dynamics diagram with stocks for each of the system components as well as flows for each stock,
- Assignment of units and valid ranges to the values of stocks and flows,
- Definition of the functional relations between stocks and flows,
- Introduction of variables to simplify the relations if possible,
- Completion of the system dynamics diagram by adding variables and arrows for relations,

The result of this process is a complete system dynamics model. In the next section, we will discuss numerical methods for simulating a system dynamics model as it develops over time.

Although it is possible to find general solutions analytically for some models, this is generally neither possible nor required. A range of numerical simulation techniques exist that provide quickly accurate simulations. One class of such simulation techniques are the Runge-Kutta schemes (Runge 1895; Kutta 1901) which we will use in this chapter.

3.2 *Optimal Control of System Dynamics Models*

As we discussed in the previous sections, in its basic form, SD aims at describing and simulating influence networks. This is an important step in pursuit of understanding the mutual dependencies. In addition to obtaining a mere understanding however, what we would like to do is to intervene in the network, bring it to a desired stable state, or get as close as possible to that state.

In system dynamics, the points of the system which can be influenced by a conscious decision of an actor are modeled using the concept of *policies*.

Policies constitute a basic and important concept of system dynamics modelling. A policy is a function in some variables that describes the rates of flow in a system and hence the dynamic behaviour of the model (Richardson and Pugh 1981). Thus, a policy is a decision rule which specifies how a decision-maker processes available information from model variables (Sterman 2000). Questions regularly arise concerning whether a given policy can be improved, or even what a “good” policy “actually constitutes or entails. In this context, the need for efficient computational methods for policy analysis as well as policy improvement and design has been recognized in system dynamics, see, e.g., Yücel and Barlas (2011), Keloharju and Wolstenholme (1988), and is an active field of research.

When developing a simulation model, the modelling step of “policy formulation and evaluation” also compares the performance of two or more candidate policies (Sterman 2000). When two simulations with different policies lead to different system behaviors, one has to evaluate which of the two simulations is more suitable or “better” for a given model purpose. To answer this question, one needs to define an objective function so that the higher the value of the objective function for a given simulation, the more favorable or “better” the policy (Dangereld and Roberts 1996). Once an objective function is defined, several approaches to computer-aided policy improvement are at one’s disposal.

Direct parameter policy design starts with the definition of an analytic, parametrized, and usually nonlinear policy function (Keloharju and Wolstenholme 1989). The parameters of this function are set to starting values, and for each parameter, a range of valid values is defined. These parameters constitute then the free variables of the optimisation problem, i.e., the variables which can be varied freely in pursuit of an optimal solution. Consequently, the goal of the policy improvement is to find a set of parameter values within the given range that improves the value of the objective function. The solution space in this case is reduced by the *a priori* definition of the shape of the policy function. The solution found by the optimisation algorithm depends strongly on this definition and therefore on the expectations of the modeler. If a software package offers parameter optimisation capabilities, it is usually possible to attempt producing the solution of such direct parameter policy design problems.

Table function policy design is one possible way to generalizing direct parameter policy design, by defining a parametrized table function instead of an analytic function (Keloharju and Wolstenholme 1989). In this case, the modeler has to define the number of data points of the table function and two intervals that define the range of valid values of the data points on the *x*- and *y*-axis. This approach removes the modeler’s expectations of the shape of the policy from the optimisation process. However, the possible policies are reduced to the space of the piecewise linear functions with the selected number of points. If the data points are then required to have a pre-defined distance on the *y*-axis, the possible solutions are reduced further, but at the same time, the number of parameters and thus the number of free variables decreases. As in the previous case, the goal of the policy improvement is to find parameter values (i.e., data points of the table function), that improve the value of the objective function. A software package that supports table function policy design is found with the Powersim Studio plug-in SOPS (Moxnes and Krakenes 2005).

In both cases, the modeler has to define the functional dependencies of the policy function. This choice is closely related to the concept of bounded rationality (MoreCroft 1985; Simon 1984) models.

A policy function, i.e., a decision rule, is a model about what information cues an actor employs in order to make decisions in a given system. If this actor has only a limited view of the system, then the policy will only depend on the variables and information that are available to this particular actor (Sterman 2000). An improved policy will enable this actor to make better decisions based on the limited information available to him/her. Recent work has focused on improving policies for such actors, using, for instance, co-evolutionary analysis (Liu et al. 2012).

In this paper, we will consider a different kind of actor. Our actor has a global view of the model, i.e., he or she has information on all the state variables at all times within the simulation time horizon.

Modeling the policy of an actor with such a comprehensive level of awareness with the application of conventional approaches to policy analysis constitutes a difficult endeavor. One option would be to define a table function for each state, that depends only on that state. A mixed policy function that depends on all states, can then be defined as a sum of these functions (Keloharju and Wolstenholme 1989).

One conventional approach to System Dynamics optimisation is based on "optimisation by repeated simulation" (Liu et al. 2012). This has the advantage, that any model which can be simulated, can also be optimized, since there are no requirements on the properties of the model equations. However, approaches using repeated simulation suffer from the "curse of dimensionality" Bellman (2003) dynamic, where the significant dimension is that of the space of free variables. An additional free variable adds a dimension to the optimisation algorithm's search space. Solving optimisation problems with a large number of free variables therefore quickly becomes impractical. As a consequence, the degrees of freedom in a mixed policy function situation, are limited from a practical perspective, in the case of an optimisation of the policy by repeated simulation being attempted.

We present a different approach and in so doing, directly optimize the values of the policy function. This is equivalent to defining the policy as a time-dependent table function with one data point for each time step of the time horizon. In the context of physical systems, this kind of problem is known as an "optimal control problem" Betts (2011). With this approach no assumptions on the properties of the policy function are made *a priori*. It is only necessary to select the "free variables". In a conventional approach, these "free variables" would contain the values of the policy functions. For each of these variables, a range of valid values must be defined. It is then the task of the optimisation process, to find the optimal value for each free variable at each time.

The resulting optimisation problem based on a system dynamics model can be written as follows:

$$
\begin{array}{ll}
\max & c(x,y,z), \\
\text{s.t.} & \dot{x} = f(x,y,z), \\
& y = g(x,y,z), \\
& x(0) \in X_0 \\
\\
\text{State variables:} & x = x(t) \in \mathbb{R}^n \\
\text{Algebraic variables:} & y = y(t) \in \mathbb{R}^m, \\
\text{Control variables:} & z = z(t) \in \mathbb{R}^s. \\
\\
\text{Time horizon:} & t \in [t_i, t_f]
\end{array}
$$

In order to solve such a problem, we differentiate between two approaches:

3.2.1 Local Approach

In the local approach, the goal is to find a locally optimal solution. Local optimality means, that in a small neighborhood around the given solution, there is no solution with a better objective value. For this approach, standard methods exist for dynamical systems, which reliably deliver local solutions for small and moderately sized problems. The task at hand is to reformulate and adapt a system dynamics model, so that these methods can be used. Work on the local optimisation of system dynamics models can be found for instance in Vierhaus et al. (2014). In this chapter, we will focus only on the global approach.

3.2.2 Global Approach

In the global approach, the goal is to find a solution, and in addition to prove its global optimality. This means that no feasible solutions of the problem with a better objective function value exist. Hence, the global solution approach has two steps: Find an optimal solution and prove that no better solution exists.

Both of these approaches can prove successful using techniques from mathematical optimisation.

In the next section, we will show how modern optimisation techniques can be used in the global approach to system dynamics optimisation. The basis is the formulation of an optimisation problem, based on the control problem introduced in Sect. 3.2. As mentioned before, the simulation of a system dynamics model using numerical methods is well-established. This simulation is based on a time-discretisation of the model, which we will also use for our optimisation problems.

In order to discretise the model, we introduce a fixed time step of length Δt. We then consider the equations of (Sect. 3.2) no longer at any $t \in [0, T]$, but only at n_t points in time defined by $t = j \cdot \Delta t, \quad j \in \{0, 1, \ldots, n_t - 1\}$. The derivatives appearing in (Sect. 3.2) need to be replaced by an appropriate discretisation scheme, for example a Runge-Kutta scheme. The resulting system can then be written as follows:

$$\max c(x_0, \ldots, x_{n_t-1}, y_0, \ldots, y_{n_t-1}, z_0, \ldots, z_{n_t-1}), \tag{5a}$$

$$\text{s.t.}\, x_{j+1} = f(x_j, y_j, z_j), \quad j \in 0, 1, \ldots, n_t - 2 \tag{5b}$$

$$y_j = g(x_j, y_j, z_j), \quad j \in 0, 1, \ldots, n_t - 1 \tag{5c}$$

$$x_0 \in X_0 \tag{5d}$$

$$\text{State Variables: } x_j \in \mathbb{R}^n \tag{5f}$$

$$\text{Algebraic Variables: } y_j \in \mathbb{R}^m, \tag{5g}$$

$$\text{Control Variables: } z_j \in \mathbb{R}^s. \tag{5h}$$

This system now has the standard form of an optimisation problem, similar to the one introduced in (1). In contrast to (1), we now only have a single objective function. On the other hand, we have nonlinear equality constraints in place of linear inequality constraints.

3.3 MINLP Approach

After the discretization of the system dynamics optimisation problem, it is possible to attempt to solve it with existing solvers. Since we are interested in global solutions, the algorithm used should be able to provide a certificate of global optimality. One group of solvers that can provide this certificate are the branch-and-cut solvers that were introduced in Sect. 2.3 This approach has been successfully applied in the solution of Mixed Integer Linear Programs as well as MINLPs from a range of applications [for example, see Defterli et al. (2011), Borndörfer et al. (2013), Humpola and Fügenschuh (2013)]. Solving a control problem derived from a discretised dynamical system with a standard branch-and-cut solver is, however, in many cases unsuccessful, since the solver does not take into account the special structure of the MINLP that arises from the discretization, and from the handling of non-smooth functions via integer variables. Without considering this structure, even finding a single feasible solution can exceed a reasonable time budget of several hours or even days.

In the remainder of this section, we will present the concept of a tailored solver for system dynamics optimisation problems. Like PolySCIP, this concept has been implemented in the framework of the modern MINLP solver SCIP and results can be found in Fügenschuh and Vierhaus (2013a, b), Vierhaus et al. (2014),

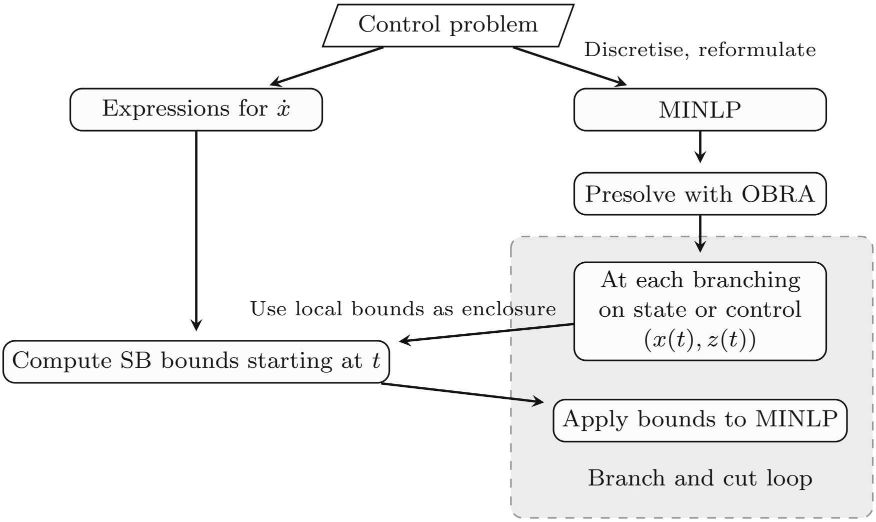


Fig. 7 Concept of a global solver for system dynamics optimization problems

Fügenschuh et al. (2013). A diagram describing the improved solution process is shown in Fig. 6.

3.3.1 Transcription

The first step is the reading and transcription of the system dynamics model and the optimisation parameters. Once the model and the optimisation parameters have been read, the optimisation model is processed in two ways. An equivalent MINLP is, then set up. This includes the time discretisation. At the same time, expressions for the function $\dot{x}(t)$ are derived from the model (Fig. 7).

3.3.2 Optimisation Based Reachability Analysis

To improve on the dual side of the algorithm, an Optimisation Based Reachability Analysis (OBRT) is performed for every problem. This analysis computes bounds for the possible states of the system using the dynamic behaviour and the initial values x_0 as input.

3.3.3 Primal Heuristic

In the interest of producing quickly feasible solutions, we implemented a simple heuristic that reduces the control problem to a simulation problem by fixing the control variables to their lower (or in a second run upper) bounds. If there are no path constraints, this process will always yield a feasible solution.

3.3.4 Bound Propagation Based on Differential Inequalities

To improve the bounds within the branch-and-cut process, we compute differential inequalities as outlined in Scott and Barton (2013). This involves the solution of an auxiliary simulation problem using the expressions for $\dot{x}$ derived in the reading of the problem.

3.3.5 System Dynamics SCIP

The concepts mentioned above have been implemented as the solver System Dynamics SCIP (SD-SCIP). Like polyscip, SD-SCIP is an extension of the modern MINLP solver SCIP and is publicly available (Füegenschuh and Vierhaus 2013a, b).

4 Conclusion

This chapter introduced the framework of multi-criteria optimization and system dynamics optimisation together with different modelling techniques. It showed that mathematical optimisation is a useful tool for modelling a wide variety of problems from the sustainability context. The two solvers presented PolySCIP (Schenker et al. 2016) and SD-SCIP (Fuegenschuh and Vierhaus 2013a, b) were specifically developed with applications from sustainability in mind. They can be used as decision support instruments for a wide range of problems, from scheduling, manufacturing and production to planning subsidies and taxes and exploring dynamical pathways into the future. Both tools are publicly available and present an opportunity for the sustainability community to benefit from recent advances in mathematical optimisation.

References

Achterberg, T. 2009. Scip: Solving constraint integer programs. *Mathematical Programming Computation* 1(1): 1–41. http://mpc.zib.de/index.php/MPC/article/view/4.

Bellman, R. 2003. *Dynamic programming*. Dover Books on Computer Science Series. Dover Publications.

Betts, J.T. 2010. *Practical methods for optimal control using nonlinear programming. Advances in design and control*. Philadelphia, PA: Society for Industrial and Applied Mathematics.

Bixby, R.E. 2002. Solving real-world linear programs: A decade and more of progress. *Operations Research* 50: 3–15.

Borndörfer, R., A. Fügenschuh, T. Klug, T. Schang, T. Schlechte, and H. Schülldorf. 2013. The freight train routing problem. Technical report, ZIB Technical Report ZR-13-36.

CPLEX. 2016. IBM ILOG CPLEX Version 12.6.3. www-03.ibm.com/software/products/en/ibmilogcpleoptistud.

Csirmaz, L. 2016. Inner. https://github.com/csirmaz/inner.

Dangerfield, B., and C. Roberts. 1996. An overview of strategy and tactics in system dynamics optimization. *Journal of the Operational Research Society* 47: 405–423.

Dantzig, G. 1963. *Linear programming and extensions*. Rand Corporation Research Study. Princeton University Press.

Defterli, O., A. Fügenschuh, and G.-W. Weber. 2011. Modern tools for the time-discrete dynamics and optimization of gene-environment networks. *Communications in Nonlinear Science and Numerical Simulation* 16(12): 4768–4779.

Ehrgott, M. 2005. *Multicriteria optimization*, 2nd ed. Berlin: Springer.

Fügenschuh, A., and I. Vierhaus. 2013. A global approach to the optimal control of system dynamics models.

Forrester, J.W. 1961. *Industrial dynamics*. Waltham, MA: Pegasus Communications.

Fügenschuh, A., S.N. Grösser, and I. Vierhaus. 2013. A global approach to the control of an industry structure system dynamics model. Technical Report 13-67, ZIB, Takustr.7, 14195 Berlin.

Fügenschuh, A., and I. Vierhaus. 2013. A global approach to the optimal control of system dynamics models. Technical report, ZIB Technical Report ZR-13-28.

Gurobi. 2016. GUROBI Optimization Version 6.5. www.gurobi.com.

Humpola, J., and A. Fügenschuh. 2013. A unified view on relaxations for a nonlinear network flow problem. Technical report, ZIB Technical Report ZR-13-31.

Keloharju, R., and E. Wolstenholme. 1988. The basic concepts of system dynamics optimization. *Systemic Practice and Action Research* 1(1): 65–86.

Keloharju, R., and E. Wolstenholme. 1989. A case study in system dynamics optimization. *Journal of the Operational Research Society* 40(3): 221–230.

Koch, T. 2004. *Rapid mathematical prototyping*. Ph.D. thesis, Technische Universität, Berlin.

Kutta, W. 1901. *Beitrag zur näherungsweisen Integration totaler Differentialgleichungen*. B.G Teubner.

Ladanyi, L., T. Ralphs, M. Guzelsoy, and A. Mahajan. 2016. SYMPHONY 5.6.14. https://projects.coin-or.org/SYMPHONY.

Liu, H., E. Howley, and J. Duggan. 2012. Co-evolutionary analysis: A policy exploration method for system dynamics models. *System Dynamics Review* 28(4): 361–369.

Löhne, A., and B. Weißing. 2014. Bensolve 2. http://www.bensolve.org.

Morecroft, J.D.W. 1985. Rationality in the analysis of behavioral simulation models. *Management Science* 31(7): 900–916.

Moxnes, E., and A. Krakenes. 2005. SOPS—a tool to find optimal policies in stochastic dynamic systems. In *Proceedings of the 23rd International Conference of the System Dynamics Society*, ed. by J.D. Sterman, N.P. Repenning, R.S. Langer, J.I. Rowe, and J.M. Yanni.

MPS Format. 2016. Mps format—Wikipedia, the free encyclopedia. Accessed 28 July 2016.

Richardson, G.P., and A.L. Pugh. 1981. *Introduction to system dynamics modeling with dynamo*. Cambridge, MA: MIT Press.

Runge, C. 1895. Ueber die numerische Auflösung von Differentialgleichungen. *Mathematische Annalen* 46: 167–78.

Schenker, S., R. Borndörfer, M. Skutella, and T. Strunk. 2016. PolySCIP. In *Mathematical Software –ICMS 2016, 5th International Congress, Proceedings*, ed. by G.-M. Greuel, T. Koch, P. Paule, and A. Sommese, vol 9725 of *LNCS*, Berlin, Germany. Springer. http://polyscip.zib.de.

Scott, J.K., and P.I. Barton. 2013. Bounds on the reachable sets of nonlinear control systems. *Automatica* 49(1): 93–100.

Simon, H.A. et al. (1984). *Models of bounded rationality*, volume 1: economic analysis and public policy. MIT Press Books 1.

Sterman, J.D. 2000. *Business dynamics—systems thinking and modeling for a complex world*. Boston: Irwing McGraw-Hill.

Vierhaus, I., A. Fügenschuh, R.L. Gottwald, and S. Groesser. 2014. Modern nonlinear optimization techniques for an optimal control of system dynamics models. In *Proceedings of The 32nd International System Dynamics Conference*.

Xpress. 2016. FICO Xpress Optimization Suite Version 7.9. www.fico.com/en/products/fico-xpress-optimization-suite.

Yücel, G., and Y. Barlas. 2011. Automated parameter specification in dynamic feedback models based on behavior pattern features. *System Dynamics Review* 27(2): 195–215.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the book's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the book's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

Inducing Behavioural Change in Society Through Communication and Education in Sustainable Manufacturing

Ina Roeder, Wei Min Wang and Bernd Muschard

Abstract The United Nations considers the mobilization of the broad public to be the essential requirement for achieving a shift towards a more sustainable development. Science can play a vital role in Education for Sustainable Development (ESD) by contributing to ESD-related research and development on the one hand, and by becoming active awareness raisers themselves in education and multiplier networks. Specifically, the use of special *Learnstruments*, and investment in *Open Education* formats among other educational tools, may pave the way for accelerated apprehension and appreciation of sustainable manufacturing topics among the greater populace.

1 The Challenge of Creating Proper Understanding of Sustainable Manufacturing

For all liveable future scenarios, a change of manufacturing paradigms is mandatory, not only by producers but also by customers and users. In order to realize such a behavioural change in society, it is essential to establish proper appreciation of sustainable manufacturing or in a broader perception the general concept of sustainable development. One conceptualization of a learning process holds that people have to acquire knowledge and interpret and apply it to their own personal contexts (Kolb 1984; Kirkpatrick 1996) in order to learn the lessons at hand. To assist people in undergoing this learning process, awareness of sustainable development has to be

I. Roeder (✉) · W.M. Wang · B. Muschard
Institute for Machine Tools and Factory Management,
Technische Universität Berlin, Berlin, Germany
e-mail: ina.roeder@tu-berlin.de

© The Author(s) 2017

R. Stark et al. (eds.), *Sustainable Manufacturing*, Sustainable Production, Life Cycle Engineering and Management, DOI 10.1007/978-3-319-48514-0_16

raised first and foremost, and the respective knowledge has to be disseminated accordingly. A range of factors however stands in the way of that pursuit.

Firstly, the complexity attached to the concept of sustainable development impedes distinct understanding. It is often criticized as missing clear outlines and being applied inconsistently (Grunenberg and Kuckertz 2005; Michelsen 2005; Brand 2005). The predominant sustainable development model used today entails the three pillars or spheres of sustainability, which emerged with the United Nations Report "Our Common Future" by Harlem Brundtland in 1987. This model states that sustainable development is only possible when all three spheres—economic, social and environmental—are equally addressed. It was this attempt of a super-framing that successfully combined the diverse perspectives and claims that competed for leadership within the sustainability discourse in the beginning of the 1990s (Brand 2005). It was a concept that everyone could agree upon, as it was broad enough to contain contrary perspectives. The other side of the coin is that such a concept is inevitably inconsistent and therefore lacks clear outlines. From a layperson's viewpoint, this concept leads to contradictory scenarios, wherein singular measures serve to increase sustainable development and reduce it at the same time, e.g. when a turn towards environmentally friendly products and more selective consumption patterns leads to job cuts, unemployment and higher poverty rates at the production site.

Secondly, the popular spin of the term fails to mobilize people. As of the 1990s, the public debate that later turned into sustainability communication still had a clear environmental framing. Fuelled by catastrophes such as in Bhopal (*1984*) and Chernobyl (*1986*), with strong media coverage, environmentalism became a social representation, an element ultimately endowing social groups with identity (Kruse 2005). Consequences were political activism, broad framing in educational institutions, the media and the private sphere alike, and a sheer explosion of well-designed information. In short, it triggered strong reactions in civil society and central tenets which were fully embraced into people's thinking. Yet the phenomenon did not get repeated when the debate turned from environmentalism to sustainable development in the aftermath of the United Nations Conference on Environment and Development in Rio de Janeiro, 1992. In this case, social and economic concerns were added to the agenda of environmental threats (Michelsen 2005). However, this did not translate into an increase in private activism nor into the internalization of higher urgency due to heightened threats to societal welfare. On the contrary, when the concept of sustainable development as a multi-perspective issue was introduced, a strong trend of "de-dramatization" (Grunenberg and Kuckertz 2005) set in, which persistently increased in the following decade. The challenges and possible measures were communicated and regarded as less immediate and rather long-term in their effects, which resulted in lower level short-term mobilization.

Consequently, despite society's increasing familiarity with the sustainability terminology, appreciation of the overall concept and awareness of its concrete meaning in everyday life remain low. In Germany, for instance, 15 years of intensive efforts to communicate sustainability through federal institutions and

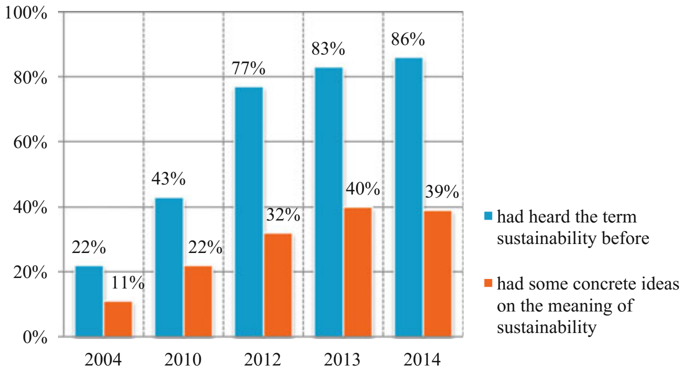


Fig. 1 Average Germans' acquaintance with the term sustainability over time (Roeder et al. 2015)

broad media coverage endured with some effect on people's awareness of the topic as shown in Fig. 1 (Roeder et al. 2015). Still, in 2014 only 39 % of the people had some concrete ideas on the meaning of sustainability and less than about 4 % associated it with future-aware behaviour. As these facts apply to Germany, a nation known to have an elaborated educational system and easy universal access to information, the direness of the information campaign can be expected to apply even more seriously to people from parts of the world with little access to information and a low level of basic education.

With the sustainability challenge becoming increasingly urgent, awareness training continues to be a central task of all activities aiming at sustainable development. This holds especially true for the field of sustainable manufacturing, which is so far widely neglected in public discourse, in spite of its great impact on all areas of human living. To be sure, the educational frameworks for school education have been recently rewritten in Germany to incorporate sustainable development into the curricula as a basic principle as well as a specific learning objective. Nevertheless, the sustainability impact of manufacturing is hardly considered (Roeder et al. 2016). However, considering the German example described before, classic measures seem to have failed so far in communicating the complexity of sustainable development, and especially sustainable manufacturing, to people with little previous knowledge. Just as sustainable development can only be achieved when activating the majority of populace, this majority can only be won over when stakeholders from diverse fields of sustainable manufacturing are activated to join in and strengthen change in society.

This chapter is meant as a guide to support the planning of knowledge dissemination measures in multi-disciplinary research projects. A general approach for sustainability communication is introduced to highlight integral aspects in the planning process. Furthermore, present gaps regarding mediation of knowledge about sustainable manufacturing are identified. By providing best-practice examples, it will be demonstrated how specific challenges can be met. A central aspect addressed in this context is Education for Sustainable Development (ESD), which aims at teaching competencies as a combination of certain skills and knowledge that enable the learner to understand, judge and act according to the sustainability maxim (Wals 2015). Education for Sustainable Manufacturing (ESM) in this regard is seen as a partial aspect of ESD with concrete focus on industrial aspects. The importance of education is also stressed by the Organisation for Economic Co-operation and Development (OECD) and the United Nations (UN), as, both organizations agree on education being the main resource for societal change towards sustainable decision-making (Bormann 2005). It is further argued that science, in its unique position as a neutral and reliable source of knowledge, should figure into the equation as a key stakeholder in spreading the word of sustainable manufacturing.

2 General Approach for Science-to-Public Sustainability Communication

As sustainability communication intends to reach a great number of people, it can be considered as a form of mass communication. Following the fundamental model of mass communication developed by Lasswell (1948), every action in this context should be designed by asking the "five Ws": who says what, in what way, to whom, and with what effect? Although widely criticized for its ignorance of the receivers' active role in influencing the communication by giving feedback to the sender of the message, those "five Ws" represent, to this day, the major fields of mass communication science. Answering these questions in the context of sustainability communication from a scientific point of view, forms the boundary conditions for the respective communication framework.

"Who"—The Communicator

The role of communicators in their domain and their intended communication goal, imparts a strong influence on the message, the channels and the target groups. This matter of *who* does the communicating is also key to where the problem lies. Communicator credibility depends on status and expertise on the one hand and on affectionately ascribed trustworthiness on the other. For the US it has been shown that professors are ascribed both, expertise and trustworthiness (Fiske and Dupree 2014). This gives them an excellent initial position as communicators for people will tend to believe them and agree with their opinions. Contrarily, scientists, researchers and engineers are seen as experts but tend to be allocated less trust, which reduces their credibility ascribed by the broad public. However, people's trust in someone changes significantly with this person's position in relation to the position of those who judge. This means, while the majority may not ascribe great trustworthiness to scientists, researchers and engineers, the result is different when asking sections of society that have certain aspects in common with those communicators, e.g. a high educational level. Also the ascribed trustworthiness is expected to increase when those scientific communicators show concern for humanity and the environment; both being the case for manufacturing-oriented sustainability communication.

For people transmitting sustainability knowledge, such as teachers, the greatest capital is knowledge. These educators need to be sceptical towards new information which they are persuaded to implement in their teaching activities by non-official bodies, and, furthermore, be concerned, among other things, about the correctness of the information and the underlying interests of the persuader. This locates them near science communicators, making them a convenient target group for science communication. When it comes to decision-makers (e.g. in politics), the reputation of an information provider who is well-established in a certain field of expertise, offers opportunities with influential stakeholders and increases the chances of being heard. This is where publically funded science has an invaluable advantage. It is considered neutral and exact in the highly competitive arena of sustainable manufacturing.

As a communicator, science has a vital position in passing on knowledge. Hence, it has a triple role to play in (1) generating communicable knowledge about sustainable manufacturing, (2) developing new scientifically sound dissemination techniques and acting as a communicator with great credibility, and (3) promoting knowledge dissemination and awareness raising for sustainable manufacturing. Consequently, communication and teaching aspects should be considered in every research project within the field, right from the very planning phase onwards.

"What"—The Message

The overall message of sustainable development is clear—we need to live in such a way that future generations can have an average standard of living which is at very least equal to the one we have today. The message of sustainable manufacturing is even more narrowly defined, insofar as stating that dynamics of global competition and cooperation can be used for lending wings to processes of innovation and mediation towards the goal of global sustainability. Clear as those definitions might appear in this abstract form, thorough understanding of the concepts requires profound understanding and perspectives that are currently lacking in the narration of the public discourse and thus hardly intuitive. To enable knowledge of sustainable development and manufacturing, and to facilitate that message getting communicated in a comprehensive way, it has to be applied to the context of the target groups, e.g. by relating it to monetary values for industrial producers or strategic advice in daily life situations for consumers. As shown in this book, a multitude of examples demonstrate how technological, social and economic innovations can be integrated with each other to contribute to sustainable development by means of saving resources, increasing the living standard throughout the world without increasing consumption, and developing business models that are based on functionality rather than on personal ownership. Particularly with regards to communication to the broad populace, a crucial aspect of the message is to raise awareness about the complex nature of sustainability. The goal should be to create a differentiated understanding of the term and hence to allow for sophisticated decision-making in daily life.

"To Whom"—The Target Group

Considering the communication goal of changing people's behaviour, and the findings on credibility described above, it becomes obvious that it is insufficient to simply view the broad public as one homogeneous target group. Moreover, experience from former sustainability communication measures shows us that mass coverage can only play a supportive role in the whole process (Roeder et al. 2015). With respect to the variety of potential recipients and communication goals, no panacea exists. Hence, addressing multipliers becomes an integral part of mediating knowledge to large numbers of diverse recipients. Multipliers can be defined as persons who have the ability to influence the opinion, the behaviour or the actions of a social group by virtue of the authority assigned e.g. by their social status or professional expertise. Their relevance results from their hybrid nature, as they constitute just as much the target group as they do the role of communicator. Multipliers can be, for example, teachers, trainers or any other people in positions who communicate with a great number of citizenry in their day-to-day work. They can also be decision-makers who influence a lot of people's behaviour by deciding on the choices they get to make, e.g. product designers or politicians. Lucky for scientifically-based sustainability communication, those are the very target groups who are likely to ascribe publicly funded science communicators high credibility, as argued above.

By involving multipliers as a mediating party, a simplified model of sustainability communication has been introduced that consists of three sets of communicators and target groups respectively. All three parties together represent the communication network of science-to-public sustainability communication (Fig. 2).

Each party has to be understood as a communication partner who possesses valuable information on sustainable development and power to influence its dissemination into society. For instance, teachers can give information on what materials or tools they require for teaching sustainability. Decision-makers have insights into the constraints that influence people's behaviour, which often go unnoticed. The

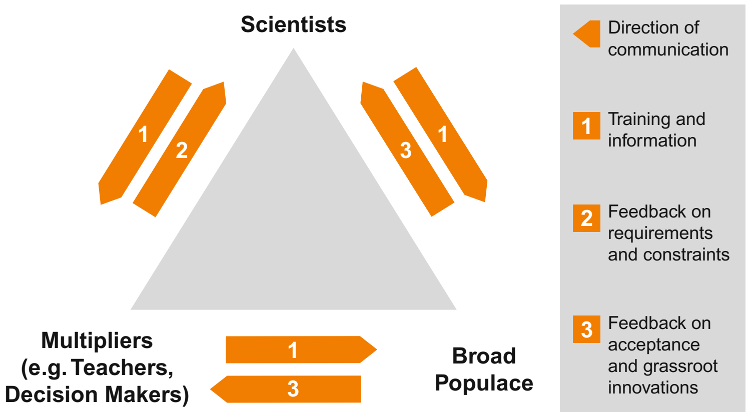


Fig. 2 Simplified communication model for dissemination of sustainability knowledge from a scientific stakeholder perspective

broad populace may have information about the acceptance of sustainability measures as well as about grassroots innovations and movements.

Viewing education as a core vehicle for transferring sustainability knowledge into society allows for a more differentiated view of the target groups. While the OECD and the UN consider education at all levels of formal and non-formal education, teaching a holistic understanding of sustainable manufacturing requires more specific target groups. Although it is useful if general ideas of sustainable development are taught from early childhood onwards in conjunction with a uniform set of values, the integration of industrial aspects such as technology, production planning and business models, should wait until the learners' cognitive ability has matured enough to process such complexity.

The human brain develops rapidly up to the age of about twelve. At the age of 13, further increase in memory performance is usually slow and marginal (Ahnert 2014). The ability of hypothetical and scientific thinking emerges, enabling the young learner to verify hypothesizes by using logic. The cognitive ability developed by adolescence enables the students to rapidly extend their semantic networks from that point on (Ahnert 2014). Well-developed semantic networks are fundamental to complex thinking, such as needed for understanding the workings of sustainable manufacturing challenges and solutions. It can be therefore clearly recommended to concentrate on target groups from the age of around 13 onwards when teaching complex aspects of sustainable manufacturing. Of course, it helps by

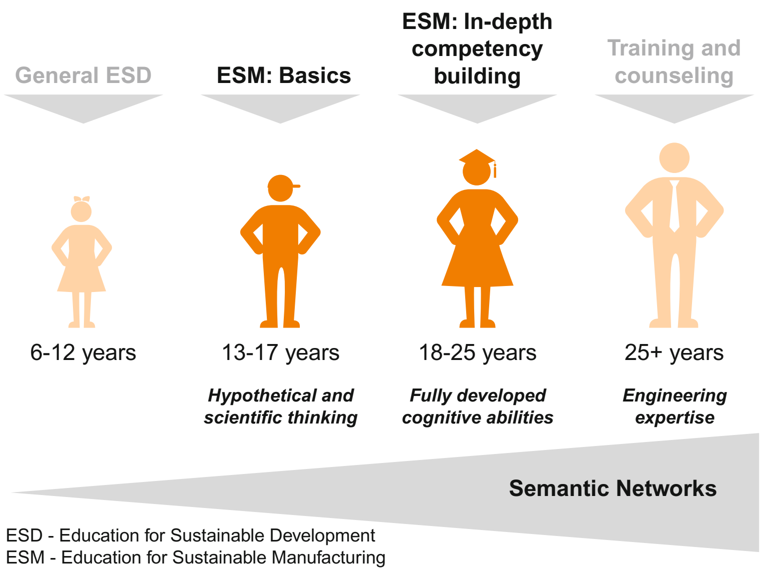


Fig. 3 Levels of education for manufacturing-related sustainable development

all means if the students are already familiar with more general aspects of sustainable development and science by that time, as demonstrated in Fig. 3.

Teaching sustainable manufacturing at the high school level again lays the foundation for easy integration of correlating assumptions into higher education. Still, the main focus of engineering and engineering economics education lies in classic paradigms such as profit maximization. Sustainability aspects are inadequately represented despite the dire need to sensitize future manufacturing experts to their responsibility as decision-makers and teach them how to plan and implement sustainable manufacturing. In summary, ESM, although generally building upon ESD, needs to target high school students in order to prepare them for further training as engineering or engineering economics students in higher education so to pave the way for new, sustainability-oriented paradigms in manufacturing. Also targeting the youth in general means targeting the next generation of consumers, whose product choices make them direct stakeholders of sustainable manufacturing if they choose to invest in sustainable products and sustainable production. Through the same mechanism they can also have indirect effects as a pressure group on enterprises that still follow unsustainable manufacturing strategies.

"In What Way"—The Channel

Target group orientation is the core of successful communication. The channels that are used are therefore as manifold as the target groups to be communicated with. Those channels can be direct or indirect, depending on the assignment of the target group as shown in Fig. 4. Apart from research-based communication such as interviews in direct communication and survey sheets in indirect communication, the focus of direct communication with multipliers is on training and through active participation on the part of the respective stakeholder networks. The broad populace can best be reached by offering exciting events with a high entertainment factor or even public educational projects. Indirect communication can work by offering specific training materials such as extended teacher manuals complete with teaching materials or materials for qualifying teachers as "Teachers of ESD" as a labelled skill enhancement, for example. Training materials and appropriate manuals for skill-enhancement likewise play a major role in the indirect communication with multiplying decision-makers, especially from industry. Broad populace is thus reached indirectly through teaching or through informational materials offered by the trained multipliers, and also through a variety of activities such as exhibitions or competitions.

Useful communication formats and tools differ greatly among the target groups. It is necessary for effective communication to choose carefully the channels that are to be used. The channels described above are meant to be supplementary to the well-established channels of scientific and journalistic media production such as articles or print media.

"With What Effect"—The Result

Just as the impact of every communication activity should be measured and every new product should be tested, the impact of innovative ESD activities needs to be monitored in order to identify undesirable effects or outright ineffectiveness. The

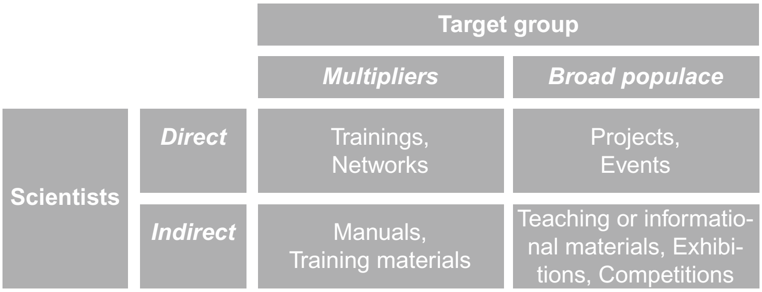


Fig. 4 Exemplary ESD communication from a scientific stakeholder perspective

outcome of studies on knowledge gained and attitudinal or behavioural change can usually not be expected to represent a fixed reality. It lies within the nature of social sciences that there are as many social realities for a surveyed person as there are social or psychological circumstances which this person experiences. The situation becomes even more complex when the participants are children whose semantic webs and other cognitional modes are not yet fully established (cf. Ahnert 2014). In that vein, planning research designs for such target groups proves to be challenging. Pre-tests of the design are thus absolutely necessary in this context. Especially if a research group's main focus lies in the technological field—as to be expected when it comes to sustainable manufacturing—social scientific expertise needs to be integrated in order to confront this challenge. However, a great number of cases and careful research design can provide valid data on knowledge, attitudinal and behavioural development subsequent to a treatment e.g. an ESD measure. This data is fundamental to developing effective ESD solutions that are capable of contributing to the societal change of paradigms towards sustainable development.

3 Present Gaps and Best Practice Solution Examples

This section presents exemplary gaps in ESD and ESM which were identified in the course of an interdisciplinary research project on sustainable manufacturing. In the following paragraphs, some of these gaps are introduced in context, along with best practice solutions.

3.1 Sustainable Manufacturing in High School Education

A special focus of the Agenda 21, the UN development program for the 21st century, lies with children and teenagers. In Germany, the programs "21" and "Transfer-21" have been set up as local forms of the Agenda 21 from 1999–2008 in order to improve sustainability teaching at German schools, with moderate success (Roeder et al. 2015). While educational frameworks have been rewritten in Germany in order to integrate sustainable development into formal education, a survey with above-average students in 2014 showed that only about 50 % had any future-oriented associations with the term.

In-depth sample interviews with high school teachers showed that they did not feel competent to teach sustainable development, let alone sustainable manufacturing (Roeder et al. 2016). They felt a lack of fundamental appreciation of the topic of sustainable development and furthermore lacked the teaching materials that would help them to overcome their knowledge deficiency in class. That this notion is a common one among teachers becomes apparent in a study with educators from schools that are implementing ESD programs under a local German program in 2015. Although all participants are already involved in ESD activities and have been offered qualification courses, 44 % say it is difficult to develop the necessary competencies for teaching ESD, and 51 % claim, moreover, that it is difficult to find adequate teaching materials.

3.1.1 Open Educational Resources

The challenge of lacking adequate teaching materials for a fast developing field with multiple perspectives could be met by solutions from the open knowledge movement. That is, high expectations for educating the populace worldwide have been raised by the concept of so-called Open Educational Resources (OER). The Paris Declaration of the UNESCO 2012 World Open Educational Resources Congress defines OER as “any type of educational materials in the public domain, or released with an open license, that allows users to legally and freely use, copy, adapt, and re-share”.

OER are dynamic. They can be quickly adapted and shared since they are supposed to be produced in an open format and shared online. They also allow for a wider variety of cases and examples than can be covered by a textbook alone. OER thereby encourage teachers to tailor their teaching units according to their students’ interests or current debates. This is where topics such as sustainable manufacturing, which are widely neglected in education so far, can still be brought to teachers’ attention.

Sustainable development is mainly scheduled for the 9th and 10th grade at German high schools (Roeder et al. 2016). A search for German OER on sustainable development linked with topics of technology or industry for this target group in 2015 brought 29 results of which 18 also included at least one working sheet to use in class. Most of them had been developed for the subjects of geography, social sciences, biology, politics, religion/ethics, and economics. An analysis using the LORI[1] method, assessing the items in seven categories on a 5-point scale with 5 being the maximum score, showed an average (arithmetic) score of 3.6. Although some

[1]Learning Object Review Instrument by Leacock and Nesbit (2007).

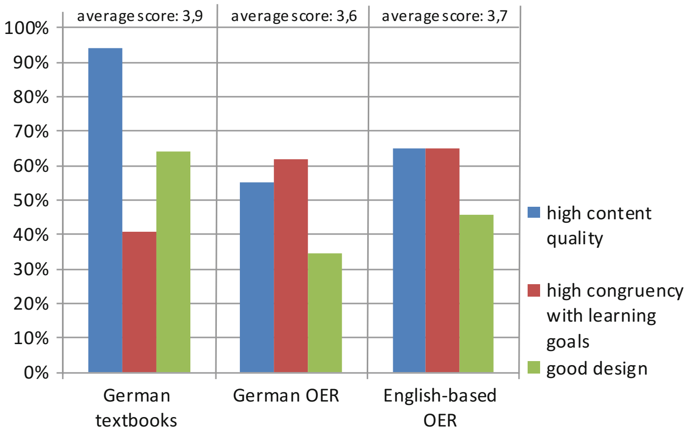


Fig. 5 Comparison of teaching materials assessed with the LORI method

resources, especially those from official bodies, scored very high, only 55 % had good (4) or very good (5) results at the assessment of content quality as shown in Fig. 5. Another weak spot has been identified to be design: Only 10 out of 29 items scored good to very good. 62 % had high or very high congruency with the defined learning goals and 63 % included motivational elements such as varying assessment types. Generally the OER scored lower than the sustainability sections of geography text books for the same target group; those having an average (arithmetic) score of 3,9.

The exemplary international search for English OER on sustainability and technology or sustainability and industry for the same target group (n = 48, 23 including working sheets, 131 identified items total) revealed the USA and Canada to be the main producers of OER on the topic for this specific target group. However, there are also free English teaching materials accessible by providers from the UK, Australia, Norway, and France among others. The LORI assessment of 48 items that met the requirements of topic and target group best showed a slightly higher score of the English OER than of those produced in German language, the average (arithmetic) score of the international OER being 3,7. 65 % of the English-based OER were assessed to have good or very good content quality and congruency with the learning goals. 22 out of 48 assessed items scored good to very good with regard to design.

Apart from often poor didactic design, the connection to core sustainable manufacturing topics were only marginal in most cases. This is a gap that needs to be filled if the topic stands a chance of getting incorporated into high school curricula. Since content quality is one of the weak spots, science has a clear advantage as a producer of up-to-date and technically sound content. Critical in that pursuit is that the research teams intending to produce OER as a tool for raising awareness for sustainability must be multidisciplinary and bring together technical and didactic expertise. An example of this has been done within the Collaborative Research Centre (CRC) 1026 “Sustainable Manufacturing—Shaping Global Value

Creation" (Roeder et al. 2016). When developing and producing their teaching unit on "Sustainable Manufacturing," the scientists followed a 3-step action plan covering content definition (1); didactic structuring (2); and material production (3).

Content Definition

Resource consumption in manufacturing is the central theme of the OER developed by CRC 1026, addressing matters of human, natural and economic resources. In a first teaching unit, general information on sustainable development built up to the connection with manufacturing issues, so that, for example, the three pillars of sustainability were explained from a manufacturing perspective. This was then exemplified by a second unit discussing bicycle production in the context of more specific sustainability issues within global value creation, such as producing in low-wage countries, distributed production and CO_2 emissions. A third unit addressed Maintenance, Repair and Overhaul as clearly technical topics of sustainable manufacturing, also addressing, for example, planned obsolescence.

Didactic Structuring

In the interest of implementing the educational frameworks with the ultimate criteria of introducing teacher materials, nationwide educational programs were analysed for their explicit reference to sustainable manufacturing. It became clear that sustainable development is mostly set to become a fixed part of the 9th and 10th grade curricula and for all geography classes in nearly all federal states. To that end, the content was defined according to these frameworks' competencies and learning goals, such as "cosmopolitan acquisition of knowledge, including multiple perspectives" which was met, for example, by means of a role-playing exercise in which students take on various roles of producers, workers and customers from different geographical and cultural backgrounds. The learning goals of each exercise and their links to the educational framework, along with further didactic information, were all made explicit in an accompanying teacher's guide.

Each unit was structured following a reduced learning spiral oriented at Mattes (2011). To sum up, the procedure starts with teacher-oriented learning, requiring increasing self-study and group study as the lessons proceed, and finally ending with teacher-led concluding elements which follow up on individual learning results. Obviously the content must be general in the beginning, using everyday experiences of the target group as the starting point. It gets more specific as the lesson proceeds. At the end of the lesson, exercises are designed to ask students to transfer the acquired principles to other fields.

Since the material is supposed to be usable at different proficiency levels, a focus has been set on internal differentiation. Hence, exercises are set in three levels of difficulty.

Material Production

The best content will be ignored by teachers and students alike if the design is not appealing. The CRC 1026 invested in a professional designer for layout and graphics. OER are free of charge and free to adapt. In using OER, it is however of utmost importance either only to use graphics that are offered under a global commons license, or to produce them explicitly as such. A challenge when creating OER is adaptability. A publishing licence allowing for adaption is no benefit if the format and design of the materials offered are themselves not adaptable. It is thus paramount that the designer does his/her work with software that most teachers or even students have access to. In that vein, CRC 1026 decided to do its layout in Microsoft Powerpoint in order to foster easy exchange of graphics or text blocks.

3.2 *Sustainable Manufacturing in Higher and Vocational Education*

Promoting excellence in engineering has emerged as a strategic goal on the part of industry, society and nations in pursuit of improving living standards. The European Technology Platform for Future Manufacturing Technologies (Manufuture) highlighted the role of engineering education explicitly as a key driver in achieving this goal (Manufuture 2006). Chryssolouri recommends "*manufacturing education should follow new approaches so as to prepare industry for the next-generation innovation and the support of its growth*" (Chryssolouris 2005).

Innovative sustainable manufacturing offers a vehicle for coping with the challenge of sustainability. New training and education activities within organizations comprise the lever for achieving higher education in this area. For structuring an engineering design course with respect to teaching aspects of sustainability, Pappa et al. (2013) took Bloom's taxonomy of the cognitive domain as a basis. Yet the development of an approach in engineering wherein instruments are used to convey aspects of sustainable manufacturing with regards to the affective and psychomotor domains, was however hardly discussed.

3.2.1 Learning Through the Support of Technology—*Learnstruments*

Great potential for increasing the awareness and the learning and teaching productivity on sustainable manufacturing topics is seen in addressing the matters of technical content and the learner's feeling, values or psychomotor skills at the same time. Such instruments for learning could be found in so-called *Learnstruments*.

Learnstruments are production technologic objects both tangible and intangible, automatically demonstrating their functionality to the user. They aim at increasing the learning and teaching productivity and expanding the awareness of the environmental, economic and social perspective of sustainability. By their application, Learnstruments enhance organizations' human, structural and relational capital through higher skills and knowledge, structure and collaboration.

The neologism Learnstrument consists of the words *learning* and *instrument*. Learnstruments support the learning process by providing adequate learning goals to the user. Instruments in this sense are considered as objects supporting the user effectively and efficiently in achieving the learning goals. Furthermore, learning processes can be designed in a new fashion, focusing on sustainability to shape people's understanding of this important topic during training and learning.

They address cognitive, affective and psychomotor learning goals and strive towards the fulfilment of high level learning goals. Enabled by new and existing information and communication technology, Learnstruments allow the determination of the user's cognitive learning level and provide adequate learning goals towards the fulfilment of creation. Repetition strengthens the user's psychomotor ability for adaptation of human skills to execute manufacturing tasks.

The concept of Learnstruments is introduced and illustrated with two prototypical implementations.

3.2.2 CubeFactory

The CubeFactory is a Learnstrument addressing the understanding of a closed loop material cycle of polymers by an application-oriented mediation process. This mini-factory constitutes self-sustaining learning and production equipment which contain the main components involved in value creation, such as material processing, energy supply, manufacturing tools and tools for knowledge transfer. Based on the learning cycle of Kolb (1984), the CubeFactory considers aspects of perception and processing continua designed to increase learning productivity. The user is methodically supported in knowledge creation by the elements of concrete experience, reflective observation, abstract conceptualization and active experimentation. An open source 3D printer is the main value creation tool. The additive manufacturing process is regarded as sustainable since it places material exactly where it is needed to build up the workpiece. Unlike subtractive processes such as turning, milling, drilling, virtually no waste or by-products are generated in the whole process.

The so-called Home Recycling Device (HRD) serves as a material supplier for 3D printer consumables and demonstrates the value and potential of plastic recycling. A mechanical knife-shredder granulates thermoplastic waste that is further processed into an electrically heated screw extruder. This can turn a non-valuable object like thermoplastic domestic waste, into a valuable product like 3D printer filament. "Comparing the cost of 100 kg of sorted plastic waste ($1.00) with 1 kg of 3D printer ABS-filament ($25), an up lift ratio of 2500:1 is realized" (Muschard and Seliger 2015; Reeves 2012). Through the application of the HRD, the user learns that local processing of raw materials can shorten or even eliminate distribution channels, can reduce the volume of waste, can save on CO_2 emissions, and at the same time ultimately make the production of goods more cost effective. An important lesson in the mediation of sustainability is that energy cannot be produced, but only converted. In a sustainable manner, it applies to abdicating non-renewable resources and to making renewable resources available.

For those purposes, the CubeFactory contains a self-sufficient energy supply system formed by solar modules, rechargeable batteries and a battery management system. The knowledge transfer device is a learning environment implemented in a touchscreen tablet computer, supporting the user in exploiting the potential of the mini-factory. It assists the user in comprehending the CubeFactory's manner and in carrying out learning tasks in a simple and intuitive way.

To address a broad spectrum of users, to arouse curiosity and to motivate the learner, the CubeFactory is designed taking differences in knowledge, skills, age, disability or technological diversity into account (Fig. 6).

Fig. 6 CubeFactory: mobile, self-sufficient mini-factory

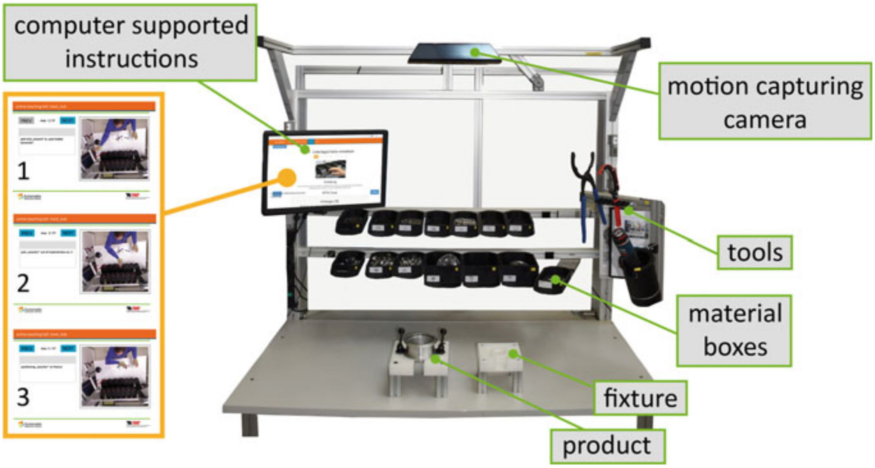


Fig. 7 Smart Assembly Workplace: assembly sequence of bicycle e-hubs is automatically transmitted to the user

3.2.3 Smart Assembly Workplace

The Smart Assembly Workplace (SAW), shown in Fig. 7, is a learning workplace for manual (dis-)assembly tasks with the example of bicycle e-hubs. It equips the worker with the tools and know-how needed to improve and plan such a workplace on their own. The learning-path is structured in initial learning and consecutive in-depth e-learning. It consists of fixtures, material boxes, tool holders and a camera to be affixed at the workplace.

During initial learning, users less experienced in assembly obtain a basic overview of the assembly sequence. The main requirement for this is to give the user immediate feedback referring to her/his current constitution and actions. By means of a marker-less motion-capturing software (Krüger and Nguyen 2015), the hands of the user are tracked by the system. Whenever the learner enters a so-called event-zone, an internal time stamp is logged and the assembly description automatically reveals the next assembly step on the display. In case of a mistaken action, a message is displayed to the user.

When the user enters, for example, the nuts-bunker with her/his hand, it can be assumed that at least one nut has been picked. On the basis of the time spent, conclusions with respect to the current work performance or level of learning of the user can be drawn. As soon as the worker's performance reaches the target time according to Methods-Time Measurement (MTM), the respective MTM-code is displayed to the user via the computer-supported instruction. It is utilised for the purposes of analysis and planning of working systems. By this representation, the user implicitly learns about the composition and meaning of the respective code.

The learner can use an e-learning module facilitating MTM knowledge in a self-explanatory way. The module consists of descriptions, hints and recommendations about the usage of MTM with the example of the bicycle e-hub. In a final stage, generic suggestions for improvement are displayed to the learner. These improvements are dedicated to assisting in the process of creating ideas for improvements in the learner's workplace (McFarland et al. 2013).

Although learning and understanding are intrinsic processes, this happens mostly in the setting of an interaction between the learner and the environment. Intelligently designed technologies and artefacts can assist the human in her/his learning process, and help to enhance teaching and learning productivity. The increasing digitization of manufacturing opens up new opportunities for knowledge transfer, in which the teacher and the learner no longer need be present at the same location.

The SAW replicates the production technology laboratory of the Vietnamese-German-University in Ho Chi Minh City, Vietnam. An assembly description, recorded at the German SAW, was transferred to the Vietnamese one. It was shown that the students in Vietnam—having scant knowledge about assembly—were able to assemble e-hubs with the help of this description. An expert was not required to be present in Vietnam to that end at all.

3.3 Facilitating Appreciation of Sustainability Aspects Through Gamification

As described above, the topic of sustainability is rather complex and it therefore takes time to supply an interested person with the necessary knowledge. In the context of the general public, the interest in picking up information without being forced to (by work, school or similar) decreases if too much time is required to supply the knowledge. Gamification addresses this topic by the use of game design elements in non-game contexts (Tan et al. 2011). Gamification provides elements that keep the interest of a person in a specific topic by using design elements like scores, achievements and storylines.

One way to transfer and demonstrate the challenge of sustainable product development is to let people experience this process first hand. Therefore, a "Product Configuration Game" (PCG) was developed in which the user is put in the role of a product developer who has to configure a new product from a limited set of options (Wang et al. 2014). The product in that case is a simplified model of a so called Pedelec (Pedal-Electric Bicycle). The configurable parts of the Pedelec comprise the basic frame and additional functional features. Furthermore, three different suppliers for the basic frame are available. This limited set of configuration options simulates existing supply chains and product politics. All features and product options are assigned with sustainability scores indicating their impact on respective sustainability indicators, such as global warming potential, primary energy consumption or fairness of salary. These scores where derived from results from a LCA conducted by Neugebauer et al. (2013) for a similar use case. By aggregating all sustainability score of one specific setting, a total sustainability score is calculated and visualized as bar chart for each of the sustainability dimensions (see Fig. 8). To demonstrate the fact that product developers usually do not have all necessary information about the impact of their choices the visualization of the total sustainability impact is also not available at the beginning of the game. Instead, the users have to rely on vague descriptive characteristics of features, such as material price, weight or design style. Only when they confirmed their decisions the bar charts representing the sustainability impacts are revealed. Then the users can change their decisions to explore the influence of different options. The impacts of their changes are then shown in real time. A further PCG feature, called the "Ontology Browser" allows the user to investigate the complex network of relationships between the product options and the sustainability indicators in a controlled way by using ontological trees developed for this game (Wang et al. 2014).

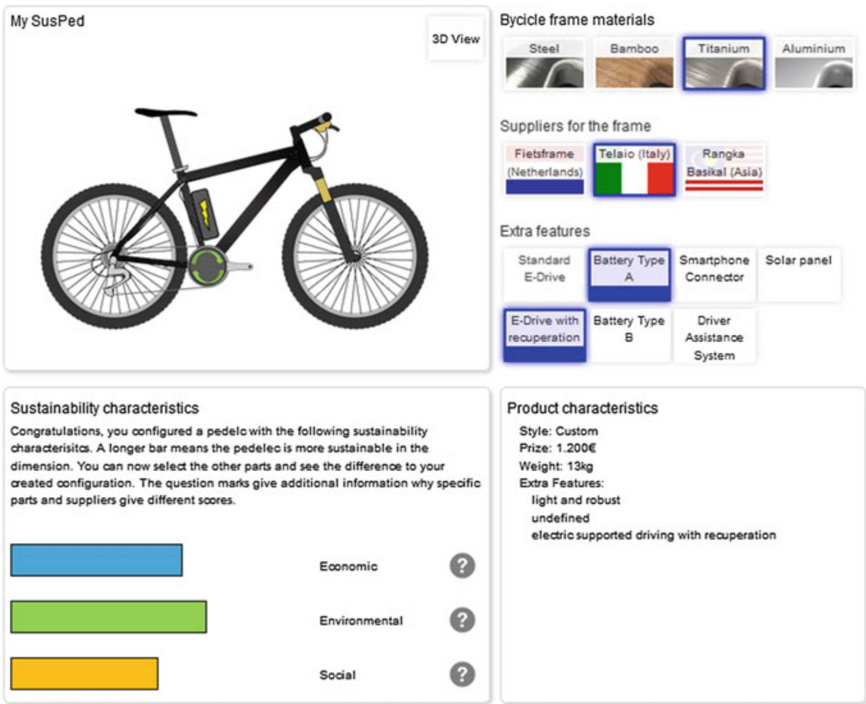


Fig. 8 Product Configuration Game: the user interface provides graphical feedback in the product model and shows impact of configuration decisions on all three sustainability dimensions in real time as bar charts

Various Gamification Design Elements (Tan et al. 2011) where chosen to motivate the user:

- Mechanics of the configurator construct a system of interacting parts that can be combined to achieve different results, so that exploring the different types of sustainability impact of the pedelec parts is necessary in order to understand the game mechanics
- Feedback visualization shows the result of the combination by delivering not only values in terms of graphs but also by providing a visual of them using a 2D/3D representation of a pedelec, therein enabling one to create her/his own custom-designed bike
- Fun motivator—role-play puts the user into the role of a design engineer with the task of creating a sustainable pedelec
- Fun motivator—research uses the ontological mechanisms for providing a visualization of the complex network behind the sustainability of the pedelec, which then allows the user to explore those networks discovering new relations

Using these gamification elements enriches the configurator in a way that users are kept interested as they are supplied with more information about sustainability during the usage of the configurator.

4 Conclusion

If the lifestyles of both economically up-coming and economically developed communities are persist to be shaped by the existing, currently predominant technologies, then resource consumption will exceed every accountable ecological, environmental and social boundary known to man (Seliger 2012; Ueda et al. 2009). However, human initiative and creativity opens up a panoply of paths for future development in pursuit of coping with the challenges of sustainability on a globe scale. Their chances of successful implementation essentially depend on their ability to take hold in an increasingly globalized arena of market driven activities. Both, demand and supply, are thus not only abstract financial figures, but concrete goods in the sense of products and services as artefacts of human activities in manufacturing and design. Manufacturing technology significantly determines how exactly humans create these artefacts, and thus how they shape their environment, communities and individual lives. Directing these human activities to coping with challenges of sustainability is, consequently, a relevant research contribution in manufacturing technology.

In the politically charged arena of sustainable manufacturing with its high economic impact and huge variety of conflicting interest groups, the comparatively neutral position of science can serve to help win over people's trust. At the same time, innovative approaches, methods and tools need to be scientifically developed in order to overcome the educational gap regarding sustainable development and even more sustainable manufacturing. The triangle of researching, educating and networking that determines schools' and universities' daily agendas likewise involves the three pillars of ESD science: researching and developing innovative didactic approaches (1), putting them into direct use by integrating them into education as awareness-raising activities (2), and making use of universities' unique localization as experts standing in between politics, industry and a great number of learners in pursuit of building networks for promoting ESD (3).

References

Ahnert, Liselotte. 2014. *Theorien in der Entwicklungspsychologie*. Heidelberg: Springer.

Bolscho, Dietmar. 2005. Der Beitrag der Erziehungswissenschaften für die Nachhaltigkeitskommunikation. In *Handbuch Nachhaltigkeits-kommunikation,* ed. Gerd Michelsen, Jasmin Godemann, 143–150. Munich: Oekom.

Bormann, Inka. 2005. Zwischen Wunsch und Wirklichkeit: Nachhaltigkeitskommunikation in Schulen. In *Handbuch Nachhaltigkeits-kommunikation,* ed. Gerd Michelsen, Jasmin Godemann, 793–803. Munich: Oekom.

Brand, Karl-Werner. 2005. Nachhaltigkeitskommunikation: eine soziologische Perspektive. In *Handbuch Nachhaltigkeitskommunikation,* ed. Gerd Michelsen, Jasmin Godemann, 151–161. Munich: Oekom.

Bormann, Inka, Kristina Broens, Felix Brümmer, Bettina Klaczinski, Markus Lindner, Carina Lücke, Sebastian Niedlich, and Sonja Warning. 2015. *Evaluation der Kampagne "Schule der Zukunft – Bildung für Nachhaltigkeit".* Düsseldorf: Ministerium für Schule und Weiterbildung des Landes Nordrhein-Westfalen, and Ministerium für Klimaschutz, Umwelt, Landwirtschaft, Natur- und Verbraucherschutz des Landes Nordrhein-Westfalen. http://www.schule-der-zukunft.nrw.de/fileadmin/user_upload/Schule-der-Zukunft/Aktuelles/Abschlussbericht_Evaluation_Schule_der_Zukunft_ENDVERSION.pdf. Accessed 27 Sept 2016.

Chryssolouris, George. 2005. *Manufacturing systems: Theory and practice*. New York: Springer.

Crawley, Edward F., Johan Malmqvist, Sören Ostlund, and Doris R. Brodeur. 2007. *Rethinking engineering education: The CDIO approach*. New York: Springer.

Dave, Ravindrakumar H. 1970. Psychomotor levels. In *Developing and writing behavioral objectives*, ed. Robert J. Armstrong, 33–34. Tucson: Educational Innovators Press.

Fischer, Daniel, and Matthias Barth. 2014. Key competencies for and beyond sustainable consumption. An educational contribution to the debate. *GAIA* 23(S1): 193–200.

Fiske, Susan T., and Cydney Dupree. 2014. Gaining trust as well as respect in communicating to motivated audiences about science topics. *PNAS* 111(4): 13593–13597.

Gosling, David, and Jennifer A. Moon. 2001. *How to use learning outcomes and assessment criteria*. London: SEEC.

Griese, Kai-Michael, Christel Kumbruck, and Christin Michaelis. 2014. Der Einfluss von Humor auf die Nachhaltigkeitskommunikation. *Ökologisches Wirtschaften*, 29(4): 35–38.

Grunenberg, Heiko, and Udo Kuckartz. 2005. Umweltbewusstsein. Empirische Erkenntnisse und Konsequenzen für die Nachhaltigkeitskommunikation. In *Handbuch Nachhaltigkeitskommunikation,* ed. Gerd Michelsen, Jasmin Godemann, 195–206. Munich: Oekom.

Harrow, Anita J. 1972. *A taxonomy of the psychomotor domain: A guide for developing behavioral objectives*. New York: Longman.

Kirkpatrick, Donald. 1996. Great ideas revisited. Techniques for evaluating training programmes: Revisiting Kirkpatrick's four-level model. *Training and Development* 50(1): 54–59.

Kolb, David A. 1984. *Experiential learning: Experience as the source of learning and development*. Englewood Cliffs: Prentice Hall.
Krüger, Jörg, and The Duy Nguyen. 2015. Automated vision-based live ergonomics analysis in assembly operations. *CIRP Annals—Manufacturing Technology* 64(1): 9–12.
Kruse, Lenelis. 2005. Nachhaltigkeitskommunikation und mehr: die Perspektive der Psychologie. In *Handbuch Nachhaltigkeitskommunikation*, ed. Gerd Michelsen, and Jasmin Godemann, 109–120. Munich: Oekom.
Lasswell, Harold D. 1948. The structure and function of communication in society. In *The communication of ideas: A series of addresses*, ed. Lyman Bryson, 32–51. New York: Harper.
Leacock, Tracey L., and John C. Nesbit. 2007. A framework for evaluating the quality of multimedia learning resources. *Educational Technology & Society* 10(2): 44–59.
Manufuture High Level Group and Support Group. 2006. *Strategic research agenda: Assuring the future of manufacturing in Europe*. Brussels: ManuFuture Platform. https://www.um.es/operum/plataformas/files/manufuture.pdf. Accessed 27 Sept 2016.
Mattes, Wolfgang. 2011. *Methoden für den Unterricht: Kompakte Übersichten für Lehrende und Lernende*. Paderborn: Schöningh.
Mayer, Horst Otto, Johannes Hertnagel, and Heidi Weber. 2009. *Lernzielüberprüfung im eLearning*. München: Oldenbourg.
McFarland, Randy, Carsten Reise, Alexandra Postawa, and Günther Seliger. 2013. Learnstruments in value creation and learning centered work place design. In *Proceedings of the 11th global conference on sustainable manufacturing—innovative solutions*, ed. Günther Seliger, 624–629. Berlin: Universitätsverlag der TU Berlin.
Michelsen, Gerd. 2005. Nachhaltigkeitskommunikation: Verständnis – Entwicklung – Perspektiven. In *Handbuch Nachhaltigkeitskommunikation,* edited by Gerd Michelsen, Jasmin Godemann, 25–41. Munich: Oekom.
Muschard, Bernd, and Günther Seliger. 2015. Realization of a learning environment to promote sustainable value creation in areas with insufficient infrastructure. *Procedia CIRP* 32: 70–75.
Neugebauer, Sabrina, Ya-Ju Chang, Markus Maliszewski, Kai Lindow, Rainer Stark, and Matthias Finkbeiner. 2013. Life cycle sustainability assessment & sustainable product development: A case study on pedal electric cycles (Pedelec). In *Proceedings of the 11th global conference on sustainable manufacturing—innovative solutions*, ed. Günther Seliger, 549–554. Berlin: Universitätsverlag der TU Berlin.
Pappas, Eric, Olga Pierrakos, and Robert L. Nagel. 2013. Using Bloom's taxonomy to teach sustainability in multiple contexts. *Journal of Cleaner Production* 48: 54–64.
Reeves, Phil. 2012. Democratizing Manufacturing: 3D Printing in the Developing World. Yumpu. https://www.yumpu.com/en/document/view/46578172/democratizing-manufacturing-econolyst/1. Accessed 27 Sept 2016.
Roeder, Ina, Matthias Scheibleger, and Rainer Stark. 2015. How to make people make a change: Using social labelling for raising awareness on sustainable manufacturing. *Procedia CIRP* 40: 359–364.
Roeder, Ina, Mustafa Severengiz, Rainer Stark, and Günther Seliger. 2016. Open educational resources as driver for manufacturing-related education for learning of sustainable development. Paper to be presented at 14th Global Conference on Sustainable Manufacturing, Stellenbosch, South Africa, October 3–5, 2016.
Simpson, Elizabeth J. 1972. *The classification of educational objectives in the psychomotor domain*. Urbana: Gryphon House.
Seliger, Günther. 2012. Sustainable manufacturing for global value creation. In *Sustainable manufacturing: Shaping global value creation*, ed. Günther Seliger, 3–8. Berlin: Springer.
Seliger, Günther, Carsten Reise, and Rand McFarland. 2009. Outcome-oriented learning environment for sustainable engineering education. In *Proceedings of the 7th global conference on sustainable manufacturing—sustainable product development and life cycle engineering*, ed. Günther Seliger, 91–98. Berlin: Universitätsverlag der TU Berlin.
Tan, D., S. Amershi, B. Begole, W.A. Kellogg, M. Tungare, S. Deterding, et al. 2011. Gamification using game-design elements in non-gaming contexts. In *Proceedings of the 2011*

annual conference extended abstracts on Human factors in computing systems, ed. D. Tan, 2425–2428. New York, NY: ACM.
Ueda, Kanji, Takeshi Takenaka, Jozsef Váncza, and László Monostori. 2009. Value creation and decision-making in sustainable society. *CIRP Annals—Manufacturing Technology* 58(2): 681–700.
UNESCO. 2012. 2012 World Open Educational Resources Congress: Wednesday 20–Friday 22 June, 2012. http://www.unesco.org/new/fileadmin/MULTIMEDIA/HQ/CI/CI/pdf/CI_Information_Meetings/2012_world_oer_congress_en.pdf. Accessed 27 Sept 2016.
Wals, Arjen E.J. 2015. Social learning-oriented capacity-building for critical transitions towards sustainability. In *Schooling for sustainable development in Europe: Concepts, policies and educational experiences at the end of the UN decade of education for sustainable development*, ed. Rolf Jucker, and Reiner Mathar, 87–107. Cham: Springer.
Wang, Wei M., Lars Wolter, Kai Lindow, and Rainer Stark. 2014. Graphical visualization of sustainable manufacturing aspects for knowledge transfer to public audience. *Procedia CIRP* 26: 58–63.
Weintraub Austin, Erica, and Bruce E. Pinkleton. 2015. *Strategic public relations management: Planning and managing effective communication programs*. New York: Routledge.
Zirfas, Jörg, and Michael Göhlich. 2007. *Lernen: Ein pädagogischer Grundbegriff*. Stuttgart: Kohlhammer.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the book's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the book's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.