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Engineering for Sustainable Value

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1 Introduction

In recent years, engineering companies are facing challenges from the depletion of resources, the rising price of material and energy, the environmental legislation, and the pressure from society (Evans et al. 2009). These challenges have been forcing engineering companies to develop new technologies and strategies to do business in a more sustainable way, in which less environmental and social negative impact is caused. Global production has affected economic and social development, as well as environment in a direct way. At a macro-level, industrial growth, globalisation, resource use (energy, water, and minerals), climate

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change, household/consumer behaviour, and population growth amongst others have impact on high value engineering. At an industry (micro-) level, sustainability challenges refer to resource use and scarcity (human, physical, and financial), technology development, infrastructure design, workplaces (patterns of consumption), advertising and marketing to sell more stuff, and role of value and culture in shaping businesses and market (Michaelis 2003).

Engineering sustainability faces many challenges—from increasing scarcity of raw materials to reducing climate change impacts—that are broadly summed into the concept of sustainability. Without adequate responses to these challenges our highly engineered products will not be able to be produced and may not be able to be sold (Garetti and Taisch 2012). These challenges that shape the mainstream thinking on high value sustainable engineering require technical and business model changes. Companies are increasingly embracing approaches to sustainability such as eco-efficiency and clean technology. However, such innovations are not sufficient to address the pressing problems of unsustainability in engineering, in particular manufacturing. More fundamental changes in the way companies conceive and operate businesses are required. As such, a radical shift is required, where industry is considered pivotal in pursuing engineering for sustainable value.

The literature suggests (Lebel and Lorek 2008; Tukker and Tischner 2006) engineering for sustainable value requires systems approach that deals with systemic interdependencies and complexities and life cycle thinking, which takes into account products and processes view. Both approaches supplement each other and are considered necessary to address consumption and production patterns at different levels. Authors such as Evans et al. (2009) and Krantz (2010) suggest 'sustainability as an innovation platform' for a fundamental shift towards a sustainable economy with significant changes in people's lifestyle and mindset/behaviour, redesigning business models and value network 'to embrace a transformational sustainability that moves beyond incrementalism and eco-efficiencies'. Addressing these challenges both at macro-level and micro-level calls for significant changes to production and consumption, which requires participation and collaboration of companies, governments, non-government organisations, academia, and communities. The extended global value networks with multiple suppliers interacting with other networks and interrelationships between different industries through product use and disposal phase make collaborations between stakeholders across networks for innovating value integral to understand failed value exchanges. The World Economic Forum Report (2011) suggests that 'businesses are the builders of a sustainable consumption economy through their investments and innovation. The strategic use of life cycle thinking offers an opportunity to re-engineer business models and value chains'. Hence, such transition implies rethinking the business model to generate sustainable value (i.e. environmental, social, and economic value).

2 Literature Background

2.1 Sustainable Manufacturing

Industry, as estimated to be responsible for some 30% of CO_2 emissions on the planet, is a major consumer itself of primary resources and non-renewables and is the primary driver of end-user consumption of material goods (Evans et al. 2009). The huge impact on sustainability is also demonstrated by the relevance of energy consumption in manufacturing, primarily due to electrical energy and oil. Industry also develops and promotes demand for products that through their use cause significant additional CO_2 emissions and other forms of subsequent pollution and waste. Furthermore, the magnitude of the industrial sector, its global nature, use of natural resources for production, its role in technological innovation, its driving influence in most societies, and its primary position in a consumer-based culture make it central in impacting sustainability.

As Burke and Gaughran (2007) state, 'sustainability issues in manufacturing are growing exponentially. Initially referring to environmental considerations, sustainability now also encompasses social and economic responsibilities'. Garetti and Taisch (2012) define sustainable manufacturing as 'the ability to smartly use natural resources for manufacturing, by creating products and solutions that, thanks to new technology, regulatory measures and coherent social behaviours, are able to satisfy economic, environmental and social objectives'. Technological understanding is a part and not enough for a comprehensive view of sustainable manufacturing. Another perspective of sustainable manufacturing is related to consumer behaviour—people using smart products, services and in general for new technological capabilities in order to meet the sustainability challenges. Garetti and Taisch (2012) argued that sustainable consumption is part of sustainable manufacturing and emphasised that 'education is the prerequisite for consumer and people in general to correctly address the sustainability objectives through appropriate life-styles and the appropriate use of products and technology'.

Sustainable manufacturing has been the main focus of various researches supported by the European Commission, which has encouraged thinking of new perspectives in manufacturing linked to the sustainability challenges and, more recently, developing correspondent approaches, systems, and tools. Having concern to the new envisioned perspectives, it is worth mentioning research initiatives such as the IMS international project IMS 2020: supporting Global Research from IMS 2020 vision (IMS 2020 2009), which is in charge of preparing a roadmap for future manufacturing research and the Factory of the Future Strategic Multi-annual Roadmap (European Commission 2010), prepared by the Industrial Advisory Group for the Factories of the Future Public–Private Partnership. Furthermore, concern over social and environmental issues has resulted in a rising consumer pressure for responsible corporate behaviour has highlighted the need for responsible corporate behaviour to prove that complete focus on short-term financial results can lead the company towards jeopardy and total closure.

In summary, engineering for sustainable value requires changes to overall business processes and activities through collaboration amongst stakeholders in the value network. More specifically, a holistic solution focusing on redesigning business models and innovating value through the sustainability lens appears to be important. As Krantz (2010) proposes 'companies will need even bigger changes, including new business models, greater trust, and greater stakeholder engagement' based on a 'long-term vision' for pursuing sustainable consumption and production. Although environmental and social approaches are developed and implemented by companies, it is often through compliance with regulations or incremental environmental and social initiatives such as eco-efficiency, eco-innovation, and waste management and add-on corporate social responsibility activities in the community. These initiatives are helpful but incremental and limited in their ability to drive system-wide changes.

2.2 Business Model Innovation for Sustainability

Technological understanding is a part of engineering sustainability. It needs also suitable business models to achieve its commercial potentials (Chesbrough 2010). An increasing number of scholars and practitioner argue that technology and process innovation alone are no longer enough to create sustained competitive advantages, and the business model itself is key to unlocking the latent value potential of new technologies (Chesbrough and Rosenbloom 2002; Teece 2010). Recent research and practice show that business model innovation is a promising approach for improving sustainable manufacturing.

The concept of business model first appeared in the 1950s, but only became prevalent in the 1990s with the advent of the Internet (Teece 2010; Yip 2004). Business model in simple terms depicts 'how a firm does business' (Magretta 2002). All companies have some form of business model, even though they might not explicitly have considered or defined their model (Teece 2010). The concept of business model is closely linked to the concept of value in most business model literature. Majority of the existing literature defines business models in terms of value creation, capture, and delivery (Osterwalder and Pigneur 2010; Teece 2010). The literature (Chesbrough 2010; Zott and Amit 2010) suggests that business model innovation is a key to business success define business model innovation as 'a multi-stage process whereby organizations transform new ideas into improved business models in order to advance, compete and differentiate themselves successfully in their marketplace'. Björkdahl and Holmén (2013) regard business model innovation as '*a new integrated logic of how the firm creates value for its customers or users and how it captures value*'.

Lüdeke-freund (2010) defines a sustainable business model as '*a business model that creates competitive advantage through superior customer value and contributes to the sustainable development of the company and society*'. To develop sustainable business models, it is essential to consider the integration of social and environmental goals into a more holistic meaning of value (Schaltegger et al. 2012).

2.2.1 Product–Service Systems: A Pioneer of Sustainable Business Models

Product–service systems (PSS) is a set of business models that describe the selling off services rather than products alone. PSS is commonly classified into three types depending on the rate of service: product-oriented; use-oriented; and result-oriented PSS (Tukker 2004). Product-oriented PSS is that manufacturers sell products and provide added on services, for example, maintenance. Use-oriented PSS is that manufacturers sell utility of products instead of the physical products, such as products sharing, leasing and renting services. Result-oriented PSS is that manufacturers sell the result of products, such as selling printed documents instead of selling printers.

PSS business models are considered as promising ways to achieve sustainable production and consumption (Goedkoop et al. 1999; Maxwell and Van Der Vorst 2003; Mont 2002; Tukker 2015). The main reason is that engineering companies, in the context of PSS business models, have the incentive to prolong the lifetime of products and gain a long-term profit from service and end-of-life strategies, e.g. remanufacturing, reconditioning, repair, and recycling (Baines et al. 2007). It leads to a reduction of total material consumption throughout life cycle—dematerialisation, as well as a change of customers' consumption behaviour from buying products to buying services (Goedkoop et al. 1999). Therefore, PSS is regarded as a pioneer of sustainable business models with a potential to reorient both production and consumption towards a more sustainable direction (UNEP 2009).

All three PSS types have the potential of reducing environmental impact (Tukker and Tischner 2006). For example, the retaining of products ownership enables manufacturers to have the incentive to design for remanufacturing, recycle, reuse, and repair, which aligns with the purpose of sustainable design (UNEP 2009); the delivery of function or result increases the utilisation of products (Beuren et al. 2013). The use- and result-oriented PSS could deliver a higher potential to be dematerialised due to the retaining of ownership for manufacturer (Beuren et al. 2013) and thus are considered as the key to sustainable PSS (Roy 2000). Apart from environmental benefits, PSS also has the potential to be beneficial to society. For example, more jobs could be created from labour-intensive services (Beuren et al. 2013). However, it does not imply that PSS would inherently bring sustainable effects (Tukker and Tischner 2006).

The implementation of sustainable PSS business models is still challenging (Vezzoli et al. 2012). Sustainable PSS needs to be carefully designed at an early stage, since the design of PSS affects the material and energy consumption, cost, and customer behaviour through the entire life cycle (Ullman 2003). Various PSS development methods and tools have been proposed in the literature, for example Service Explorer (Sakao et al. 2009), Sustainable Product and/or Service Development (SPSD) (Maxwell and Van Der Vorst 2003), Methodology for Product–Service System Development (MEPSS) (Van Halen et al. 2005), and Solution-Oriented Partnership (Manzini et al. 2004). The existing methods and tools show that the development of sustainable PSS is still at an early stage. Few of the existing tools fully consider the social and environmental aspects of sustainability (Vasantha et al. 2012), which emphasises the need for methods and tools to support sustainable PSS development.

2.2.2 Cases of Sustainable Business Models

Two case studies in the manufacturing engineering sector are briefly presented here as examples of innovative business models that consider sustainability and generate sustainable value, despite being in a sector where continuous technological innovations and obsolescence tend to be key drivers for growth.

Riversimple

The car company is at an early start-up phase and was conceived to provide a personal and environmentally sustainable mobility solution encompassing technology solution and full service provision, adopting a total systems perspective. The company is based on a sale of service business model (PSS solution), which is about moving from resource consumption to resource efficiency. Current sales-based model rewards selling more and hence rewards the company directly for resource use; by shifting to a sale of service model the company retains ownership and responsibility of the vehicle and its operating costs for the product life and so is incentivised to design and build for durability, longevity, and efficiency in use, and end-of-life solutions. The company has an innovative governance model, where the company's stakeholder board elects the board of directors and executives. The stewards' board oversees the board of directors, and the custodian body represents the owners in limited partnership structure. This model is considered to assist in enhancing interactions and collaboration between stakeholders, to deliver sustainable value, by ensuring that financial interests are balanced with the interests of the other stakeholders.

It was observed that business modelling for sustainability in the company is ad hoc and driven by a visionary leadership. The breakthrough in the automotive industry, according to the founder, will come in the way a car is put together with the business model and delivery system (systems integration). It can be very powerful, particularly where there is a disruptive technology. The founder believes that for innovation in the automotive sector, the barriers are not really technological, but business and politics. Furthermore, the innovation is not in the individual component, but comes out of the synergy between the elements of the car (carbon fibre, fuel cells, ultra-capacitors, electric motors). However, with respect to the PSS solution there are significant questions around consumer adoption and ownership and how this might hinder the business model. The role of fashion and status and financial investment needs further understanding as these may represent significant barriers.

Elcon

Elcon is specialised to develop, market and produce uninterrupted AC and DC power systems, customised DC power supplies, DC/DC converters, custom tailored electronics and wireless solutions, while importing components for green power systems. The company's main focus is on solutions for energy and industrial plants. The battery backup systems are necessary to guarantee the 24/7 operation of critical devices also at any failure situations of the electrical mains network. Battery backed up DC power supply system solutions are being used in many power plants and stations, substations, and many other locations including, for example, an uninterrupted power supply of process automation. Elcon were interested in exploring and developing a service model for their business—new revenue streams through lease and reuse, and configuring the new value proposition with the potential new business model.

The development of business models for sustainability is a temporal process made up of a series of incremental activities building progressively towards a more completely integrated solution. It requires a long-term vision and focus on redesigning business models for value propositions that deliver sustainability. Companies adopt very different approaches to sustainability, but the common theme is that there is a business case for pursuing sustainability. Assisting companies in understanding the true scope of the impact of their activities on the broad range of stakeholders and identifying possible pathways to adaptation is only part of the challenge. A greater challenge is to persuade companies to do better when the business case is not so clear or when the payback period is unattractive.

In Elcon's case, 'the implementation of the new business model brought new challenges to the company's every-day operations. In order to respond to its value proposition, operational arrangements were made and new requirements for product development were identified. In this case operational changes were accomplished by networking with another manufacturing company. In this new setting the company's responsibilities are in operations related to sales, services, product and service design and development, while their partner is responsible for the manufacturing of the products.

2.3 Sustainable Value

At the core of the business model is the concept of generating value. The literature (Chesbrough and Rosenbloom 2002; Richardson 2008; Zott and Amit 2010) introduces the terminology of the 'value proposition' to describe the product/service offering that the company makes to its customers and other stakeholders for which it receives payment and aims to return a profit.

A holistic view of the value proposition requires active consideration of all stakeholders who are influenced directly or indirectly by activities of the firm (Rana et al. 2013). The key stakeholders discussed frequently in relation to sustainability include suppliers and partners, society, environment, suppliers, customers, investors and shareholders, governments, international organisations, non-government organisations (international and local) and the media. All business relationships include not only formal contractual activities, but also informal value exchanges of information and benefits. Greater visibility of all the value flows within a network potentially provides insights for innovation and improvement. Allee (2011) discusses the importance of tangible and intangible value flows in network. Understanding of intangible flows is important in understanding network relationships and identifying opportunities for further collaboration, including environmental and social aspects.

Sustainable value is defined as the well-being, improvement, continuity and preservation of the individual (human life), company, society and environment, in such a way that satisfies the needs of the present without compromising inter-generational equity. It is conceived as 'environmental' sustainability which covers sustainable use of natural resources, biodiversity conservation, recycling of waste and pollution, and provision of additional ecological services such as climate regulation, pollination, and enhancing soil fertility; 'social' sustainability is concerned with issues such as stakeholder participation, responsibility, labour standards, human rights, community relations, welfare, culture, poverty alleviation and equality; and 'economic' is concerned with traditional measures of financial profitability, risk management, and long-term economic viability or continuity of the company.

3 Conceptual Model of Engineering for Sustainable Value

In order to build a conceptual model of engineering for sustainable value, the authors further explored the existing literature and developed three key factors as below.

3.1 Factor 1: Life Cycle Value Creation

Life cycle thinking has been regarded as an essential concept for sustainable engineering in a holistic way. It seeks to identify possible solutions of improving goods and services by reducing resource use and environmental impacts throughout the entire product life cycle (European Commission 2011). The product life cycle can be divided into beginning of life (BOL), middle of life (MOL), and end of life (EOL) (Jun et al. 2007), as shown in Fig. 1. BOL is when the product is designed and manufactured; MOL is when the product is distributed and used; EOL is when the used product is reprocessed (e.g. recycled, reused, remanufactured) and disposed. Traditional manufacturers usually focus on the value creation in BOL since selling products is their main source of profit. The nature of sustainable business models extends the business relationship between manufacturer and customer from BOL to MOL and EOL, and thus brings more opportunities of value creation in MOL and EOL. For example, PSS business models could enable a long-term

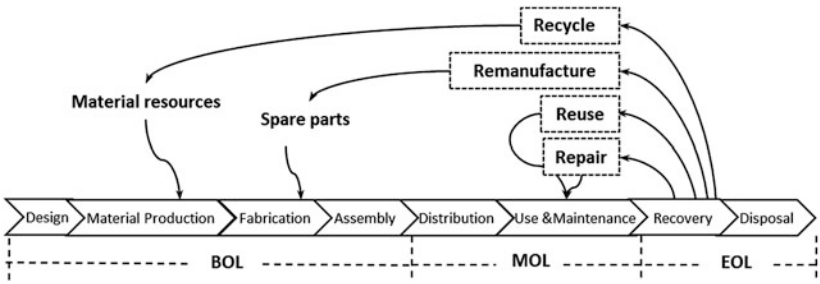

Fig. 1 Life cycle value creation, developed from (Jun et al. 2007)

profit for manufacturers from service, allow their access to data in use, and could achieve an improved utilisation of product. This motivates manufacturers to identify the opportunities of sustainable value creation in MOL and EOL (Toossi 2011).

3.2 Factor 2: Sustainable Value Analysis

Value refers to a broad set of benefits derived by a stakeholder from an exchange, which, in the context of sustainability, does not only include monetary profit, but also include social and environmental aspects (Rana et al. 2013). Figure 2 shows the three dimensions of sustainability and their interactions. Many researchers suggested that a sustainable manufacturing needs to take all three dimensions of sustainability into consideration (Maussang et al. 2009; Morelli 2002; Sakao et al. 2009). Sustainable value should cover all three dimensions, and sustainable value creation is proposed as a promising way of integrating sustainability into business modelling (Rana et al. 2013). Therefore, the concept of sustainable value could be integrated into engineering in order to also consider environmental and social aspects of benefits.

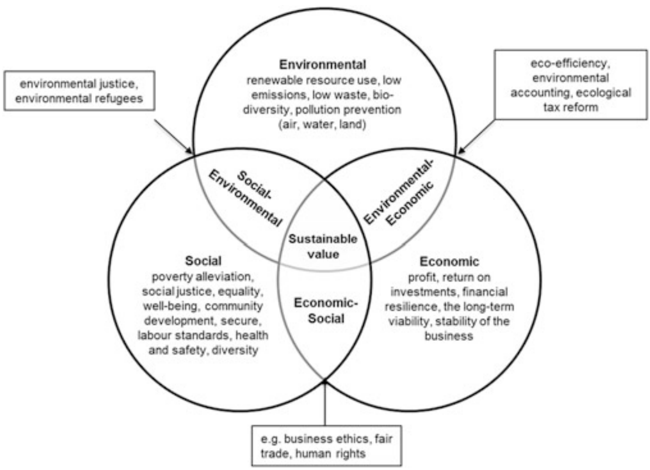

Fig. 2 Sustainable value (Yang 2015)

3.3 Factor 3: Comprehensive Forms of Value Analysis

This factor comes from the 'value mapping tool' for sustainable business modelling (Bocken et al. 2013). The value mapping tool has been successfully used in companies from various sectors, aiming to assist companies in the analysis and design of sustainable business model. This tool proposed the concepts of value destroyed and value missed to present the negative aspect of current business model. The rationale of this tool is that by analysing various forms of value companies can identify value creation opportunities through analysing value exchanges from the perspective of multiple stakeholders across the industrial network (Bocken et al. 2013; Short et al. 2012).

Based on this rationale, Yang (2016) further proposes value uncaptured, as a new perspective for sustainable value analysis. Value uncaptured is defined 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 were proposed as shown in Fig. 3 (Yang 2015; Yang et al. 2013).

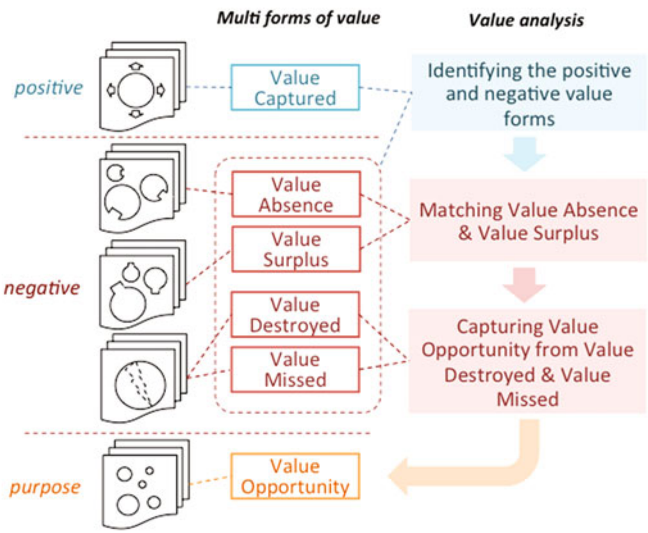

Fig. 3 Comprehensive forms of value analysis (Yang 2015; Yang et al. 2013)

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. Figure 4 introduces the different forms of value uncaptured and explains how value uncaptured can trigger the identification of value opportunities.

The *Factor 1* and *Factor 2* are commonly presented in sustainability literature, while the *Factor 3* is newly proposed as a way of value innovation in our work. We believe that the analysis of multiple forms of value could be applied to support the development of sustainable engineering. Thus, we propose that the three factors could be combined to build a conceptual model of engineering for sustainable value as shown in Fig. 5.

This conceptual model aims to improve the understanding engineering for sustainable value by analysing comprehensive forms of value across the entire produce life cycle through the dimensions of economic, social, and environmental sustainability.

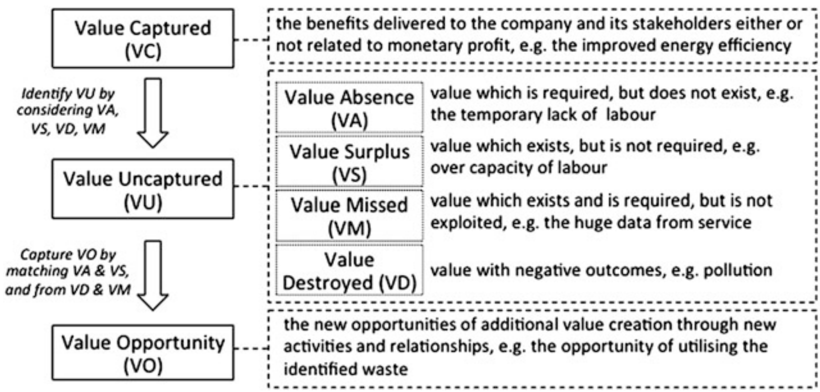

Fig. 4 Multiple forms of value uncaptured (Yang 2015)

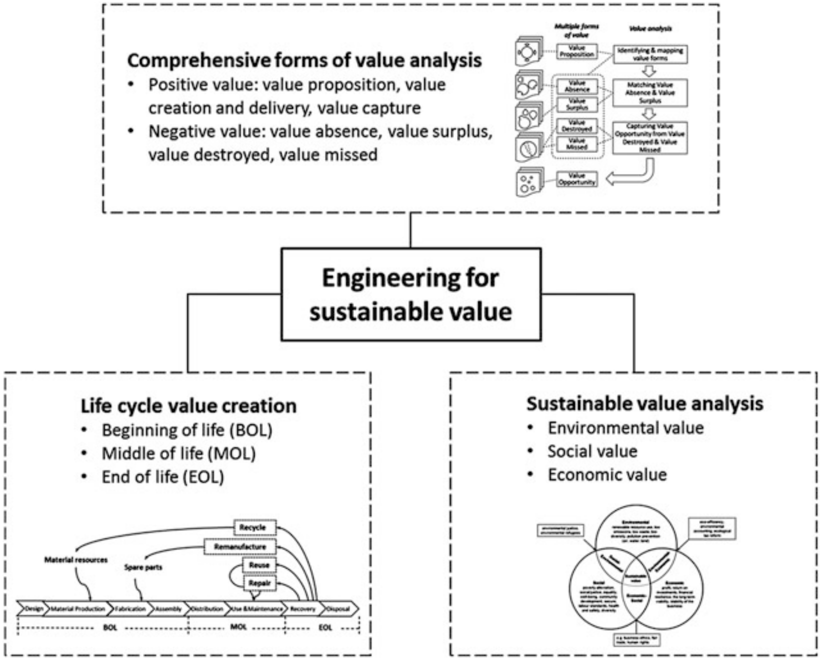

Fig. 5 Conceptual model of engineering for sustainable value

4 Sustainable Value Analysis Tool: A Tool for Engineering for Sustainable Value

Based on the conceptual model, SVAT is built to help manufacturers analyse multiple forms of value (including value uncaptured) across the entire product life cycle, and then to identify new opportunities for sustainable value creation. Identifying the value uncaptured and creating value from it is not always easy. SVAT is proposed to support this process, providing companies with a scheme to systematically look for each form of value uncaptured (i.e. value surplus, value absence, value destroyed and value missed) at the beginning, middle and end of the product life cycle, and with a method to turn the identified value uncaptured into value opportunities (Yang 2013).

Seven interviews and workshops with eleven managers/directors from five engineering companies were conducted to validate the conceptual model. Several common key feedbacks emerged:

- The life cycle thinking provides an extended view to look at the value creation opportunities at MOL and EOL, which is currently missed in most companies.
- The concept of value destroyed—negative value outcome—is clear. This concept could help identify the negative impacts to the environment and society. However, the concept of value missed needs further clearness—value currently squandered, wasted, or inadequately captured by current model. Besides, selling service is intangible, flexible, and unpredictable, and therefore requires a broader analysis on more value forms to identify the hidden value opportunities. The value surplus (e.g. waste) and value absence (e.g. need) proposed by the interviewers were regarded as helpful value forms.
- The conceptual model provides the interviewees a systems way of thinking about the economic, social, and environmental dimensions of a particular solution in the whole life cycle. A common interest to use a practical tool based on this conceptual model was raised from all of the five companies.

4.1 Development of Sustainable Value Analysis Tool

Based on the conceptual model and empirical validation in industries, SVAT is designed to help engineering companies identify opportunities to create sustainable value by analysing the captured and uncaptured value throughout the entire life cycle of products. The rationale of SVAT is to discover value opportunities by identifying and analysing value uncaptured (see Fig. 6).

It is not easy to identify value uncaptured in practice, so different forms of value uncaptured, i.e. value absence, value surplus, value destroyed, and value missed, is used to inspire the identification of value uncaptured. It is also difficult to discover value opportunities from value

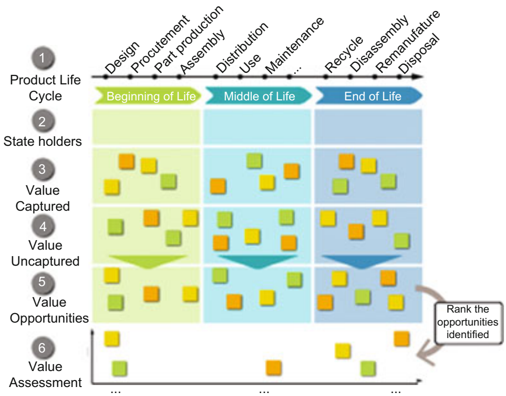

Fig. 6 Rationale of sustainable value analysis tool (Yang 2015)

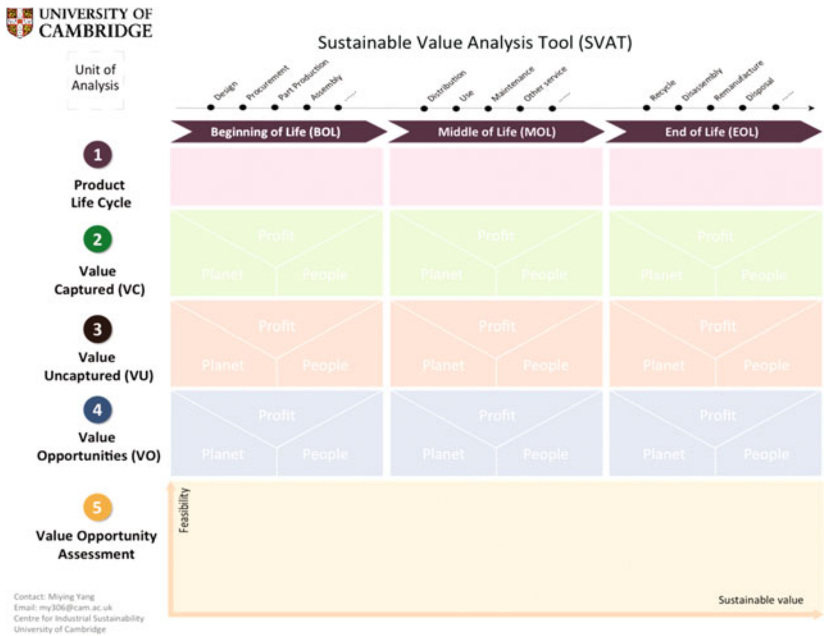

Fig. 7 Poster of sustainable value analysis tool (Yang 2015)

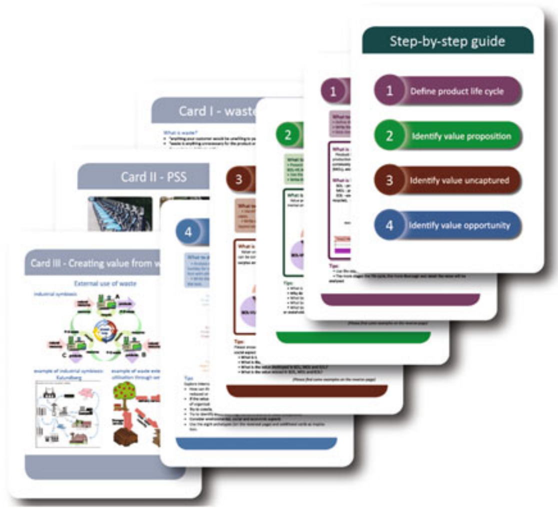

Fig. 8 Cards of sustainable value analysis tool (Yang 2015)

uncaptured, and different mechanisms are used to guide the process, e.g. by aligning value absence and value surplus, and reducing value destroyed and value missed.

SVAT consists of a poster (see Fig. 7) and a set of cards (see Fig. 8 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. 7, the tool combines the concepts of *life cycle thinking* and *value forms analysis*. A product life cycle could be divided into three phases: beginning of life (BOL), middle of life (MOL), and end of life (EOL). The three phases could be further divided into more specific stages. For example, MOL can be further divided into distribution, use, maintenance, and service. The value forms 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.

SVAT consists of five steps. 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.

4.2 Use of Sustainable Value Analysis Tool

This SVAT can be used in facilitated workshops with managers, designers, or engineers in companies. It can be a stand-alone tool without support from other tools and can also be complementary to engineering tools or management tools. For the former case, the tool can be used to support decision-makings by identifying the value forms in the current business. For the latter case, the tool can be used during the conceptual design of product and service to support the integration of sustainability into PSS design.

Before using the tool

The industrial participants were asked to describe the current business model in their company. The researcher described the concepts and rationales underlying SVAT, explained the purpose of the tool and how to use it.

The process of using the tool

Step 1 *Define product life cycle*
The participants were asked to subdivide their product life cycle into more specific stages, depending on the depth of analysis desired and the time available. The more stages the life cycle is divided into, the more thoroughly the value will be analysed, but the more time-consuming it will be.

Step 2 *Describe the value captured*
Prompting questions and examples are provided on the card for Step 2. Users are encouraged to explain the economic, social, or environmental value they have identified, write them on post-it notes, and put them on the poster. Any value that involves more than one dimension should be placed on the boundary between them. For example, using recycled and healthy materials in BOL is considered valuable in terms of both social and environmental sustainability. These data therefore need to be posted on the boundary between the environmental and social dimensions.

Step 3 *Identify the value uncaptured*

This step included identifying the *value uncaptured* at each phase of the life cycle (i.e. BOL-VU, MOL-VU, and EOL-VU). The identification of *value uncaptured* involved identifying VS, VA, VD, and VM.

The researcher played a key role in helping the participants to identify the invisible and hidden *value uncaptured*. Firstly, the use of the tool requires both facilitator and practitioners to have substantial knowledge and experience of the entire product life cycle. Secondly, due to the intangibility and flexibility of service provision, the identification of hidden *value uncaptured* in MOL and EOL is difficult because the practitioners might not be aware of this concept. For example, many companies were not aware of redundant services as part of value destroyed. Therefore, facilitated brainstorming sessions were required, with practical examples, to provide inspiration and guidance.

Some *value uncaptured* could cover more than one dimension of sustainability. For example, 'no recycling and remanufacturing strategies' represents *value uncaptured* both in the economic and the environmental dimensions at the EOL stage. The particular advantage of considering the overlapping areas of the three dimensions is that it can help companies to identify *value uncaptured* across two or three dimensions of sustainability

Step 4 *Identify value opportunities*

Once the previous steps had been completed, the captured or uncaptured value was added to the table. The life cycle stage with a substantial concentration of value uncaptured could then be identified. The interviewer then helped the interviewees to analyse the root causes for this value uncaptured and the ways in which value might be created, inspiring the participants to explore opportunities for value creation.

It should be noted that the techniques used at this stage of tool development were still notional and lacked strong empirical evidence. This suggested there was a need to identify new techniques by building up experience of using the tool.

This step is similar to Step 4 for SVAT v1 and v2. The main difference is that by this stage the researcher had gained more facilitation experience and collected more examples and techniques to stimulate the users to identify value opportunities.

Step 5 *Assess the value opportunities*

The identified value opportunities (potential solutions) can be assessed briefly by discussing their impact on economic, social, and environmental areas. The opportunities offering high sustainable value can be selected and further analysed from the perspectives of feasibility, effectiveness, and ease of implementation. This provides a means of ranking the value opportunities.

It should be noted that in the context of sustainability, value does not only mean economic benefit, but also includes social and environmental aspects (Rana et al. 2013). Therefore, each value form needs to be considered from the three dimensions and their intersections.

The feasibility, usability, and utility of SVAT has been tested in a number of companies. Now the tool has been well received in 35 engineering companies across various sectors and of various sizes. It helped them find opportunities to create value internally and to discover the potential of creating mutual value externally. The tool has also been used for other purposes such as research, consultancy, business education, and university education.

5 Case Studies

The tool was used for case studies in an Air Separation Unit manufacturing company in China. The main business of this company is selling air separation units, petrochemical equipment, and industrial gases. This company has a yearly capability of designing and manufacturing more than 50 sets of large and medium air separation units sold to more than 40 countries and regions of the world. The reason of choosing this company is that it has successfully transformed from a traditional product-dominant manufacturing company to a company selling various types of PSS business models.

5.1 Business Model of This Company

Four main PSS business models have been implemented in this company. According to the classification of PSS types proposed by Tukker (2004), there are mainly four PSS solutions in this company as below.

1. *Technical service:* Apart from just selling air separation equipment to customers, this company provides technical services as added package to their products, such as maintenance, repair, and installation. This is the product-oriented PSS, and also the most common business model in this company.
2. *Special leasing:* This company leases the air separation units to customers, and the contract usually lasts for 10 years. During the contractual years, this company provides technical service to customers. After a certain amount of years, the ownership is transferred to the customer and a new contract will be made. Leasing contracts are not common in this company. They are mainly tailored for customers without the fanatical ability to buy equipment or build projects.
3. *Engineering procurement construction (EPC):* A subsidiary company was built to especially run EPC projects on April 2009. The main strategy of EPC in this company is extending the business from only selling a gas generator to selling an entire functional air separation system that customers need. The system includes the engineering system design, the procurement and production of facilities (e.g. refrigerator, compressor, fittings, rectifying tower, heat exchanger), the engineering construction, the installation of equipment, and related service (management, maintenance, etc.). EPC has generated big profit to the company and been regarded as their business trend.
4. *Industrial gas projects:* This is a result-oriented PSS that the company selling 'industrial gas' rather than 'gas generator'. This company

started the industrial gas projects in 2003 and has developed its own business model—combining air separation unit manufacturing and industrial gas management. Until 2012, 25 sub-gas companies have been built in 17 cities in China, reaching 980 km^3, covering the various industrial sectors, and producing gases such as O_2, N_2, CO_2, H_2, rare gases (Ar, He), and special gases. The investment is above 6.5 billion RMB. There are four commercial activities of providing gases: bottled gas, liquid gas and cold air separation of liquid, gasification, and pipeline industrial gas supply for industrial parks.

5.2 Using SVAT to Identify Value Opportunities in the Company

The SVAT was used with the director and two engineering designers from the engineering design sector of this company.

- The life cycle of the main products was defined as: BOL—customised design, procurement, part manufacturing, assembly; MOL—distribution, installation, use, maintenance, repair, management; EOL—disposal as scrap metal.
- The main value proposition was mainly identified at BOL and MOL phases. For example, the advanced technology has improved the energy efficiency; the customised design at BOL provided a better fulfilment of customer satisfaction; the PSS solutions brought long-term economic value to the company, and saved cost for customers, etc.
- The value uncaptured mainly existed at MOL and EOL phases. The company has implemented lean production, and there was little value uncaptured identified at the BOL. However, it has not taken any EOL strategies due to the limited market demand and high cost of recycling and remanufacturing. Also, the participants' awareness and knowledge of EOL is limited, so the value analysis in EOL is challenging. So, the

Table 1 Examples of identifying value opportunities from value uncaptured and their assessment

Value uncaptured	Value opportunities	Sustainability			Internal/External	Potential partners
		Economic	Environmental	Social		
Over-staffing	Reduce staffs	+	0	−	Internal	NA
	More work for company	+	0	0	Internal	NA
	More work for customer	+/0/−	0	+	External	Customer
Emissions of customer companies	Provide emission reduction solution to customer (RPSS)	±	+	+	External	Customer
Maintainers working far away from home if the projects are located in other cities	Hire local employees	±	+	+	External/Internal	Customer
	More holiday for far staff	−	−	+	Internal	NA
Co-products, e.g. N_2, O_2, Ar, liquid O_2, liquid N_2	Ar can be used for welding, and bulbs gas; O_2, N_2, etc. could be complementarily used for companies who need it;	+/0	+	0/+	External	Bulb company, etc.
Gold gas: Kr, Xe, etc.	The gold gases can be used in military industry, lamination;	+/0	+	0/+	External	Lamination company, etc.
High-purity O_2 and N_2	High-purity O_2 and N_2 can be used in electronic industry;	+/0	+	0/+	External	Electronic company

(continued)

Table 1 (continued)

Value uncaptured	Value opportunities	Sustainability			Internal/External	Potential partners
		Economic	Environmental	Social		
The waste of mechanical energy of expansion engines	The expansion movement can produce electricity to directly drive the engine itself or other engines.	+	+	0	Internal	NA
The waste of heat produced by the compressor	The wasted heat can be used to produce electricity or drive the compressor or vaporise the liquid O_2.	+	+	0	Internal/External	Steam turbine company

use of the tool is mainly focused on the identification of value uncaptured in MOL phase. The first column of Table 1 illustrates the selected identified value uncaptured at MOL in this company based on a sample of the data collected.
- Each of the main identified values uncaptured was analysed, and the value opportunities (potential solutions) were identified as shown in the table. For example, the value opportunity for the co-products (e.g. N_2, O_2, Ar, liquid O_2, liquid N_2) is identified to be that: Ar can be used for welding and bulbs gas (externally); O_2 and N_2 could be complementarily used for companies who need it (externally). The difficulty of this implementing the value opportunity is to identify and collaborate the 'external' company that the company can work with.

The tool has helped the company to identify value uncaptured and turn it into value opportunities. For example, the waste of low-grade heat and water was identified to be a major value uncaptured in the MOL, and the value opportunity is that it can be used to produce electricity or drive the compressor, or vaporise the liquid O_2. It can both be realised by the company internally or externally. Another example of value uncaptured is the waste of heat produced by the compressor. This is low-grade heat, which is difficult to reuse. The opportunity was identified to use the wasted heat to produce electricity or drive the compressor or vaporise the liquid O_2, which could bring positive economic and environmental impact. The company further analysed and found that a local steam turbine company could be the partner to implement it. Using the tool provides the company a broader vision that value opportunities could be identified by analysing the positive and negative aspects of the current business model.

6 Conclusion

This chapter proposes a conceptual model of engineering sustainability, using engineering for sustainable value and SVAT for this purpose. The concept of value uncaptured provides a novel way to improve engineering sustainability in the context of high value engineering.

The research contributes to theory by proposing that the combination of the three key factors—life cycle value creation, sustainable value analysis, and comprehensive forms of value analysis—could support the integration of sustainability into engineering operations. Life cycle thinking provides a holistic picture of the product from a design concept to the disposal, which allows for a system approach to examine the value creation in each stage. Sustainable value emphasises the combined consideration of environmental, social, and economic aspects of sustainability, which allows for the integration of sustainability concerns into value analysis. The multiple forms of value include value proposition and value uncaptured (i.e. value surplus, value absence, value missed, value destroyed), which allows for a thorough and comprehensive analysis of the positive and negative aspects of current business throughout the life cycle.

The chapter contributes to engineering operations practice by presenting the SVAT that integrates the three factors. This tool is developed to support engineering companies in their decision-making process to embed sustainability into the development of product–service systems. The tool is built upon a multi-disciplinary literature analysis and qualitative data from semi-structured interviews and workshops in five companies. The feedback of using the tool further confirms the need for developing a simple, usable, and workable tool for supporting the decision-makings in high value engineering areas, and for integrating sustainability into the consideration of this process.

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