Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 69 (2018) 25 – 30

www.elsevier.com/locate/procedia

25th CIRP Life Cycle Engineering (LCE) Conference, 30 April – 2 May 2018, Copenhagen, Denmark

Product life cycle design for sustainable value creation: methods of sustainable product development in the context of high value engineering

Jing Tao, Suiran Yu*

School of Mechanical and Power Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, PR China

* Corresponding author. Tel.: +86-21-34206057;. *E-mail address:sryu@sjtu.edu.cn*

Abstract

This study proposed a framework for sustainable product development in the context of high value engineering, using life cycle based approaches combined with methods of sustainable value modeling and analysis. A Sustainable Value model was proposed based on the understanding of Value from economic, social and environmental perspectives. Then, a QFD-based approach of life cycle scheming driven by sustainable value requirements was proposed for generating product concepts and life cycle plans of total high value, while Life Cycle Simulation was employed for modeling complicated close-loop type product life cycles and evaluation of sustainable values. The proposed framework may help bring experts in fields of product and process engineering, industrial management and ecological assessments to a common vision, and therefore accelerate design convergence for more sustainable products, processes and business.

Peer-review under responsibility of the scientific committee of the 25th CIRP Life Cycle Engineering (LCE) Conference

Keywords: Sustainable Value, Life Cycle Engineering, QFD, Discrete Event Simulation

1. Introduction

Competition in the modern global economy relies on gaining superior engineering capabilities to create high value added products and services rather than focusing solely on the output of manufacturing. This leads to a new knowledge area of increasing importance-high value engineering, which is focused on how to effectively create value through engineering excellence in the current business environments and for the future. With growing demands for sustainable products, there are clear implications for developing high value engineering capabilities from the perspectives of industrial sustainability. There is an urgent need to develop process and tools to better integrate sustainability into global value chain [1]. Sustainable value implies profits, improved environmental performance and safety amongst other parameters in an organization. The aim of a value-based managed organization is to create value, manage value and measure value to create more value based on the identified improvement potential [2]. However, the question arises as existing value concept and definitions sufficient when viewing values form broader perspectives of sustainability. Just to quote: Long-term thinking has to be instilled; old fashioned value perspectives have to be refreshed so that a sustainable growth and survival becomes realistic [3]. Thus, a broad view of what makes product and services "valuable" and competitive in the market with growing concerns of sustainability should address all the significant ways in which attributes of the product impact interests of involved partners.

Sustainable Value refers to a broad set of benefits derived by a stakeholder from an exchange, which, in the context of sustainability, do not only include monetary profit, but also include social and environmental aspects [4, 5]. In the research of Henriques and Catarino[6], a Sustainable Value concept was proposed using the synergies between tools from Value Management, Value Analysis and from Eco-efficiency, Cleaner Production, resulting in an indicator that integrates the three aspects of Sustainability: economic, environment and social and enables the monitoring of the evolution of those aspects in

Peer-review under responsibility of the scientific committee of the 25th CIRP Life Cycle Engineering (LCE) Conference
doi:10.1016/j.procir.2017.11.099

a company. The philosophy behind this concept is the delivery of products and services that satisfy human needs at lower costs while reducing the ecological impacts and resource intensity. Study of Baldassarre et al [7] was focused on the business model innovation for achieving sustainable development. Their research aims to develop more successful, radical and user-centred sustainable value propositions, which is the core of a sustainable business model, by combining principles from both sustainable business model innovation and user-driven innovation. It is inevitable that some judgements and decisions must be based on hard numbers and quantitative assessments. This naturally leads to a question that "how can the sustainable value be evaluated and compared in order to reach a decision". Figge and Hahn [8] proposed a Sustainable Value model aims at the quantitative assessment of the value-creating use of environmental, economic and social resources. The approach can be used to answer the financial-economic question of "where environmental and social resources should be allocated in order to achieve an optimal overall return". Mastre and Vogtlander [9] proposed an indicator for eco-efficient value creation, which is the Eco-cost/value ratio (EVR). In their study, eco-costs was used as a single indicator in LCA for the environmental burden of a product, while market price is used as value for existing products and the Willingness to Pay(WTP) for products not yet on the market. The EVR was developed to link production side of the environmental problems (i.e. make products with lower eco-costs) to the consumer side (i.e. give green products a higher value so that customers will buy it). Then, eco-efficient value creation for the product system was addressed by analysis and reduction of EVR. However, the common disadvantage of the above mentioned two studies is lacking of value perspectives of various involved stakeholders throughout the value chain. That is, to maximize the overall value of the value chain, it is important to identify, in the first place, what is value to different stakeholders involved in the business.

It is found that sustainable value and/or sustainable value creation are generally studied from managerial perspectives such as business strategy making and business model innovation. Business strategies and models need to be continuously cross-linked to engineering activities to adapt to the ever changing market environment and vice versa. The awareness of sustainability concepts and applying these concepts to products, processes and services holistically require engineering capabilities. That is, instead of looking at the implementation of single elements, engineers must be aware of multiple interactions among value creation factors (i.e. product, process, service), life-cycle stages (i.e. design, manufacturing, use and EoL), and sustainable principles of engineering practices (i.e. reduce, recycle, remanufacturing). It is important that engineering activities bring value, and engineers should properly comprehend value demands and integrate them into their daily work. Given the existing researches, we found that there are still needs for 1) better conceptualities of sustainable value that taking both the desires of involved partners throughout the value chain and equally important the interests of the environment and 2) approaches and tools that translates sustainable value demands into terms that are immediately meaningful to design engineers. To address the above problem, this study proposes a novel approach to guide engineers on how to achieve sustainable solutions that respond to both requirements of high value creation and environmental concerns by sustainable innovation.

2. Development of Sustainable Value Model with multi-view of sustainability and perspectives of different stakeholders throughout product life cycles

Sustainable value requires performance on multiple dimensions:

Sustainable value=total satisfaction of value requirements from perspectives of economic, social and environment

$$V_{sus.} = f_{eco.}(vr_{eco.}, S_{LC}) + f_{soc.}(vr_{soc.}, S_{LC}) + f_{env}(vr_{env}, S_{LC}) \quad (1)$$

where,
$V_{sus.}$: Sustainable value ;
S_{LC}: Sustainable product life cycle solution;
$vr_{eco.}$: Economic value requirements;
$vr_{soc.}$: Social value requirements;
vr_{env}: Environmental value requirements;
$f_{eco.}$: Evaluation function of economic value requirement satisfaction ;
$f_{soc.}$: Evaluation function of social value requirement satisfaction;
$f_{env.}$: Evaluation function of environmental value requirement satisfaction.

$$f(vr, S_{LC}) = g(\Delta\left(vr_{target}(S_{LC}), vr_{estimate}(S_{LC})\right)) \quad (2)$$

in which,
$vr_{target}(S_{LC})$: Target value settings of value requirement indicators;
$vr_{estimate}(S_{LC})$: Estimated (or evaluated) value of value requirement indicators;
Δ: Difference between the estimated and target value of VR indicators;
g: Evaluation function based on Δ.

The keys to understand and make use of the proposed sustainable value model include the concept of Sustainable Value Requirement (SVR) and value requirement satisfaction. First, value can be economic and/or social and/or environmental demanded by customers and/or businesses to fulfil the customer's requirements and/or to achieve strategic goals. Value requirements are the demands for the value by both customers and businesses. These requirements are related to sustainable value based on it dynamics in the sustainable value frame (i.e. Ref[[10]).

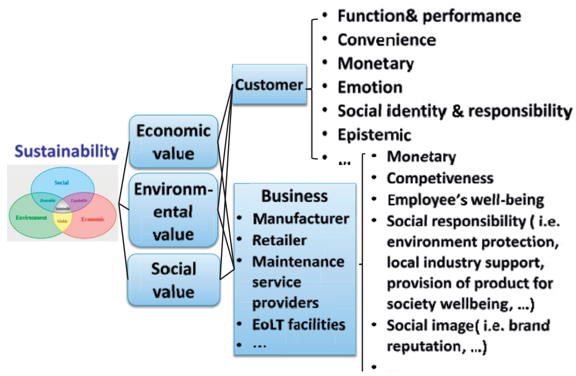

Fig.1 Sustainable value requirements

Therefore, combining the multi-views of sustainability and perspectives of different stakeholders, SVRs can be categorised into 6 major groups as shown in Fig.1, including consumers' economic, environmental and social value requirements, and business economic, environmental and social value requirements. The ultimate goal of sustainable value engineering is to maximize the overall value perceived by different stakeholders by increasing level of satisfaction of value demands. SVRs answer to the critical question of **WHAT** is valuable to different shareholders.

3. Proposal of sustainable value-driven Life Cycle Design (LCD) framework

With the growing concerns of sustainability, sustainable product development is taking on a greater role. Proper sustainable product development helps to use a company's resources, usually in terms of materials and energy in the most economical way, which implies the least environmental impact. This constitutes a benefit for both, the organization and their customers at the same time. Life Cycle Design (LCD) is a promising approach for reduction of environmental impacts and promotion of product performance throughout its life cycle. LCD requires a structural change of design; namely, while designers traditionally are focused on designing just products, now they should design their life cycles. In this study, the framework for sustainable-value driven life cycle design is proposed (Fig.2) by integration of life cycle thinking and sustainable value concepts. The concept of "domain" [11] is introduced to the framework as one of its fundamental element. Three design domains which are sustainable value requirements (SVR) domain, the design requirements (DR) domain and the technological solution domain are then constructed. Sustainable-value driven life cycle design is then organized as the structured and strategic mapping course of sustainable value requirements to both artifact-and process-focused design requirements, and then into engineering characteristics of product life cycle which include both artifact concepts and life cycle plans. Furthermore, in order to realize an integrated design, the consistency between the artifact concepts and life cycle plans should be carefully managed during the second stage of the design course.

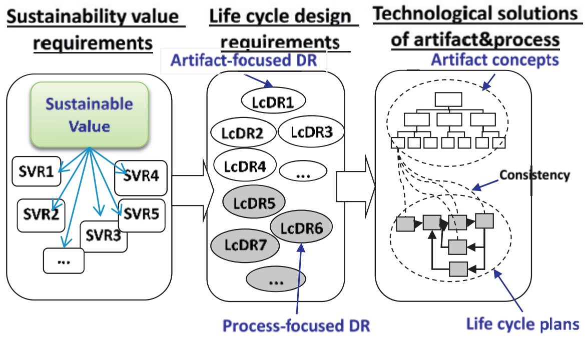

Fig.2 Sustainable value-driven Life cycle design: Methodolgical framework

■ Life cycle design requirements (LcDRs)

Design requirements also known as **HOWs** of life cycle engineering capabilities to fulfil the 'value' requirements. LcDRs are categorized into artifact-focused and process-focused DRs. Artifact-focused DRs are those on product itself including function and performance, quality, structure, appearance, material, cost, etc, while process-focused DRs are those on various activities associated with the product throughout its life cycle (Fig.3).

■ Life cycle solutions

Life cycle solutions includes both artifact design concepts and its life cycle plans. In the stage of life cycle solution generation, artifact design concept (ArfD) tells the basic structure of product such as major components and their key engineering characteristics such as material, weight, shape, etc. A hierarchical product model can typically characterizes the artefact concept. The life cycle plan here is characterized a set of life cycle engineering options (LCEOPs). LCEOPs include measures to close the life cycle loop such as reuse, remanufacturing and recycle, as well as other measures such as computer aided design (CAD), eco-design, cleaner manufacturing and logistics, which potentially contribute to sustainable value creation throughout product life cycle (Table 1).

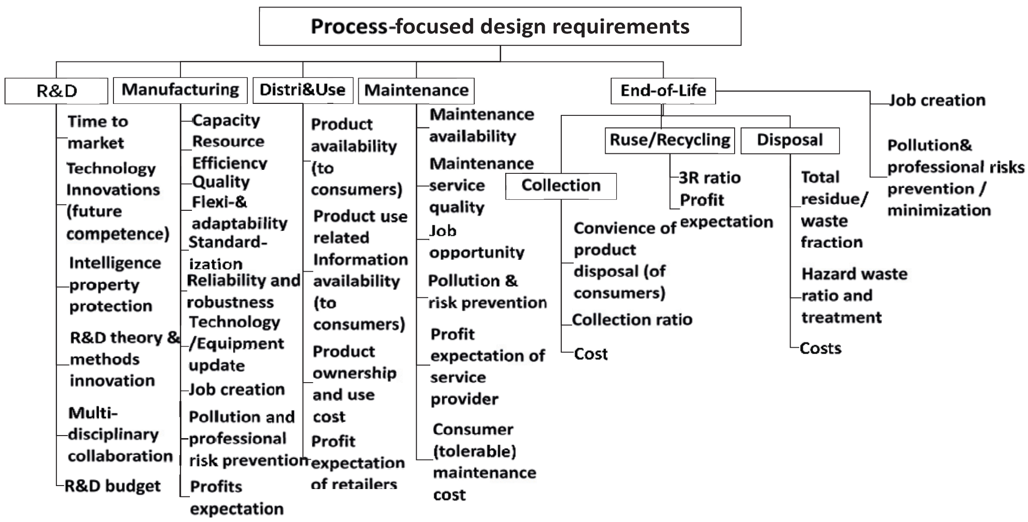

Fig. 3 Process-focused LcDRs

4. Generation of sustainable life cycle design solutions by QFD-based approach

In this study, a QFD-based method is proposed to realize the sustainable value driven LCD framework. As shown in Fig.4, the modified QFD creates two interlinked mappings. The first mapping starts with SVRs (inputs) and then translates these requirements into LcDRs. The second mapping follows through these LcDRs and translates them into the artefact design concepts (ArfDs) and LCEOP attributes. The ArfDs and LCEOPs are linked to the LcDRs in the second HoQ. The correlation matrix in the second HoQ is divided into three matrices: two self-correlation matrices of ArfDs (i.e. module, part, component, etc.) and LCEOPs, and one attaching matrix between each ArfD and LCEOP. The calculation of the weight of LcDRs, artifact and life cycle plan solutions is the same as that of the conventional QFD. By the proposed QFD approach, it can be convenient for the designers to conduct systematic analysis. Designers can quantify the strength of relations between SVRs and engineering characteristics of artifact and its life cycle plans, as well as those between artifact and life cycle plan, i.e. components and its adaptive life cycle engineering options.

5. Life Cycle Simulation-based sustainable value driven product life cycle design evaluation

LCS makes it possible to estimate the effectiveness of circulation of product, components and materials, as it can simulate the flows of material, energy, information, and cost in product life cycles [12-14]. In this study, product life cycle is considered as a complex system including product entities, process and stakeholders. Indeed, the dynamics of the life cycle system are characterized by various interactions between product entities, process and stakeholders. Simulation methods are used for the description of how product, process and stakeholders interacts (with consideration of various stochastic factors in the system), and for estimation of results (i.e. VR indicator) of the interactions. With LCS，engineers can have more in-depth understanding of how product design and life cycle engineering decisions affecting the sustainable value of stakeholders in the life cycle system. Thus, LCS as a powerful tool of describing and analysing product life cycles can effectively handle the complexity and innovation in sustainable value driven product life cycle design.

A product life cycle design evaluation model based on LCS is proposed in this study (see Fig.5). It includes three major components, the life cycle builder, the simulator and the evaluator. The life cycle builder consists of sub-models of stakeholders, product and process. The stakeholder model contains information of preferences and behaviour characteristics of different stakeholders (i.e. consumers, manufacturers, retailer and wholesaler, etc). This information is important to modelling the dynamics of product life cycle. For instance, consumer's preference of product (i.e. preference of price, tolerance of maintenance cost, tolerance of function deterioration or outdate) is deterministic to their actions of product purchase and disposal. For another instance, both consumer and corporate's preference of recycled material or remanufactured parts affect the total resource recirculating rate. The product model contains information of product hierarchical structure, material composition, function deterioration and designed lifetime. The process model contains information of product life cycle process network which describe the sequential or conditional relations between various unit process of product life cycle, and the environmental (i.e. materials, energy, emissions) and economic input and outputs of each unit process.

Table 1 Life cycle engineering options and attributes

Life Cycle Engineering Options(LCEOPs)-Attributes	
Sustainable R&D	● CAX utilization (i.e CAD, CAE) ● PLM\PDM utilization ● Ecological assessment (i.e. LCA) employement ● Adoption of Industiral and company standards ● Patent applications and management ● ……
Sustainable manufacturing	● Energy efficiency improvements(%); ● Material efficiency improvement (i.e.Use of recycled material/ reconditioned parts) (%wt); ● Pollutions prevention methods; ● ……
Sustainable Distribution&Use	● Ownership: Purchase;Leasing; ● Distribution channel: Internet sales; Store sales;… ● Logistics service choice & efficiency; ● Pricing stategy; ● ……
Sustainable Maintenance	● Maintenance Strategy(i.e.warranty, etc.); ● Upgrade Strategy(i.e availability to uprade service); ● Maintenance service standards (i.e. Trainning of maintenance stuff; Specialized equipments and tools,etc.) ● Pricing stategy ● ……
Collection of used products and components	● Colletion service choice; ● Logistics service choice; ● Pricing stategy; ● ……
Reuse/Recycling	● Disassembly plan & efficiency(i.e. disassembly time,etc) ● Reburishing/recycling technologies; ● Reuse choice: installation reuse/maintenance reuse/ global resue; ● Recycling choice: product manfucturing/global ● Ratio of poison residues; ● ……

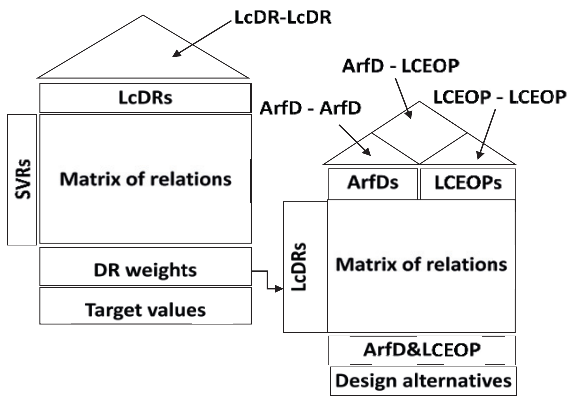

Fig.4 QFD for sustainable value-driven life cycle design

Second, a life cycle simulator is developed based on discrete-event system simulation theory. For a typical instance of discretely manufactured products, the dynamics of life cycle process is as followed: the manufacturing process is executed on the order of new products. Components can be manufactured using recycled materials (according to manufacturer's reference) provided by the recovery process. Product can be assembled using either newly manufactured components or reusable ones. After the product's arrival at an end user, the use process is initiated. The usage of products is terminated due to product obsolescence, and interrupted by product failures or planned maintenance. Product obsolescence occurs at the end of product useful lifetime or due to failures. Some of the collected products are disassembled, inspected, and recycled or reconditioned according to the life cycle plan. The maintenance process is executed on requirements of repair or scheduled conditioning. Either new or reusable ones could replace the failed parts. The failed parts are either to be recycled or just disposed. The life cycle design alternatives are evaluated based on the simulation outputs which generally include resource and energy demands, waste and emission amount, recovery rate, recycling and reuse rate, end user costs, corporate costs and profits.

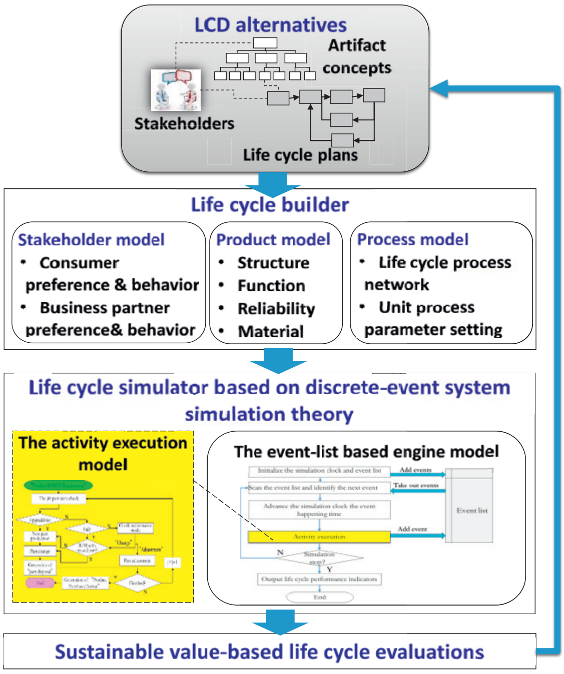

Fig.5 Product life cycle design evaluation by LCS

6. Case study

In this case study, the proposed sustainable value driven life cycle design methods are applied to a Chinese kitchen electric appliance, soybean milk maker. It has the functions of crumbling soybeans, blending the crumbled soybeans and water, and cooking the blend into soybean milk. First, SVRs are identified from economic, environmental and social perspectives (see Fig.6). With the first HoQ of the proposed QFD method, the artifact-focused DRs are generated as: "Weight", "Size", "Capacity", "Disassembability", "Eco-material", "Particle size of mixture", "Deposit in the milk" "Heating temperature control", "Insulation performance", "Working noise", "Designed life time" and "Shape and color matching", while process-focused DRs include: "Time to market", "IP protection", "R&D budget", "Manufacturing resource efficiency", "Standardization", "Manufacturer profit expectation", "Product availability (to consumers)", "Maintenance availability", "Maintenance service quality", "Disposed product collection ratio", "3R ratio", and "Hazardous waste treatment". For instance, function and performance related SVR "sufficient blending" indicates smaller "particle size of mixture" and less "deposit in the milk", while business competiveness related SVR " Quality certification" and Social responsibility related SVR " Eco-labelling" both indicate artefact- focused DR "eco-material" and low "working noise" , as well as process-focused DR high "disposed product collection ratio", "3R ratio" and "Hazardous waste treatment".

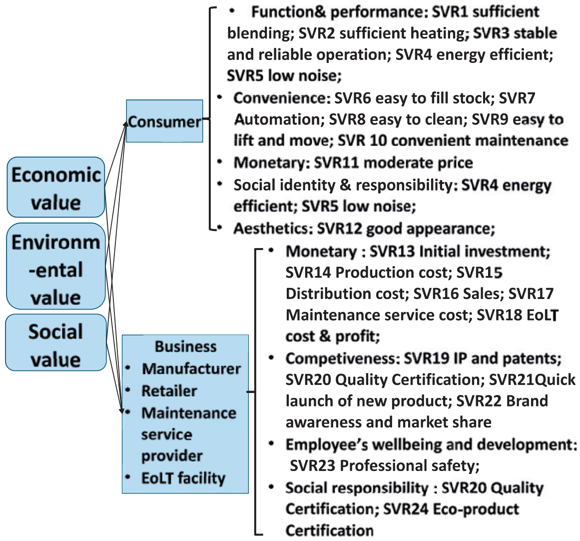

Fig. 6 Sustainable value requirement: soybean milk maker

Then, with the second HoQ, characteristic of major components of the soybean milk maker are specified and the LCEOPs potentially contribute to total sustainable value are identified (Fig. 7). A life cycle simulation based on the proposed product concept and it life cycle plan is performed. Model parameters about product such as material type, weight, and cost of each component, and the energy demands and costs of product assembly, delivery and use are set by modification on the baseline product data. Especially, LCS is used for evaluate the effect of the proposed life cycle plan on resource save and waste reduction and impacts on consumer costs and business profits. Fig.8 presents part of the simulations results-plastic material recycling, and total material demands, wastes generation, energy consumption, consumer costs and corporate profits. Compared to the baseline life cycle solution, the proposed life cycle solution is effective to decrease material demands and amount of waste, but it cannot reduce energy consumption because additional energy is demanded for the material recycling and component reconditioning. The corporate revenue is slightly reduced, very likely due to the increase of component failure within the guarantee time caused by use of reconditioned components, which are usually less reliable than new ones. However, compensated by cost reduction from recycled materials and reconditioned components, the total corporate profit is slightly increased. Given the simulation results, the proposed life cycle plan seems to be reasonable from both economic and environmental value perspectives.

Concept Sketch	Parts	Key Characteristics
	Head Shell	PP shell with handler for easy opening and stock feeding
	Ope. panel	Digital
	Motor	Snap-in motor
	Control Unit	Steam and heat resistant MCU; Spilling detector; Temperature sensor; Anti-dry burning alarm; Operation finish alarm;
	Power supply	Power supply PCB (with voltage transformer) ; PVC wires; Chinese standard 3-pin plug
	Blending	Stainless steel X-shape blades; Stainless steel net with fine mesh;
	Heating	High efficiency tubular electric heater
	Cup	PP exterior (for improved insulation) ; Stainless steel interior (for cleaning and durability); Cup (1.5L) with volume indicators;

	Life cycle engineering options-Attributes	
Design	CAX utilization (i.e CAD, CAE) Adoption of Industiral standards RoHS; "P.R.C Law on Cleaner Production Promotion"; "P.R.C Law On the Prevention and Control of Environmental Pollution by Solid Wastes"	Ecological assessment employment "Technical specification for green-design product assessment- soymilk maker" Patent applications and management: Blending module_utility ; Heating module_invention
Manu.	Use of recycled material/ reconditioned components) (%wt): Plastic<20%; Staineless steel<60%	
Distri. & Use	Distribution channel: Internet sales 70%; Store sales 30%	Pricing strategy: Launching:299rmb; Discount: 259rmb
Mainte-nance	Maintenance Strategy: Exchanging of blades (by end comsumers); Corretive maintenance(by authorized maintenance shops)	Guantee Time: 1 yr Trainning of stuff: Moderate Specialized equipments: Motor
Collection	Collection plans: Contracted door-to-door collection service; Local by tracks;	Pricing strategy: Free for end consumers
EoLT	Required reconditioning/recycling technologyies:Manual diassembly; Motor reconditioning of; Plastic, Metal and PCBs recycling	Reuse choice: Maintenance spare part reuse of Motor, PCBs Recycling choice: Product manufacturing(PP ; Staineless steel) ; Global (Plastic; Metal; PCBs)

Fig.7 Life cycle solution: soybean milk maker

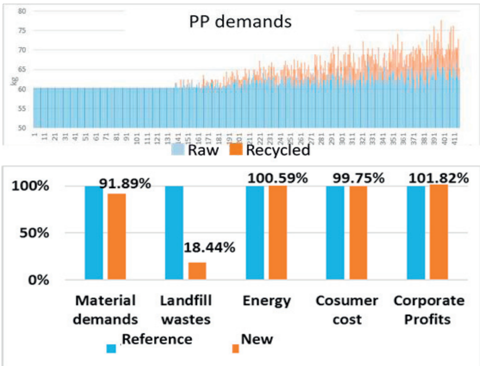

Fig. 8 LCS results: soybean milk maker

7. Conclusions

This paper presents the life cycle design methodologies for sustainable value creation. First, a sustainable value model was proposed based on the understanding of value from a sustainable point of view that includes economic, social and environmental perspectives. Sustainable value requirements are the demands for the value by both customers and businesses. The total sustainable value (of a product life cycle solution) can be evaluated as the level of total satisfaction of value requirements. Sustainable value creation should be considered as a multi-dimensional problem. This study proposed a sustainable value driven life cycle design framework. In this framework, life cycle design is a strategic process of translating sustainable value demands into terms immediately meaningful to design engineers. A QFD method is used for mapping the sustainable value requirements into both artifact- and process-focused design requirements, and then into engineering characteristics of product and the whole life cycle process. By the QFD, high value artifact designs are generated and life cycle engineering options that potentially contributes to the total sustainable value are identified. Life Cycle Simulation methods are employed for description of complicated circulation in close-loop type life cycle, execution of complicated logics (i.e. consumer and corporate behaviour mechanism that can be determinative to the dynamic of life cycle processes) and evaluation of different sustainable value requirement indicators (i.e. resource and energy efficiency, emissions and wastes, customer cost, corporate profits, local social benefits such as job opportunities, tax income, etc.).

The proposed life cycle design framework can bring experts of product and process engineering, industrial management and ecological assessments to a common vision of value. The integrated life cycle solution of product and life cycle is also beneficial in that it provides the direction towards a more sustainable business.

Acknowledgements

This research is financially supported by National Natural Science Foundation of China (Project No. 51505287 and Project No. 51675344).

References

[1] Patala S, Jalkala A, Keränen J, et al. Sustainable value propositions: Framework and implications for technology suppliers. Industrial Marketing Management, 2016. 59: 144-156
[2] Brigham EF and Ehrhardt MC, Financial Management: Theory and Practice. 12th edition edition, 2008
[3] Ostad Ahmad Ghorabi H and Jerlich J , Value Based Life Cycle Analysis for Occupational, Environmental and Legal Compliance in Organizations 1st International Conference on Industry Safety, Occupational Health and Safety in Organizations, Isfahan, Iran, 2008
[4] Bocken N.M.P., Rana P. and Short S.W. Value mapping for sustainable business thinking, Journal of Industrial and Production Engineering, 2015, 32 (1):67-81
[5] Yang M, Vladimirova D, Rana P, et al. Sustainable value analysis tool for value creation. Asian J. Management Science and Applications, 2014, 1(4):312-332.
[6] Henriques J., Catarino J, Sustainable Value and Cleaner Production – research and application in 19 Portuguese SME, Journal of Cleaner Production, 2015, 96:379-386,
[7] Baldassarre B., Calabretta G., Bocken N.M.P., et al, Bridging sustainable business model innovation and user-driven innovation: A process for sustainable value proposition design, Journal of Cleaner Production, 2017, 147:175-186
[8] Figge F and Hahn T. Value drivers of corporate eco-efficiency: Management accounting information for the efficient use of environmental resources. Management Accounting Research, 2013, 24(4):387-400.
[9] Mestre A, Vogtlander J. Eco-efficient value creation of cork products: an LCA-based method for design intervention[J]. Journal of Cleaner Production, 2013, 57(20):101-114.
[10] Milstein H. Creating sustainable value. Acad. Manag. Exec. , 2003, 17 (2)
[11] Suh NP. Axiomatic design - advances and applications. New York: Oxford University Press, 2001
[12] Takata S and Kimura T. Life Cycle Simulation System for Life Cycle Process Planning. CIRP Annals - Manufacturing Technology, 2003, 52(1): 37-40.
[13] Umeda Y, Kondoh S, and Sugino T. Analysis of reusability using 'marginal reuse rate'. Cirp Annals-Manufacturing Technology, 2006, 55(1):41-44.
[14] Matsuyama Y, Matsuno T, Fukushige S, et al. Study of Life Cycle Design Focusing on Resource Balance throughout Product Life Cycles. Procedia CIRP, 2014, 15:455-460