More with Less

Exploring sustainable design through application and development of an integrated multi-level design approach

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of an integrated multi-level design approach

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Summary

There is a need to accelerate the transition towards a sustainable society. Within this transition, there is a role for designers to contribute to the reduction in environmental impacts that arise from design. To enable designers to do so, Eco-design approaches, methods and tools have been developed over the past decades that can result in design solutions with low(er) environmental impact. However successful application of Eco-design appears to be in need of upscaling, since environmental impacts on societal level are not yet decreasing, or not yet decreasing rapidly enough. Having experienced the challenge of achieving successful application of Eco-design first-hand, I was curious to investigate this issue further, which led to the creation of this thesis.

This thesis is aimed at enhancing the contribution of designers to the acceleration of the transition towards an environmentally sustainable society. The main research question concerns how designers' contribution to the acceleration of the transition towards a sustainable society can be further enhanced. It is the result of an explorative, mixed-methods research project that focuses on further exploring application of the Eco-efficient Value Creation (EVC) approach. Based on the challenge of bridging the gap between scientific theory and its practical implementation, it is chosen to follow an action research case study approach, taking the role of a reflective practitioner whilst exploring most case-studies.

The main proposition is that the application of the EVR Model and the EVC approach has the potential to enable designers to integrate contextual actor pre-conditions and multiple system levels into the

design process towards viable sustainable products and services, through which they could contribute more effectively to accelerating the transition towards a sustainable society.

In order to explore the application of the EVC design approach, the EVC approach, as well as its underlying model of the Eco-cost/Value Ratio (EVR), is applied to 6 cases, where each case study is specifically aimed at exploring the underlying research questions as described in this thesis. These research questions were derived from literature review and observations before and during the research trajectory.

The first case study explores the application of the EVR model and the EVC approach to the practical case of an innovation project aimed at enhancement of water recreation systems in a province in The Netherlands. The focus of the innovation project was on increasing tourist expenditures whilst reducing the water recreation system environmental impacts by means of design and development of an IT application service (publication 1 in this thesis).

The second case study explores qualitative application of the EVC approach to the practical case of regulatory design and the subsequent product service system design solutions. The initial focus of this case study is on evaluating the chosen regulatory driver mandating Ballast Water Treatment Systems on board of international shipping vessels. The aim is to explore whether qualitative application of the EVC approach would influence decision making on multiple system levels including the product service system level (publication 2 in this thesis).

The third case study explores the application of the EVR model and EVC approach to the practical case of a sustainable design project in Vietnam. The initial focus is to explore whether the EVR model and EVC approach would be beneficial to enable successful sustainable design within the context of low-income economies (publication 3 in this thesis).

The fourth case study explores the application of the EVR Model and the EVC approach to analysis and design of sustainable business model, specifically remanufacturing. The focus of this case study is explore the usefulness of the EVR model and EVC approach for analysing the barriers for widespread adoption of remanufacturing business models, as well as providing potential solutions (publication 4 in this thesis).

The fifth case study explores the application of the EVR Model and EVC approach within the context of domestic energy use and rebound effects. The focus in this case-study is to explore whether application of the EVR model and EVC approach would lead to specific decision making resulting in potentially different PSS design than initially proposed, concerning the choice whether to insulate more, apply Home Energy Management Systems, or both (publication 5 in this thesis).

The sixth case study is aimed at exploring whether novice designers are able to grasp the concept of the EVR model and the EVC approach, and consequently whether it can be applied successfully, i.e. whether a feasible, eco-efficient design solution can be produced. The case study describes the application of the EVC approach to the design of a new urban street lighting product service system (publication 6 in this thesis).

The results obtained from exploration of the application of the EVC approach and the EVR model have shown that the associated design process leads to solutions that have significantly lower environmental impacts whilst increasing the likelihood of being able to combine the impact reduction with potentially viable business models.

In the first case study, application of EVR and EVC has led to a system level re-design while initiating the project with a perspective from IT service design. The re-design process generated design criteria for service design, but also product design, PSS design, infrastructure and regulatory design, as well as a framework to manage the complex interrelationships between various stakeholders in the current and future system.

In the second case study has shown that qualitative application of the EVR Model, or “EVR thinking”, has led to another systemic design direction with implications for the international regulatory framework design aimed at minimizing an isolated problem of invasive species proliferation. It has led to the proposal of a functional result Product Service System design with high environmental impact reduction combined with higher value creation potential.

The third case study has provided clear recommendations towards local sustainable design developments in a low-income economy, where at the same time it has shown that some design approaches, although slightly different, overall have similar characteristics as the EVC approach and as such, generate design solutions that have relatively low EV Ratios.

The fourth case study has shown that application of the EVR model can explain the lack of widespread adoption of remanufacturing, as well as provide potential solutions through application of the EVC approach.

The fifth case-study shows that application of the EVR model provides clear recommendations for domestic heating systems design through defining the building design intervention which has the most potential for eco-efficient value creation on system level, taking potential rebound effects into account. The sixth case-study (as well as other student projects) results show that the approach of EVC and the application of the EVR model is transferable to novice designers, and enables them to use the approach to generate new design solutions which have a low environmental impact, and at the same time provide high value for the end-user.

The combined results of exploring the EVR model and EVC approach application to the different cases as described in this thesis leads to the conclusion that the Eco-efficient Value Creation approach has the potential to enable designers to enhance their contribution to the acceleration of the transition towards a more sustainable society, based upon evaluation of dissemination, applicability and impact of the results of the explored case studies in this thesis.

The primary application of the EVC approach and the EVR Model is by design engineers within the business context. However, this thesis has also shown the approach and model's applicability within the regulatory context, and that it is possible to apply the approach and model not only on product or service level, but also on system level, taking multiple perspectives from different contexts into account.

The main implication of this research project is that the EVC approach and EVR Model, if one agrees to their potential, provide the required tools, approaches and sustainable design thinking perspectives for designers (and also business decision makers and policy makers) to achieve what is required in order to accelerate the transition towards a sustainable society:

Designers will increasingly be facing the challenge of designing sustainable product systems which can compete with unsustainable offerings, and further research is therefore needed to investigate whether application of the EVR model and the EVC approach consistently leads to the design of viable sustainable product systems, on a large scale, at sufficient speed. This implies that widespread education in-, adoption of-, and further research on- application of the EVR model and the EVC approach is required.

This thesis consists of three parts:

PART I, the Chapeau of this thesis

PART II, the published papers:

- Two LCA based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable
- Innovation in product and services in the shipping retrofit industry: A case study of ballast water treatment systems
- Evaluating the sustainability of Vietnamese products: the potential of ‘designed in Vietnam’ for Vietnamese vs. Dutch markets
- Combined analyses of costs, market value and eco-costs in circular business models: eco-efficient value creation in remanufacturing
- Insulation or Smart Temperature Control for Domestic Heating: A Combined Analysis of the Costs, the Eco-Costs, the Customer Perceived Value, and the Rebound Effect of Energy Saving
- Eco-Efficient Value Creation of Residential Street Lighting Systems by Simultaneously Analysing the Value, the Costs and the Eco-Costs during the Design and Engineering Phase

PART III, the appendix

Samenvatting

Er is behoefte aan een versnelling van de transitie naar een duurzame samenleving. Binnen deze transitie is er een rol voor ontwerpers om bij te dragen aan het verminderen van de impacts die voortkomen uit ontwerp. Om ontwerpers in staat te stellen dit te doen zijn de afgelopen tientallen jaren Eco-design aanpakken, methodes, en hulpmiddelen ontwikkeld die kunnen leiden tot ontwerpen met minder/weinig impact. Echter lijkt succesvolle toepassing van Eco-design verdere opschaling te behoeven, omdat milieu-impacts op maatschappelijk niveau niet, of niet snel genoeg, afnemen. Omdat ik eigenhandig de uitdaging van het succesvol toepassen van Eco-design heb ervaren, was ik nieuwsgierig om deze uitdaging verder te onderzoeken, wat uiteindelijk heeft geleid tot het schrijven van deze dissertatie.

Dit proefschrift is gericht op de bijdrage van ontwerpers aan de transitie naar een milieukundig duurzame samenleving. De centrale onderzoeksvraag betreft hoe ontwerpers' bijdrage aan de versnelling van de transitie naar een duurzame samenleving kan worden vergroot. Het is het resultaat van een verkennend, gemengde methodes onderzoeksproject dat zich richt op het verder verkennen van de toepassing van eco-efficiënte waarde creatie (EVC) benadering. Op basis van de uitdaging van het overbruggen het gat tussen wetenschappelijke theorie en kennis, en de praktische implementatie daarvan, is ervoor gekozen om een actie-onderzoek gevalsstudie aanpak te volgen, waarbij de onderzoeker in de meeste gevallen de rol van reflectieve beoefenaar aanneemt.

De centrale propositie is dat de applicatie van het EVR Model en de EVC

aanpak potentie heeft om ontwerpers in staat te stellen voorwaarden van contextuele actoren en meervoudige systeemniveaus te integreren in het ontwerpproces richting succesvolle producten en diensten, waarmee ze effectiever zouden kunnen bijdragen aan het versnellen van de transitie naar een duurzame samenleving.

Om de toepassing van de EVC aanpak, alsook het onderliggende model van de EVR, te verkennen, is het toegepast op 6 gevalsstudies, waar elke gevalsstudie specifiek is gericht op het verkennen van de onderliggende onderzoeksvragen welke in deze dissertatie zijn beschreven. Deze vragen zijn afgeleid van literatuuronderzoek en observaties voor en tijdens het onderzoekstraject.

De eerste gevalsstudie verkent de applicatie van het EVR Model en de EVC aanpak om het praktische geval van een innovatief project gericht op het verbeteren van waterrecreatiesystemen in een provincie in Nederland. Dit innovatieproject was gericht op het doen toenemen van toeristische uitgaven terwijl tegelijkertijd de milieu-impact van het waterrecreatiesysteem door middel van het ontwerp en de ontwikkeling van een IT-service applicatie (publicatie 1 in deze dissertatie).

De tweede gevalsstudie verkent kwalitatieve applicatie van de EVC aanpak in het praktische geval van de ontwikkeling van wetgeving, en de daaropvolgende product-dienst combinatie ontwerpoplossingen. De initiële aandacht gaat in deze gevalsstudie uit naar het evalueren van de gekozen wetgeving die het hebben van ballastwaterbehandelingssystemen aan boord van internationale transportschepen. Het doel is om te verkennen of kwalitatieve applicatie van de EVC aanpak invloed zou kunnen hebben op meerdere systeemniveaus, inclusief het producten en diensten niveau (publicatie 2 in deze dissertatie).

De derde gevalsstudie verkent de applicatie van het EVR model op het praktische geval van een duurzaam ontwerpproject in Vietnam.

De initiële aandacht gaat uit naar het verkennen van de vraag of toepassing van het EVR model en de EVR aanpak positieve invloed kan hebben op het in staat stellen van duurzaam ontwerpen binnen de context van lage lonen economieën (publicatie 3 in deze dissertatie).

De vierde gevalsstudie verkent de applicatie van het EVR Model en de EVC aanpak om duurzame verdienmodellen, her-fabriceren in dit geval, te analyseren en te ontwerpen. Deze gevalsstudie richt zich specifiek op het analyseren van barrières voor brede toepassing van her-fabriceren als verdienmodel, alsook het geven van potentiële oplossingen voor het overkomen van die barrières (publicatie 4 in deze dissertatie).

De vijfde gevalsstudie verkent de applicatie van het EVR Model en de EVC aanpak binnen de context van huishoudelijk energie gebruik en terugveer effecten. Specifieke aandacht gaat uit naar het verkennen of EVR en EVC applicatie zou leiden naar specifieke besluitvorming die zou resulteren in andere product-dienstcombinatie ontwerp dan aanvankelijk voorgesteld op het snijvlak van de keuze tussen het toepassen van meer isolatie, het toepassen van energie-management systemen, of beide (publicatie 5 in deze dissertatie).

De zesde gevalsstudie is gericht op het verkennen of beginnende ontwerpers in staat zijn het concept van EVR en EVC te begrijpen en daaruit volgend het ook succesvol kunnen toepassen, dat wil zeggen of er een haalbare, eco-efficiënte ontwerpoplossing kan worden gegenereerd. Deze gevalsstudie beschrijft de toepassing van de EVC aanpak op het ontwerpen van een nieuwe straatverlichtingsproduct-dienstcombinatie voor steden (publicatie 6 in deze dissertatie).

De resultaten die verkregen zijn van de verkenning van het toepassen van de EVC aanpak en het EVR Model hebben laten zien dat bijbehorende ontwerpproces leidt tot oplossingen die significant minder milieu-impact hebben terwijl de waarschijnlijkheid toegenomen lijkt te zijn dat deze oplossingen deze impact reductie kunnen combineren met potentieel haalbare verdienmodellen. In het eerste geval heeft applicatie van EVR en EVC geleid tot een herontwerp op systeemniveau terwijl het initieel enkel een ontwerpopgave betrof met een perspectief rond IT-diensten ontwerp. Het proces genereerde aan de ene kant ontwerp criteria voor diensten ontwerp, maar ook product ontwerp, product-dienst-combinatie ontwerp, infrastructuur ontwerp en de ontwikkeling van regelgeving, en daarnaast is een raamwerk ontwikkeld om de complexe relaties tussen de verschillende belanghebbenden in het huidige alsook het toekomstige systeem te kunnen beheren. De tweede gevalsstudie heeft laten zien dat kwalitatieve toepassing van het EVR model, ook wel "EVR denken", heeft geleid tot het voorstellen van een andere systeemontwerprichting met implicaties voor het internationale wetgevingsraamwerk dat momenteel gericht is op het oplossen van het geïsoleerde probleem van de verspreiding van invasieve soorten. Het resulteert in een voorstel voor een functioneel-resultaat product-dienst-combinatie herontwerp, waarbij gesteld kan worden dat deze hoge impact-reductie kan combineren met hoge waarde creatie voor eindgebruikers. De derde gevalsstudie heeft tot duidelijke aanbevelingen geleid richting lokale duurzaam ontwerp ontwikkelingen in een lage-lonen economie, waar tegelijkertijd ontdekt is dat er nog meer ontwerpbenaderingen zijn in de praktijk die, alhoewel licht afwijkend, in zijn algemeenheid vergelijkbare karakteristieken hebben met de EVC aanpak, en dus ontwerp oplossingen genereren met relatief lage EV Ratio's. De vierde gevalsstudie heeft laten zien dat de toepassing van het EVR Model het gebrek aan wijde verspreiding van het verdienmodel her-fabriceren kan verklaren, en daarbij ook ondersteunt bij het vinden van potentiële oplossingen. De vijfde gevalsstudie laat zien dat het toepassen van het EVR model zich leent voor het ontwikkelen van duidelijke aanbevelingen omtrent het ontwerp van huishoudelijke energiesystemen door middel van het definiëren van ontwerpinterventies die de grootste potentie hebben voor eco-efficiënte waarde creatie op systeem niveau, terwijl de kans op potentiële terugveer effecten worden geminimaliseerd. De zesde gevalsstudie (alsook andere projecten met studenten) laat zien dat in dit geval de EVC aanpak en het EVR model overgedragen kunnen worden aan beginnende ontwerpers, and hen in staat stelt de aanpak te gebruiken om oplossingen te ontwerpen die een lage milieu-impact combineren met een potentieel hoge waarde voor de eindgebruiker.

De gecombineerde resultaten van het verkennen van de toepassing van het EVR Model en de EVC aanpak op de verschillende praktische gevallen zoals beschreven in deze dissertatie leidt uiteindelijk tot de conclusie dat de EVC aanpak potentie heeft om ontwerpers in staat te stellen hun bijdrage aan het versnellen van de transitie naar een duurzame samenleving te vergroten, gebaseerd op evaluatie van verspreiding, toepasbaarheid en de impact binnen de verkende gevalsstudies van dit proefschrift.

De primaire applicatie van de EVC aanpak en het EVR Model is door ontwerp ingenieurs binnen de zakelijke context. Echter heeft dit proefschrift ook laten zien dat het model en de aanpak ook toepasbaar is binnen de wetgevingscontext en dat het mogelijk is het model en de aanpak niet alleen te gebruiken op product of dienst niveau, maar ook op systeemniveau, waarbij meervoudige perspectieven van verschillende achtergronden meegenomen kunnen worden.

De belangrijkste implicatie van dit onderzoeksproject is dat de EVC aanpak en het EVR model, als men het eens is met het potentieel, de benodigde hulpmiddelen, aanpak en methodes combineert voor ontwerpers (en zakenmensen, alsook beleidsmakers) om te bereiken wat nodig is om de transitie te versnellen naar een duurzame samenleving:

Ontwerpers zullen in toenemende mate geconfronteerd worden met de uitdaging van het ontwerpen van duurzame product-systemen die kunnen concurreren met niet-duurzame alternatieven, en toekomstig onderzoek is nodig om beter te bestuderen of applicatie van het EVR model en de EVC aanpak consistent leidt tot het ontwerp van haalbare duurzame productsystemen op grote schaal, en met voldoende snelheid. Dit betekent dat brede opleiding in-, adoptie van- en verder onderzoek naar- het toepassen van het EVR Model en de EVC aanpak nodig is.

Deze dissertatie bestaat uit drie delen:

DEEL I, het chapeau van dit proefschrift

DEEL II, de publicaties:

- Two LCA based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable
- Innovation in product and services in the shipping retrofit industry: A case study of ballast water treatment systems
- Evaluating the sustainability of Vietnamese products: the potential of 'designed in Vietnam' for Vietnamese vs. Dutch markets
- Combined analyses of costs, market value and eco-costs in circular business models: eco-efficient value creation in remanufacturing
- Insulation or Smart Temperature Control for Domestic Heating: A Combined Analysis of the Costs, the Eco-Costs, the Customer Perceived Value, and the Rebound Effect of Energy Saving
- Eco-Efficient Value Creation of Residential Street Lighting Systems by Simultaneously Analysing the Value, the Costs and the Eco-Costs during the Design and Engineering Phase

DEEL III, de appendix

Preface

Upon completion of my master's thesis, I was both elated as well as puzzled. Elated, because I had accomplished obtaining my MSc degree in Integrated Product Design, while focusing on lowering the environmental impacts of products through design. Puzzled, because despite my best efforts for designing a 100% sustainable product (The Rebicycle Project), I had not accomplished what I should have been aiming for in the first place: a massive shift in actual sales from cheap, imported steel bicycles towards locally produced wooden bicycles.

During my work on the Rebicycle project I realized that a focus on actual market value and the increased costs associated with minimizing environmental impacts, is essential: What is needed are products that are designed with significantly less environmental impact, and have - at the same time – an increased value for the customer to cover the extra costs associated with sustainable products. I observed that current design processes lead to the production and consumption of at best incrementally sustainable products and services, or design processes lead to radically sustainable products that failed to conquer the mainstream markets, and therefore failed to result in significant environmental impact reduction on a scale that matters.

I saw that what is needed is an integral design approach where both environmental impacts are reduced as well as value is being created, so that the widespread dissemination of sustainable products and services are actually driving the required transition in itself: People wanting sustainable solutions over the unsustainable solutions at a fair price. At the core of solving this challenge is the design of these viable sustainable products and services.

Therefore, when I decided to undertake this PhD research project within the context of innovative sustainability projects, I was eager to expand on my experiences with sustainable industrial design and explore leading theories, models and methods connecting design (value creation) and sustainable development. The selected design approach and supporting model for this research are the design approach of Eco-efficient Value Creation and the model of the Eco-costs/Value Ratio, integrating fast-track Life Cycle Assessment with innovation by design, and including the broader context of enabling design with inclusion of the required systems and business models supporting new sustainable products and services. Due to the dedication and support of the promotors Prof. Dr. Ir. J.M.L. van Engelen and Prof. Dr. Ir J.C. Diehl, I was able to successfully conclude and finalize this complex research project.

I am also deeply grateful for the knowledge, continuous support, friendship and patience of Dr. Ir. Joost G. Vogtländer, who laid the foundations for the Eco-efficient Value Creation approach and has supported me throughout the whole process from start to finish. I would also like to express my gratitude to Prof. Dr. Ir. J.C. Brezet for providing the opportunity to investigate sustainable design in an explorative manner, as well as to all my colleagues I was fortunate enough to work alongside during this research project at the research group of the Design for Sustainability program at the department of Design Engineering within the faculty of Industrial Design Engineering. I also wish to thank my co-authors for researching and publishing with me on the various topics in this thesis, as well as my colleagues and clients at EY Climate Change and Sustainability Services for providing the opportunity to advance "EVR thinking" from within the business community. Additionally, I would like to thank the external partners I had the privilege of working with throughout the different cases described in this thesis, as well as the many different students that worked with me on exploring the application of the approach of Eco-efficient Value Creation.

Finally, I am most grateful for the support from my family: Theo Scheepens, Jarry Scheepens, Vera Scheepens, Tineke Scheepens, Sam Scheepens, Josephine Scheepens and Benjamin Scheepens. Without your motivation, limitless patience and emotional support to keep me going on this thesis, I would not have been able to see it through.

Who strive - you don't know how the others strive
To paint a little thing like that you smeared
Carelessly passing with your robes afloat,-
Yet do much less, so much less, Someone says,
(I know his name, no matter) - so much less!
Well, less is more, Lucrezia.

(Robert Browning in "Andrea del Sarto", 1855)

Part I: Chapeau

1 The current role of Eco-design in the required transition towards a sustainable society

The context for the industrial design engineering profession has been, and still is, changing due to issues related to environmental sustainability. In response, industrial design engineering approaches (incl. methods, tools and frameworks) have been developed (e.g. Brezet and van Hemel, 1997) to foster environmentally sustainable design solutions: Eco-design.

1.1 The required response of designers to changing contexts

Eco-design approaches, in their response to curb environmental impacts, have traditionally focused on minimization of environmental impacts of products (and services, both products and services are referred to in this thesis as products). During the course of this research project this is confirmed by (Ceschin and Gaziulusoy, 2016) who have reviewed the evolution of Design for Sustainability approaches. They confirm the conclusion that the primary focus of Eco-design approaches is on minimizing environmental impacts by design.

(Ceschin & Gaziulusoy, 2016) have defined the following system levels:

- Product innovation level

Design approaches focusing on improving existing or developing completely new products.

- Product-Service System innovation level

Here the focus is beyond individual products towards integrated combinations of products and services (e.g. development of new business models).

- Spatio-Social innovation level

Here the context of innovation is on human settlements and the spatio-social conditions of their communities. This can be addressed on different scales, from neighbourhoods to cities.

- Socio-Technical System innovation level

Here design approaches are focusing on promoting radical changes on how societal needs, such as nutrition and transport/mobility, are fulfilled, and thus on supporting transitions to new socio-technical systems.

While (Ceschin and Gaziulusoy, 2016) have reviewed Design for Sustainability (DfS) approaches, this thesis focuses on environmental[1] sustainability, and therefore these DfS approaches are referred to as Eco-design approaches in this thesis. They also conclude that Eco-design approaches have evolved from product innovation level through the product service system innovation and spatio-social innovation level up to the socio-technical system innovation level.

Hence the ambition of Eco-design has evolved from focusing on (incremental) product sustainability innovations towards Eco-design

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[1] Although design for sustainability also includes the social dimension, social impacts are not part of the scope of this research.

supporting the overall systemic transition towards a sustainable society. This is summarized in the Design for Sustainability evolutionary framework by (Ceschin and Gaziulusoy, 2016), in which existing Eco-design approaches are also captured and mapped over time as well as their coverage of the defined system innovation levels. See figure 1.

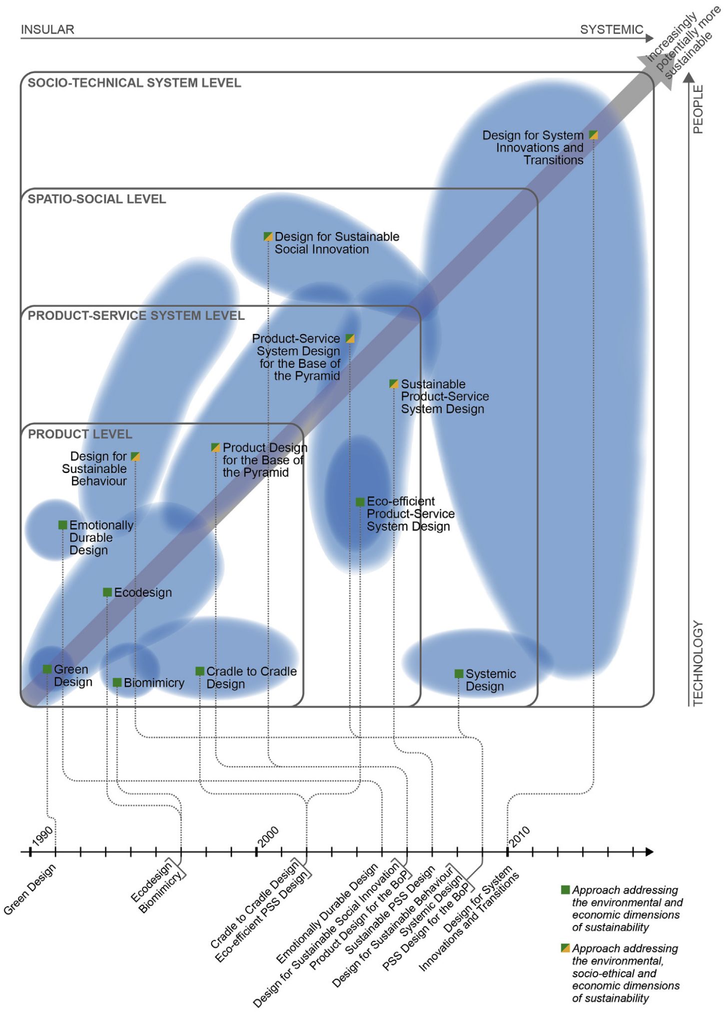

Figure 1: the DfS evolutionary framework (Ceschin and Gaziulusoy, 2016)

The broader the scope (i.e. the “higher” the system level) of the design solution is, the larger the potential contribution to support the transition towards a more sustainable society. It is however evident that no one designer can (re)design an entire sociotechnical system, as well as provide the entire roadmap towards practical implementation.

From this perspective, a sustainable transition could be defined as a sequence of sustainable design interventions that together contribute to achieving systemic transition towards a sustainable society. Other research on the role of designers in societal systems transitions also approach the challenge by focusing on four different system levels, where on the product level the design interventions elicit change in higher system levels (Joore, 2010).
This approach is further discussed in Section 1.5, figure 3. Publication 1 and 2 in this thesis describe sequences of design interventions throughout multiple system levels.

1.2 Three main actors in the transition

There is a clear need to accelerate systemic transitions towards a more sustainable society (IPCC, 2022): "Accelerating climate change and trends in exposure and vulnerability underscore the need for rapid action on the range of transformational approaches to expand the future set of effective, feasible, and just solutions (very high confidence)."

This thesis is written from a design perspective: In order to accelerate the required transition, a designer will be required to integrally take into account the potential roles and divergent interests, values and worldviews of the different actors in transition:
"Transformation towards climate-resilient development is advanced most effectively, when actors work in inclusive and enabling ways to reconcile divergent interests, values and worldviews, building on information and knowledge on climate risk and adaptation options derived from different knowledge systems (high confidence)." (IPCC 2022) This thesis adopts the view that three different actor groups are essential for enabling the required transition: "Climate resilient development is enabled when governments, civil society and the private sector make inclusive development choices that prioritise risk reduction, equity and justice, and when decision-making processes, finance and actions are integrated across governance levels, sectors and timeframes (very high confidence)." (IPCC, 2022)
In this thesis, the three above-mentioned actors are referred to as government, consumers, and business actors, in line with the "3 stakeholder model" as published in (Vogtländer, 2002). These actors

together form a multi-context solution space for sustainable design, as shown in figure 2.

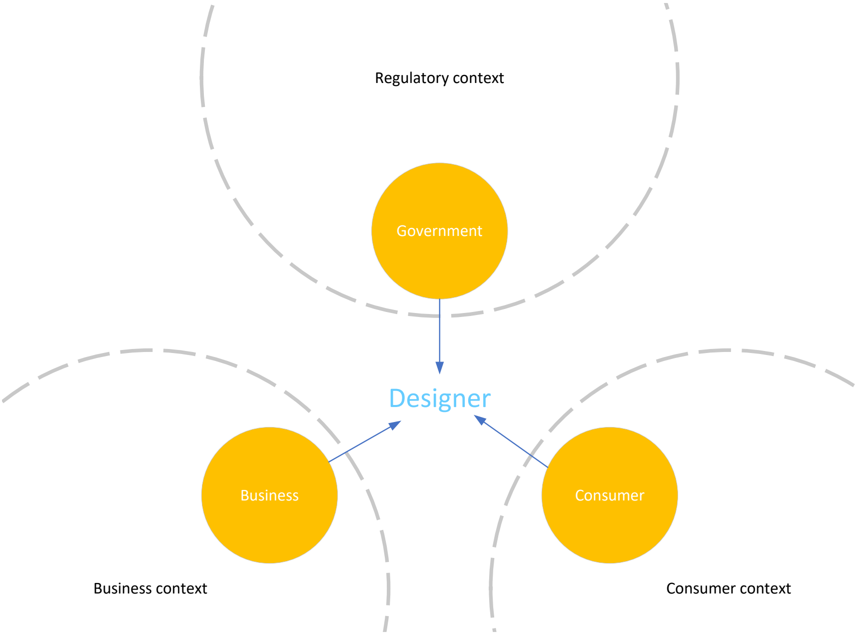

Figure 2: Conceptual representation of the three stakeholders providing designers with multi-context preconditions/design criteria

FIgure 2 depicts the concept of three societal actors that in this thesis, from their own context, provide designers with (additional) design criteria for sustainable design.

The conceptual actors can be perceived as providing "static" preconditions to designers: Governments implement laws and regulations, companies bring to market what they perceive as being the best business cases, and consumers are buying products they perceive as having the highest value for their personal needs and wants at a reasonable price. But rather than perceiving them as static contexts, an important notion is the idea that designers actually might be able to influence how these actors are acting in the transition by designing the core of the solution for sustainable production and consumption: sustainable products.

Consumer requirements for designers are based upon the individual context of each specific consumer. These are always unique to the individual consumer, however, general preconditions/design criteria are evident: consumers generally decide to buy products or services based upon their perception of the offered quality, utility and “fun” by products and services and the associated price of the different options, i.e. their “personal benefit” (Visser et al, 2015a). Increased awareness among consumers has increased their preference for sustainable products over non-sustainable products, however the increased awareness insufficiently leads to actual acceptance of higher prices (Gleim et al., 2013) or (perceived) decrease in quality (Ottman, 2008), (Visser et al. 2015a), (Visser et al., 2015b), (Kollmuss and Agyeman, 2002), (Pickett-Baker and Ozaki, 2008). According to (Gupta & O,gden, 2009)“...most consumers, despite holding a positive attitude toward environmental conservation make purchase decisions to maximize self-interest because in their view, the costs of cooperation outweigh the uncertain utility obtained from it.”, and (Kostadinova, 2016) concludes that “Green products are often more expensive, of poorer quality and are not available in all stores - price, perceived quality and lack of trust in the information provided by producers, contribute to this gap”.

Government actors operate from the societal context, and also provide designers with preconditions/design criteria. One can think of regulations, subsidies, taxes and political priorities, which the business and consumer actors need to comply with. Increasingly there are also environmental regulatory developments nudging companies and consumers towards acting more sustainably, such as the continued development of the Eco-design Directive in Europe.

The closest actor group to designers are business actors: designers usually work directly for them. Within the business context it is observed that, even though many Eco-design approaches, methods and tools have been developed to enable sustainable design, the overall success of actual implementation in the business context has been limited: "despite the great number of approaches proposed by researchers in this field and available in commercial tools, companies still have difficulty in their practical and effective implementation and use" (Rossi et al., 2016). Whilst initially Eco-design as part of DfS approaches was put forward as having potential to enhance business profitability from lower costs, new markets and consumer preferences for sustainable products (UNEP, 2009 D4S), the absence of a widespread successful implementation of Eco-design approaches in practice suggests that this might not entirely be the case for most products resulting from application of Eco-design approaches. The barriers for successful application of Eco-design approaches by design professionals in the business context is discussed in more detail in Section 1.3.

1.3 Barriers for successful implementation of Eco-design approaches in the business context

The limited success with implementation of Eco-design approaches in business is found by Rossi et al. to be due to a number of “external” as well as “internal” barriers (Rossi et al., 2016):

External Barriers

- “Market and customer influences, expectations and perceptions”
- Legislation, i.e. lack of obligatory, normative and specific compulsory regulations: “the lack of obligation and norms to respect or specific compulsory regulations (e.g. specific legislation for a limited type of product; no compulsoriness of environmental analysis)”

Internal Barriers

- There are too many methods and tools, and the tools are too complex and specific: “tools are often too complex, over formalised and not able to answer to companies’ needs”
- The additional financial, human, time as well as data resources required: “e.g. extra time and extra resources to dedicate to environmental analysis and to acquire knowledge;

economic resources to use the tool, need of dispose of a high quantity of data, often not owned by the company but by external suppliers"

- Tools are only addressing isolated issues: "The absence of a multi-objective analysis"

According to (Lofthouse, 2006) the main barriers for successful application of Eco-Design approaches are:

- Business leadership is interested in design and not in sustainability
- The client is not very interested in Eco-design
- No data are readily available
- No Eco-design examples are available
- Eco-design is not inspiring for designers (the tools do not focus on design of beautiful artifacts)
- Eco-design is too time consuming (especially LCA) to be practical in the front end
- No certainty that the Eco-design process delivers a viable business model

During the course of exploring the case discussed in publication 1 (See Part II of this thesis), it is observed that there might be another potentially major barrier for the transition: the "rebound effect" (e.g. Hertwich, 2005). Consumers tend to spend what they have: when consumers for example save money on fuel due to the purchase of a more sustainable car with better fuel efficiency, the money saved will be spent either on "more driving" or on other products and services. These other products and services might very well offset, or even increase the net environmental impact, i.e. by spending the saved money on a long-distance flight holiday. This in part could also explain the absence of a significant decline in environmental emissions over the past decades. For designers, this results in an interesting paradox, where one of the main barriers for changing consumer behaviour towards sustainable consumption is the higher price of those offerings, but the higher price for products and services is actually necessary to prevent consumption rebound effects.

The main proposition in this thesis is rooted in the reasoning that if these barriers are overcome, Eco-design methods and tools could be applied more successfully, leading to a larger relative market share of sustainable products, which should logically lead to an acceleration of the transition.

Rossi et al. (2016) provide recommendations to overcome the barriers they identified to two of the three actors, as well as to the sustainable design research community.

Towards business actors the suggestion is made to embrace the required transformation of traditional design processes, in order to reach the suggested goals that would be quantifiable and measurable.

Towards government actors the suggestion is to develop more and more restrictive legislation, specifically mentioning the need to create pressure on companies to consider the whole product-life cycle. It is reasoned that through legislative pressure, businesses and therefore consumers are expected to act more sustainably.

Towards the sustainable design research community, a number of research and development activities are proposed. They suggest that design researchers should improve tool characteristics and develop methods that meet company needs and expectations:

- Integration of tools and methods to allow multi-objective analysis
- Life-cycle perspective and market aspect inclusion
- Tools should be linked with economic aspects to allow companies to consider cost drivers
- Applicability in the early stages of the design process
- Development of customized eco-design tools, which facilitate the definition of environmental checkpoints, reviews, milestones and roadmaps
- Development of free eco-design tools, and ease of access for business
- Simple enough to be used also by non-expert users following a short training
- Development of knowledge sharing tools for the efficient reuse and evaluation of company knowledge in the sustainability field

In addition, recent scientific research on multi-context design approaches (Kersten, et al. 2018) has shown that designers operating in a multi-context set of pre-conditions are aided less by using specific tools and methods, and are appreciative of a more "open" approach to innovation. (In other words, there appears to be a gap in "design thinking" in that there might be some merit in fostering "sustainable design thinking"). Combining this notion of a lack of design approaches that are able to integrate the multi-level nature of sustainable innovation, integrate the requirements of different actors in the transition, and enable multi-objective analyses, whilst remaining practical in its application, a gap is identified in Eco-design for the development of an integrated design approach that enables designers to take the multiple systemic levels and actor requirements into account when designing sustainable solutions.

1.4 The quest for a better Eco-design approach

The contours of a potentially more effective Eco-design approach are developed based on the preceding reasoning in sections 1.1-1.3.
There is a need for a more successful Eco-design approach which:

- Can be integrated with design processes and procedures in practice (Rossi et al., 2016) to enable multi-objective analyses, e.g. that environmental considerations are integrated with viable business model development
- Enables designers to integrate preconditions of the main actors in the transition, on different system levels (IPCC 2022, Ceschin & Gaziulusoy, 2016, Rossi et al., 2016)
- Remains pragmatic and is not exceedingly complex (Rossi et al., 2016)
- Is not too restrictive or specific with regards to tools and methods to be used by the designer (Kersten et al., 2018)

It is not within the scope of this research project to come up with an entirely new sustainable design approach. The initial idea is that there are design approaches that are able to at least deal with parts of the abovementioned criteria, which might be further developed into a more successful Eco-design approach supporting acceleration of the transition.
One design approach was further explored: The design approach based

on applying the model of the Eco-costs/Value Ratio (EVR): the Eco-efficient Value Creation approach (EVC approach) (Vogtländer et al, 2010). Initially developed as an analysis model, in combination with specific methodology and tools on how to analyse the EVR of products, application of the EVC approach leads to a proposed single indicator for sustainability for products. The EVC approach is selected to be explored since it shows potential for a majority of the above-mentioned criteria:

- Integration of tools and methods to allow multi-objective analysis:

The EVR introduces the double objective as a goal for the analysis and design of sustainable products (the double objective is defined as the goal of developing products with lower environmental burden and at the same time higher market value).

- Life-cycle perspective and market aspect inclusion:

The EVR based design approach at its core integrates market aspects with the life-cycle perspective of product design.

- Tools should be linked with economic aspects to allow companies to consider cost drivers:

The double objective of the EVC approach links environmental aspects of product design with economic aspects.

- Applicability in the early stages of the design process:

The EVR based design approach is specifically developed to be applied starting from the earliest stages of the design process.

- Development of customized Eco-design tools, which facilitate the definition of environmental checkpoints, reviews, milestones and roadmaps:

Part of the proposed EVR-based design approach is a combination of tools, data and methodology for efficient modelling of product life-cycle impacts. This should allow for efficient LCA impact assessment and embedding the insights within sustainable innovation processes.

- Development of free Eco-design tools, and ease of access for business:

The Idemat database, developed at the Delft University of Technology, has been provided as open source through www.ecocostsvalue.com. Smartphone apps have also been developed to increase accessibility for designers, business managers and policy makers, also provided free-of-charge.

- Simple enough to be used also by non-expert users following a short training:

Experiments with student workshops seemed to be promising.

- Can be integrated with design processes and procedures in practice (Rossi et al., 2016) to enable multi-objective analyses:

It appears that an EVR-based design approach can be applied integrally to current design processes, and its foundation is integration of multiple objectives in the design process.

- Enables designers to integrate preconditions of the main actors in the transition, on different system levels (IPCC 2022, Ceschin & Gaziulusoy, 2016, Rossi et al., 2016):

The EVR-based design approach might have the potential to incorporate societal actor preconditions, but this would need to be explored further.

- Remains pragmatic and therefore not exceedingly complex (Rossi et al., 2016):

The EVR-based design approach is explicitly intended to simplify the immense complexity designers face when designing sustainable solutions. However while practical implementation on a product level has been studied quite well, ease of application and knowledge transfer have not been studied.

- Is not too restrictive or specific with regards to tools and methods to be used by the designer (Kersten et al., 2018):

The EVR-based design approach is also deemed to have potential for not being too restrictive or specific for designers, even though it in some areas recommends quite specific tools and methodologies, e.g. fast-track LCA and the use of eco-costs as a single indicator for LCA. On the other hand it is recognized in this approach that depending on the specific situation, different metrics might be applied for quantification of the "value" of the design solutions (i.e. costs or price). Furthermore, it is reasoned that an EVR-based design approach still works as intended when e.g. abandoning the proposed tools such as fast-track LCA combined with eco-costs, and e.g. optimize the design solutions using other metrics, or even omitting metrics. As long as the core of "EVR thinking" is maintained, and thus designers would be able to design sustainable solutions that have a lower environmental impact and are valued more by consumers, the double objective would be met in a non-restrictive and pragmatic manner. Whether the approach is still useful if applied in a more generic, qualitative manner, is explored further in this thesis.

1.5 The application of the EVR-model in design

Within the available Eco-design approaches, the model of the Eco-costs/ Value Ratio (EVR) (Vogtländer, 2001a) and the approach of Eco-efficient Value Creation (EVC) (Vogtländer et al., 2014) are aimed at achieving successful integration of environmental impact, cost and value during design processes.

The EVR Model is recognized as part of the available Eco-design approaches, such as the MEPSS approach as included in the Eco-design approaches overview by (Ceschin and Gaziulusoy, 2016). This thesis further explores the practical application of the model of the Eco-costs/ Value Ratio and the approach of Eco-efficient Value Creation.

The main proposition is that the application of the EVR Model and the EVC approach has the potential to enable designers to integrate contextual actor pre-conditions and multiple system levels into the design process towards viable sustainable products and services, through which they could contribute more effectively to accelerating the transition.

The model of the Eco-costs/Value Ratio is initially intended as a LCA-based tool to analyse and communicate the sustainability of products and services, and within the context of design engineering consecutively was applied to optimise design and resolve strategic dilemmas. It proposes the use of a three-fold approach of analysing environmental impacts, costs and market value of products and services.

The model of the Eco-costs/Value Ratio was first introduced by Dr. Ir. J.G. Vogtländer, who published the concept and underlying theory in his doctorate thesis on The Model of the Eco-Costs Value Ratio (Vogtländer, 2001b).

This thesis was preceded by the introduction of the then-called virtual pollution prevention costs '99: a single LCA indicator for emissions (Vogtländer & Bijma, 2000a). This indicator evolved thereafter into the "virtual eco-costs '99" (Vogtländer et al. 2001c) and eventually into "eco-costs", which are part of the foundation of the EVR model.

The issue of circularity, i.e. how to deal with that in LCA (Vogtländer et al, 2001d), the issue of communication (Vogtländer et al, 2002), and the meaning for design (Vogtländer, 2001) were dealt with in the same thesis.

Following these initial publications, two main EVR research paths can be identified: one path where the model of the EVR is applied for the scientific analysis and communication of products and services (Vogtländer et al., 2012), and another path to make LCA doable for designers and business managers themselves, in contrast to leaving the application of LCA to experts, which led to the concept of "Fast Track LCA" (Vogtländer, 2010).

Until today, the eco-costs model and the database of pre-calculated impacts expressed in eco-costs are made available through www.ecocostsvalue.com and are accompanied by a series of practical guides and data-books for LCA for students, designers, and business managers (Vogtländer, 2010; Vogtländer, 2011).

The main drive behind this research path is to make environmental impact measurement and quantification easier and less time-consuming. In 2017, the Idemat and IdematLightLca apps were launched containing the eco-costs database as well as some LCA functionalities “at your fingertip” to make LCA based data instantly available to designers (approx., 5500 users in April 2022). To enhance awareness of the potential benefits of a circular economy, IdematLightLca features three standard end-of-life scenarios: land-fill, post-consumer waste treatment, and closed-loop upcycling. The main drive behind this line of research is to facilitate the integration of environmental metrics into decision-making processes, aimed not only at designers, but also at business managers, and addressing policymakers as well.

This thesis is not specifically aiming at improving or validating the use of eco-costs as a single indicator for LCA. It is however investigated whether the use of the eco-costs indicator, in combination with the product value, would lead to other design decision making. (See publication 1)

Up until the start of this thesis, application of the EVR model to various products and services has shown that the EVR model is able to solve many of the challenges faced when analysing and communicating the sustainability of a product or service. The EVR model was effectively applied to deal with the complexities of end-of-life and allocation of environmental impacts (Vogtländer et al., 2001d). The EVR model was also effectively applied to analyse and design packaging products (Wever & Vogtländer, 2012). Also design for and with materials from the biosphere were the subject of studies applying the EVR Model, such as bamboo (Van der Lugt (2008) “Design Interventions for Stimulating Bamboo Commercialization”), and (Mestre (2014) “Cork Design, a design

action intervention approach towards sustainable product innovation”) Both applied the approach of Eco-efficient Value Creation, and both were focussed on the market introduction of their products.
The work of Mestre showed that ‘economy’ and ‘environment’ can be integrated in the product design process. The products were sold in a shop in Lisbon (www.corkandcompany.pt), showing that application of EVC on product level can lead to a viable sustainable product because it enables a viable business model.

In both PhD studies there was little focus on the integrative potential of the EVR model: (1) both products were (mainly) from the biosphere (intrinsically ‘green’); so would it also work in the technosphere? (2) both products were relatively simple; how would it work in far more complex ‘multi-level’ (Joore, 2010) systems? See figure 3.

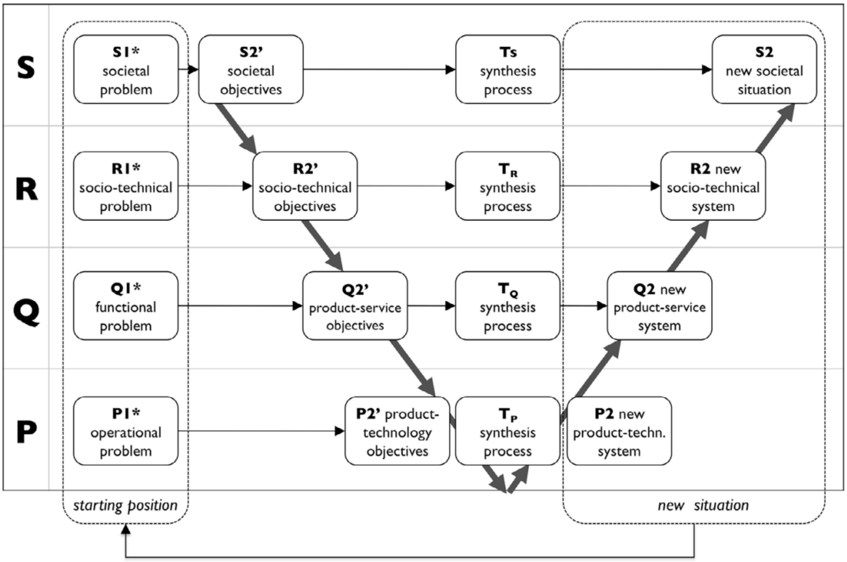

Figure 3: The multilevel design model (Joore 2010)

Figure 3 depicts the various aspects of products and services in society. The work of Vogtländer (2002) already touched upon such a complexity by the ‘3 stakeholders model’, describing the complex relationship between people (as consumer and as citizen), governments and companies. However, this complex relationship was not further analysed in terms of its consequences for design. This knowledge gap is further dealt with by exploring Research Questions 1 and 2 in Section 1.7.

An important aspect of the model shown in figure 3 is that the multilevel design has to be regarded as a global issue (in contrast to a local issue), which increases the complexity. It touches upon the issue of cultural differences and knowledge transfer (Diehl, 2010), and later (Jin, 2015). The issue for the research in this thesis is whether or not the EVR model and the EVC approach can contribute to the design of sustainable products in low-income countries. This knowledge gap is dealt with by Research Question 3, as described in Section 1.7.

The doctorate research of David Peck (2016), revealed a rather shocking lack of interest in the circular economy in SMEs (a survey in 2012). That triggered Research Question 4, described in Section 1.7 on the lack of success of circular business models in general. The issue is here: can the EVR and EVC shed light on the question why, and thereby aid designers in developing sustainable solutions?

Another thesis on the EVR model was written at the Faculty of Architecture (De Jonge, 2005) on the issue of buildings in the public housing sector. The public housing sector in the Netherlands comprises all aspects of figure 3. The role of the Dutch housing corporations is dealt with in this research (the role of government, however, was not dealt with). The thesis of De Jonge, as well as the thesis of van Dam (2013) , did not deal with rebound effects related to the important trend of energy savings in dwellings. This knowledge gap led to Research Question 5, described in Section 1.7.

1.6 Summary of Knowledge gaps

Based upon the above outlined promising initial match with the defined requirements for a more generic sustainable design approach, it was decided to further explore the EVR-based design approach to investigate whether this approach has the potential to form the basis for the required design approach by exploring the following knowledge gaps:

- The EVR-based design approach has been applied in literature on product level quite extensively, however it has not yet been studied whether the approach is useful for designing more complex systems sustainably

- Literature on the application of the EVR model in design processes has not yet explored its application without detailed quantification of impacts and value of design solutions (i.e. cases of "design thinking" only, without quantification)

- The EVR model has been applied in the context of high-income economies, but it's application has not been studied within the context of low-income economies

- Although mentioned in literature on the EVR model, it has not yet been explicitly studied whether application of the EVR model in design within the context of sustainable business models leads to sufficient inclusion of actor pre-conditions, accelerating the required transition

- During the course of this explorative research project, an additional research gap was also identified, related to the need to accelerate the transition: Designers should be capable of designing solutions that prevent rebound effects which have a very real potential for undoing the environmental benefits in one system through the increased use of other systems (i.e. the capability of designing out potential rebound effects)

- It is not yet explored whether the application of the EVR model and the EVC approach are transferable through education and can be applied by non-expert designers

1.7 From knowledge gaps to Research Questions

The main issues as described in Section 1.1 - 1.5 and the gaps summarised in Section 1.6 trigger the definition of six Research Questions (RQs) to be dealt with in this research project.

1.7.1 RQ1

The transition to a sustainable society is dependent on the economic system's ability to reduce its environmental impact significantly, whilst supporting their corresponding business models, i.e. value creation potential. To a certain extent, this can be solved by transitioning from the current linear economy paradigm to a circular economy. Part of the popularity of the circular economy concept appears to be that it promises some sort of fix-all: 'if we simply transition to a circular economy, we will have a sustainable economy'. Although the concept of a circular economy seems promising, a transition towards a circular economy requires the ability to analyse and design sustainable business models, as well as enable objective measurement of the environmental impact reduction in order to prove that an actual significant contribution has been made to improve the environmental impacts associated with the current and new solution.

After the publication of the Cradle-to Cradle (C2C) concept (McDonough and Braungart, 2010) it became clear that the "new economy" as envisioned by the Brundtland Commission had to have the characteristics of a circular economy. However, it was also clear that: (1) it is not easy to make the transition to a circular economy (2) a circular economy will not be a panacea for all environmental problems.

The concept of circular economy had in many aspects the same characteristics as the concept of Product-Service Systems: the ease of implementation and the effect on the environment were widely overestimated (Tukker, 2004). At the start of this doctorate research it was already expected what was later concluded in peer-reviewed publications on the implementation and the impact of the circular economy (Linder & Williander, 2017) (Geissdoerfer et al., 2018) (Oghazi & Mostaghel, 2018).

Both concepts:

(1) are based on the interaction between companies and consumers, but the crucial role of governments are missing (taxes, subsidies, and, most importantly, regulations).

(2) miss a crucial check on the environmental effects in the early design stage.

With regard to point (1), the EVR model and the EVC approach had the same shortcomings: the role of the government was mentioned in the '3 stakeholders model', however, the consequences for product design and business modelling were missing. There had not yet been an exploration of the application of the EVR model and the insights it can bring for the design of new regulatory drivers in concert with the design of sustainable products, services and PSS as well as their business models. The necessity for (new) infrastructure for (new) products, services and PSS, were frequently mentioned, but this had not been a focal point for previous research on the application of the model of the EVR. These

observations lead to the definition of the first research question:
RQ1: Can the model of the Eco-costs/Value Ratio and the Eco-efficient Value Creation approach enable analysis and viable sustainable design of complex products, services and systems?

Publication 1 (see Part II of this thesis): “Two LCA based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable” deals with this research question. This paper describes the application of the EVR model and the approach of EVC to a practical case: sustainable innovation for water tourism in the province of Friesland in the north of The Netherlands.

1.7.2 RQ2

During design processes, available resources such as time, are an important constraint. Designers (as well as business managers and policymakers) need to be able to make design decisions without always having the possibility to in-depth analyse and quantify environmental impacts and value.

Application of the original model of the EVR is based on quantification of eco-costs as well as value, hence application of this model requires a considerable amount of time. However, especially in the fuzzy front end of the design stage, it should be possible to apply the EVR model without in-depth measurement and quantification. This approach, which we call “EVR-thinking”, should be applicable by designers in the early stages of innovation processes to determine the best innovation direction towards the most environmentally sustainable solution space with the highest customer perceived value, whilst taking the viability of new business models into account.

Qualitative application of the EVR model was not yet studied thoroughly at the start of this doctorate research, since the application of the EVR model has been focused on quantification of impacts and value creation, its value for strategic decision making and communication of sustainability. In practice, it is inevitable that decision making should be enabled without the added burden of having to quantify all details in the early stages of design processes. Circular business approaches, in combination with EVR-thinking must provide a qualitative overview in the early stages of design processes. These observations lead to the definition of the second research question:
RQ2: Can "EVR thinking" guide the design of new sustainable business models in the early stages of the design process?

Publication 2 (see Part II of this thesis): "Innovation in product and services in the shipping retrofit industry: A case study of ballast water treatment systems" deals with this research question. In this paper, the approach is taken to apply the EVR Model in a qualitative and integrative manner (the 'circular transition framework'), in order to explore its implementation. The case that is presented is based upon the development of international regulations that require retrofitting of current solutions in the current sociotechnical system.

1.7.3 RQ3

Successful application of the EVR Model and the approach of Eco-efficient Value Creation in low-income economies might help to mitigate local problems (i.e. might 'decouple ecology and economy'), therefore it makes sense to explore the application of the EVR approach in a non-western context. This is deemed highly relevant, since people in low-income economies might have other priorities than safe-guarding

the environment: there are more pressing concerns such as poverty and hunger. It is clear that environmental impacts steadily increase in developing countries.
Thereby it is important to note that in today's global market economy, many of the products and services consumed in high-income economies are actually produced in low-income countries.

Therefore, in order to be able to effectively address the growth of global environmental impacts, the EVR model and the EVC approach should also be applicable to the design of new products and services in low-income economies as well, which until now has not been sufficiently investigated: Application of the EVR model to analyse and provide guidance for the design of sustainable products and services and their underlying systems should therefore also be possible outside of the context of high-income countries. Therefore the research question addressed in this chapter is how application of EVR can improve the design of sustainable products in the context of low-income economies:
RQ3: Can the application of EVR analyse (and thus improve) the design of sustainable products in low-income economies?

Publication 3 (see Part II of this thesis): "Evaluating the sustainability of Vietnamese products: the potential of 'designed in Vietnam' for Vietnamese vs. Dutch markets" deals with this research question. In this paper the model of the EVR is applied to the analysis of designs using bamboo by Vietnamese product designers to investigate the relative and absolute sustainability, as well as the customer perceived value of the bamboo products compared to mainstream (furniture) products. This case study explores application of the EVR model in a low-income context by focusing on a design project with Vietnamese Industrial designers and Vietnamese furniture production companies in which knowledge transfer of Eco-design approaches had taken place. To date, application of the EVR approach is not explicitly known to be applied in companies, therefore mainstream furniture designs from a successful global furniture company are used to benchmark the sustainable product designs from the Vietnamese designers. Ikea is selected because the democratic design approach used by IKEA to design its products is deemed quite similar to the EVR based approach. It uses 5 dimensions: Function, Form, Quality, Sustainability and Low Cost. These dimensions are also accounted for, although defined slightly differently, in the EVR based approach: Function, Form, and Quality are represented in the three-dimensional EVR approach through the customer perceived value, Sustainability through Eco-costs and Low-Cost through cost.

1.7.4 RQ4

In Section 1.7.1, regarding RQ1, the main issues with regard to the circular economy concept were already introduced. The circular business concept has not been proven to be the 'cure-all' as it was hoped and perhaps even expected to be. Although most appear to agree with the general philosophy, actually transitioning to circularity still appears to be challenging.

Whilst the overall focus of this thesis is the design of new products and their supporting systems, it made sense to look at remanufacturing as well, as part of the circular economy cascade. The issue here is that remanufacturing is certainly a good system concept for the reduction of environmental impacts, due to the reduction in virgin material- and production energy- use. However, the market share of "real" remanufacturing (i.e. excluding internet returns, and 2nd hand trade) is marginal, e.g. 3.8% in heavy equipment, 2.6% in aerospace, 1.1% in automotive and 0.4% in ICT.

The proposition is that application of EVR and EVC is able to offer new insights into why circular business models such as remanufacturing are not mainstream in current economies, and what could be done in order to enhance their market penetration:
RQ4: Can the application of the EVR Model explain the lack of success for circular business models in practice, and how does it shape future solution spaces for design for remanufacturing?

Publication 4 (see Part II of this thesis): "Combined analyses of costs, market value and eco-costs in circular business models: eco-efficient value creation in remanufacturing" deals with this research question. In this paper the model of the EVR and the EVC approach is applied to the analysis of remanufacturing.

1.7.5 RQ5

An important aspect of the reduction of impacts through innovation is the rebound effect. In this thesis we use rebound effect in the classical meaning of the rebound of energy savings. One of the most relevant forms of the rebound effect is related to the behaviour of people: when energy is saved by an innovation, the result is that people save money as well, but this money will be either spent on more of the same products or on other products. When these other products have a higher eco-cost/price ratio, the overall result of the energy saving will be negative on the societal level. Only when the savings are spent on products with a lower eco-costs/price ratio, the overall result is positive. This is a major cause for the slow transition of our society: In order to be able to design and implement truly sustainable products and services, designers should be able to cope with potential rebound effects that would render the innovation unsustainable in the long term.

In order for designers to include rebound effects in their design process, application of the EVR Model and EVC approach should be able to explain and provide an approach to mitigate or prevent rebound effects. This leads to the following RQ:
RQ5: Can the EVR model and the EVC approach aid designers to understand and prevent potential rebound effects?

Publication 5 (see Part II of this thesis): "Insulation or Smart Temperature Control for Domestic Heating: A Combined Analysis of the Costs, the Eco-Costs, the Customer Perceived Value, and the Rebound Effect of Energy Saving" deals with this research question. In this paper the model of the EVR is applied to the analysis of two strategies aimed at improving the sustainability of domestic heating energy use.

1.7.6 RQ6

In order to maximize acceleration of the required transition, everyone involved in design and innovation should be addressing these issues. To achieve this, full integration of eco-efficient value creation within design practice could be required across sectors, disciplines, industries and contexts. The logical path towards this integration within design practice is through design education. Hence an important question to explore is:
RQ6: Can the EVC approach be embedded into design education, and does that lead to successful results?

To this end, 2 design projects have been observed:

(1) a group of 4 students from various faculties in the final year of the bachelor's degree (see Appendix)
(2) an IDE graduation project (see publication 6)

The goal of these experiments was to investigate whether the students are able to grasp the concept, perform the required actions in the given time, and are able to design sustainable products, services as well as incorporate viable business model requirements.

Hence over the course of this research project, the EVC approach has been transferred to multiple design students, of which one Industrial Design Engineering MSc graduation thesis project led to Publication 6: "Eco-Efficient Value Creation of Residential Street Lighting Systems by Simultaneously Analysing the Value, the Costs and the Eco-Costs during the Design and Engineering Phase" (see Part II of this thesis).

In this publication, the practical challenge of designing a sustainable street lighting system using the EVC approach is explored.

1.8 Research Design

Based on Section 1.1-1.3, the research focus of Section 1.4 & 1.5, the knowledge gaps in Section 1.6, 6 different research questions were selected for publication, described in Section 1.7.

RQ 1-5 are explored by EVR application in 5 different practical cases.

RQ 6 is answered by transferring the knowledge, principles and tools of the EVC approach and testing this with design students, also to practical cases. Through case study selection (or actually absence of selection, taking on anything that came by), application of the EVR model and the EVC approach across sectors, industries and systems takes place, enabling the exploration of the main issues through the 6 defined RQs as shown in figure 4.

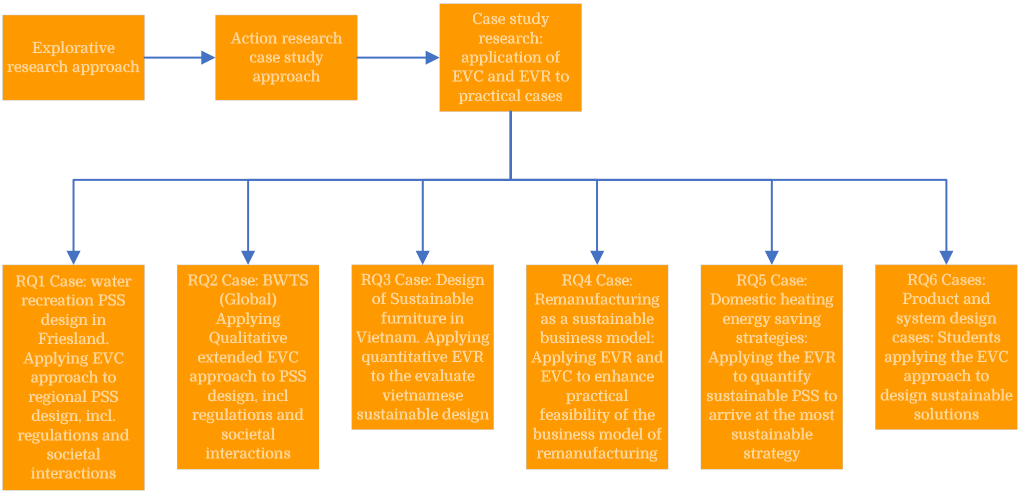

Figure 4: Line of reasoning Research design and Case Studies

1.8.1 ACTION RESEARCH

This research follows an explorative approach, since the main issues of this thesis focus on how designers can further accelerate the transition. Given the knowledge gaps as discussed in Section 1.6, the focus of this research is thus to explore how the application of the EVR model and the EVC approach can further enable designers to achieve successful sustainable design. Therefore this design research is set-up as an action research: Action research is concerned with processes and phenomena that would not have occurred without active intervention from a researcher. In all cases in this research project, the interventions are based on the application of the EVR model and the EVC approach.

1.8.2 CASE STUDY RESEARCH

Due to the pragmatic nature of the overarching goal of this research project: enabling designers to accelerate the transition to a sustainable society, it is decided to investigate the application of EVR and EVC 'in the real world'. Therefore this research is also set-up as a case-study research, since this type of research method is highly suitable for this challenge (Yin, 2009):

- The focus is to answer 'how' questions
- It is not possible to manipulate those involved in the study
- It is desired to cover contextual conditions because they are essential to the phenomenon under study
- Or the boundaries are not clear between the context and the phenomenon

In order to investigate the multi-level, multi-actor integrative applicability and usefulness of EVR and EVC, care is taken not to pre-select case studies, but rather take on cases that “came along”. In these case-studies, the researcher takes on the role of a reflective practitioner (Schön, 1983), since there is a gap between scientific approaches to Eco-design and the successful implementation of these Eco-design approaches in practice as previously discussed in section 1.3. The research design is intended for the researcher to gain experience with the application of the EVR model and EVC approach, and thereafter reflect on the gained experience.

The research design thus follows reflection in action on the level of the publications that constitute this thesis as described in Section 1.10 on the results of the case-studies. The main conclusions in this thesis are drawn based on reflection on action, to assess whether the publications have contributed to the overall goal of this thesis, addressing the main goal formulated at the start of this research project, to accelerate the transition, by focusing on three aspects: Dissemination, Applicability and Impact. These aspects will be discussed in section 1.11.
There are four major pitfalls with case-study research where the role of the researcher is that of a reflective practitioner, or a “participant observer” as it is described by (Yin, 2009):

- “The investigator has less ability to work as an external observer”
- “The participant-observer is likely to follow a commonly known phenomenon and become a supporter of the group or organization being studied”
- “The participant role may simply require too much attention relative to the observer role”
- “The participant-observer may find it difficult to be at the right place at the right time“

The first and third common pitfalls are expected to be less likely: The observations are expected to be made whilst being a participant, since the action research case study approach is applied: By applying the EVC approach to practical cases, it is explored how useful the EVC approach is for enabling designers to support acceleration of the transition. To further decrease the likelihood of these pitfalls occurring, the knowledge about the EVC approach has also been transferred to novice industrial design engineering who have applied the approach enabling the researcher to safeguard acting as an observer.

The second pitfall is more likely to occur, since the researcher is focusing on applying the EVC approach, although application of design approaches integrating ecological and economical aspects into the design process is hardly a commonly known phenomenon. By allowing for random case study selection, it is expected that it is unlikely that the researcher becomes a supporter of the organization.

The fourth pitfall is also expected to be avoided by accepting case-studies that present themselves throughout the research process.

1.8.3 ACTION RESEARCH CASE STUDY APPROACH

Hence in this thesis, a mixed methods research approach is explored. While it is not common to combine action research with case study research, an action research case study approach has been found to be particularly suitable for sustainability research (McManners, 2016).

1.9 Results: Reflection in action

This section summarizes the results of exploring the six RQs of this research project.

1.9.1 THE RESULTS OF EXPLORING RQ1

RQ1: Can the model of the Eco-costs/Value Ratio and the Eco-efficient Value Creation approach enable analysis and viable sustainable design of complex products, services and systems?

This RQ is primarily dealt with in the case of publication 1: "Two LCA based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable". The RQ is also explored in publications 2, 4, 5 and 6, since these also deal with challenges associated with complex products, services and systems.

The main result after exploring RQ 1 in publications 1,2,4,5 and 6 is that there is a positive indication that the EVC approach and EVR model can be applied to the analysis and viable sustainable design of complex products, services and systems.

This is predominantly based on the following reflections from publication 1: "To avoid further environmental deterioration, the water recreation service must be converted to a sustainable business model through the introduction of sustainable yachts, using renewable energy for propulsion and applying sustainable materials. In this analysis, it is shown that replacing the diesel technology in rental motor yachts with electric propulsion (which results in an overall eco-costs reduction of over 50%) is essential to convert the business model into a sustainable solution...." (Scheepens et al, 2016, p. 267).

Another result is that the approach provides benefits to the designer, due to the provision of a wider perspective. “The advantage of the method of Eco-efficient Value Creation is that the designer of a system is guided in a wider perspective than costs and subsidies alone” (Scheepens et al, 2016, p. 267).

The third main result is that when engaging in sustainable design of complex products, services and systems that the EVC approach and EVR model could benefit from translation into a more visual tool to support designers with a comprehensive overview on how to organize the stakeholder activities to enhance the value for sustainable products and services. Therefore another result of the exploration of RQ 1 in publications 1 and 2 is the Circular Transition Framework, integrating the EVR model with the multiple system levels as well as the involved actors: “The Circular Transition Framework has been useful for structuring the complex management of stakeholder activities within the regional business model. Incorporating the EVR approach in a holistic manner has led to a comprehensive overview of how environmental sustainability can be improved on a societal level, by using regulatory drivers for relative enhancement of the value of the regional business model for sustainable offerings” (Scheepens et al, 2016, p. 267).

1.9.2 THE RESULTS OF EXPLORING RQ2

RQ2: “Can EVR thinking and the circular transition framework guide the design of new sustainable business models in the early stages of the design process?”

This RQ is dealt with in publication 2: “Innovation in product and services in the shipping retrofit industry: A case study of ballast water treatment systems”. The conclusions of this publication leads to the result that there is a positive indication that the qualitative application of the EVR model within the early stages of the design process can be successful.

In publication 2 it is concluded that the qualitative application of the EVR model is valuable in the early stages of the design process, since the application concerned the development of future business strategies aimed at enabling eco-efficient value creation: "The EVR model has been found to be a valuable tool for developing future business strategies for Eco-efficient Value Creation in BWTS" (Rivas et al., 2015, p. 452).

It is also concluded that the approach can be applied successfully, since clear recommendations for the designer, as well as other actors could already be formulated, without the immediate need for quantification.
"It provides direction for innovation on a product and PSS level, as well as for business strategies and regulation development. The model also indicates that the regulation could be refined towards stimulating port-based BWTS, instead of on-board BWTS ..." (Rivas et al., 2015, p. 452).

1.9.3 THE RESULTS OF EXPLORING RQ3

RQ3: "Can the application of EVR analyse (and thus improve) the design of sustainable products in low-income economies?"
This RQ is dealt with in the case of publication 3: "Evaluating the sustainability of Vietnamese products: the potential of 'designed in Vietnam' for Vietnamese vs. Dutch markets".

The conclusions of this publication leads to the result that there is a positive indication that application of the EVR model is possible for the analysis of products sustainability in low-income economies, as well as to define recommendations to two of the main actors in the transition: " ...... it has demonstrated the potential for EVR application in new, 'emerging' contexts such as Vietnam. These findings have two main implications for business managers and policy makers in Vietnam. For both, EVR thinking can be applied into future projects holistically from the outset, and not only as an evaluation tool. For business managers, EVR adds holistic value to sustainability beyond environmental considerations that connect sustainability considerations more tangible, such as its potential multi-market perspective. For policy makers, promoting the integration of EVR from start to finish could widen the scope of sustainable design from creating environmental value to creating multiple forms of value: social, cultural, and economic" (Jin & Scheepens, 2016, p. 91).

Another result of the application of EVR is that benchmarking product design from low-income countries shows that products following Eco-design approaches are not environmentally sustainable when considering that consumers, especially in low-income countries, are even less likely to be willing to pay a premium for environmental sustainability in their products.
"The EVR perspective adds a valuable perspective that environmentally sustainable products are not necessarily holistically sustainable when considering whether or not consumers are willing to pay a premium for environmental sustainability. Globalized companies such as IKEA are often accused of green-washing, but the EVR analysis clearly shows that the design philosophy of IKEA is quite effective in achieving high value products with relatively low Eco-costs. The total Eco-costs of IKEA products were comparable to FLS products that were developed with environmental sustainability in mind despite their use of mixed materials and their complex supply chain" (Jin & Scheepens, 2016, p. 91).

1.9.4 THE RESULTS OF EXPLORING RQ4

RQ4: "Can the application of the EVR Model explain the lack of success for circular business models in practice, and how does it shape future solution spaces for design for remanufacturing?"

This RQ is dealt with in the case of publication 4: "Combined analyses of costs, market value and eco-costs in circular business models: eco-efficient value creation in remanufacturing". The conclusions of this publication lead to the result that application of the EVR model is possible to explain the lack of successful implementation of circular products and services on a large scale. Through application of the EVR Model, it is clear that remanufacturing, as a potentially sustainable strategy, is not always immediately more environmentally sustainable on a system level. It requires nuance: "The premise that remanufacturing is always good for the environment, since it reduces the overall use of materials, does not hold true in all cases.... When the energy consumption of a product in the use phase is high (e.g. cars, refrigerators), remanufacturing should not only address functional recovery and physical appearance. It should also deal with the fact that modern technology is more eco-efficient than technology of the past" (Vogtländer et al., 2017, p. 15).

The conclusion is also drawn in publication 4 that environmental sustainability is not a sales argument for circular products and services: "Although remanufacturing is one of the key opportunities to lower the eco-burden for a sustainable future, the use of sustainability as a sales argument seems to be rather limited. The marketing of remanufactured products should focus on the personal benefit for the buyer, rather than the environmental benefit" (Vogtländer et al., 2017, p. 15).

Publication 4 also provides clear recommendations to further enhance the viability of sustainable products, services and their systems (Vogtländer et al., 2017, p. 15): “There seem to be five aspects which are key to the development of viable business models:

- The type of buyers differ from the buyers of the ‘new product’
- The quality must be emphasised in all communication
- Risk must be taken away from the buyer (either by operational lease or by warranties)
- Top level service of repair and maintenance is required to convince the buyer
- A green brand may support the product image”

Most importantly, it is concluded in publication 4 that careful manoeuvring is required in order to enhance the viability of circular products, services and systems: “The final conclusion is that remanufacturing can lead to a circular business model which is both environmentally and economically viable. However, careful manoeuvring is required between the costs, all aspects of market value (Customer Perceived Value), and the eco-costs, including the respective communication” (Vogtländer et al., 2017, p. 15).

1.9.5 THE RESULTS OF EXPLORING RQ5

RQ5: “Can the EVR model and the EVC approach aid designers to understand and prevent potential rebound effects?”
This RQ is dealt with in the case of publication 5: “Insulation or Smart Temperature Control for Domestic Heating: A Combined Analysis of the Costs, the Eco-Costs, the Customer Perceived Value, and the Rebound Effect of Energy Saving”. The conclusions of this publication leads to the answer ”yes, in this cases it does”, see the quote below:

“The combined analyses of costs, eco-costs, and value (i.e., the EVR approach) explains the potential magnitude of the rebound effect, as it clearly demonstrates the point of economic and environmental payback and the likelihood for potential rebound effects. The rebound effect plays an important role, because of two issues, namely:

- The net environmental benefit of the energy savings is often overestimated because of the rebound effect
- A long financial pay-back time seems to be beneficial for the environmental benefit, as it reduces the rebound effect

Hence, it is concluded that the eco-efficient value creation approach and the eco-costs/value ratio are valuable design and evaluation tools for balancing ecological and economic considerations” (Scheepens & Vogtländer, 2018, p. 18).

1.9.6 THE RESULTS OF EXPLORING RQ6

RQ6: “Can the EVC approach be embedded into design education, and does that lead to successful results?”

The RQ is answered through knowledge transfer of the EVR model and EVC approach to design students in order to observe whether novice designers are able to design viable eco-efficient solutions by applying the EVR model and the EVC approach. The answer to the research question is: yes, in the cases observed (see publication 6 & the Appendix), the designers were able to grasp the concept and utilize the available tools and processes to design eco-efficient solutions with surplus value. “The new concept results in a considerable reduction of carbon footprint and eco-costs, shows the benefits for the municipality and for the residents, and results in a viable business case” (Klaassen et al., 2020).

1.10 Conclusion

Following the research design, the main conclusions in this thesis are drawn by reflecting on action, i.e. reflecting on whether the scientific contributions in this thesis have contributed to the overall goal of the thesis, by evaluating three aspects: dissemination, applicability and impact.

1.10.1 DISSEMINATION: SCIENTIFIC CONTRIBUTION OVERVIEW AND ANALYSIS

The following table summarizes the 6 publications and their respective exploration of the 6 RQ's in this thesis.

	RQ1	RQ2	RQ3	RQ4	RQ5	RQ6
P1	+	0	0	+	0	+
P2	+	+	0	0	0	+
P3	0	0	+	0	0	0
P4	+	0	0	+	0	0
P5	+	0	0	0	+	+
P6	+	0	0	0	0	+

Table 1: Overview of RQ's explored in the published case-studies

Four publications have received moderate to high research interest. Publication 1, to date (May 2022), is cited in 277 publications, publication 4 is cited in 61 publications, publication 2 is cited in 44 publications, publication 5 is cited in 8 publications and publication 6 is cited in 6 publications.

Given the high research interest for publication 1, the research presented in this paper carries most weight in drawing final conclusions on the contribution of this design research thesis towards dissemination of the scientific advances in support of design approach development enabling designers to contribute more effectively to the required transition.

Upon analysis of the ten most cited papers citing publication 1 to date (May 2022) (Lewandowski, 2016, Winans et al. 2017, Pomponi & Moncaster, 2017, Elia et al., 2017, Pieroni et al, 2019, Cayzer et al., 2017 in Saidani et al. 2019, Moraga et al., 2019, Pauliuk, 2017, Linder et al., 2017, and Nußholz, 2017), it becomes apparent that most of these papers cite publication 1 while referring to the potential usefulness of the EVC approach with regards to designing for viable sustainable business model development or the potential usefulness of the EVR model as an indicator for sustainability. The citing publications are mainly directed towards either analysing or improving circular business models, as a means to accelerate the transition towards more sustainable production and consumption systems.

Combined with the relatively high number of citations for publication 1, and moderate citations for the other publications in this thesis, it is therefore considered plausible there is a positive indication that the scientific publications constituting this thesis have contributed to the scientific debate with regards to the overall goal of this research project of exploring how the EVC approach could support designers to develop viable sustainable products and services.

Based on publication 6 and the Appendix, it is also concluded that dissemination of the EVC approach to design students has delivered promising results, since publication 6 and the Appendix describe the successful application of the EVR model and the EVC approach by design students.

1.10.2 APPLICABILITY

There is considerable evidence, based on publication 1, 2, 4, 5 and 6 that the EVC approach and the EVR model are applicable by designers in the entire process of sustainable design of complex products, services and systems. Successful application within different contexts (high-income vs low-income) leads to a positive indication the EVR Model and EVC approach can be applied in low-income contexts as well. The existing design tools within the EVR model and EVC approach literature, as described throughout publications 1-6, combined with the additional tools developed during the exploration of the RQs are successfully applied throughout the case studies, leading to the positive indication that the EVR model and the EVC approach have the potential to contribute to the ability of designers to design viable sustainable products, services and systems.

The ability of designers to actually design viable products, services and systems is however outside of the scope of this research, and presents the main challenge to be researched further: If it can be proven that designers applying the EVR model and the EVC approach come up with sustainable solutions that consumers prefer over unsustainable alternatives in the real economy, this could be a next major step in the scientific advance of the industrial design engineering profession towards its contribution to sustainable development. This thesis does provide initial indications that the resulting design solutions from application of the EVR model and the EVC approach in some of the case studies leads to viable solutions in the future, since the design resulting from publication 6 has received an international design award, combined with the observation that at least one municipality is facing similar challenges to the challenges solved by the design of the rooftop solar streetlight PSS.

1.10.3 IMPACT

The application of the EVR Model and the EVC approach to the challenges presented in the 6 different case studies has led to the design of complex products, services and systems. The resulting contribution to accelerating the transition is based on the reduction in EVR achieved in each case. Since Publication 2 concerns qualitative application of the EVR model and EVC approach, this publication is not taken into account while concluding on the achieved quantified impact as a design contribution to the transition. In publication 3, the case study was limited to the analysis of outcomes of design projects following knowledge transfer of sustainable design approaches, focusing on the use of locally renewable materials. This publication is therefore also not taken into account during evaluation of the achieved impacts of application of the EVR Model and the EVC approach.

The below table represents the amount of eco-efficient value creation achieved in the selected publication, leading to accept there is a positive indication that application of the EVR Model and the EVC approach leads to solutions which have the potential to achieve a lower environmental impact per spent monetary unit in the real economy.

Publication	EVR of benchmark design	EVR new design solution	EVR improvement
1	0,076	0,027	64%
4	0,069	0,037	46%
5	0,25	0,11	66%
6	0,046	0,027	41%

Table 2: An overview of the calculated EVR before and after the design intervention for the cases described in publications 1,4,5 and 6 in this thesis

Following the defined EVR range for sustainable products and services as described in publication 1, the EVR of sustainable products and services is below 0,04. The achieved EVR quantified in publications 1, 4 and 6 in table 2 were within this range, whereas the benchmark offerings were all above 0,04 before EVR and EVC were applied.

It is important to note with the results in EVR reduction from publication 5 and 6, the effects on system level, i.e. the energy savings, have been excluded, due to the fact that the energy savings would elicit rebound effects, for which it cannot be ascertained whether the spending of the saved money would lead to higher or lower environmental impacts than the saved energy. As is clearly shown however in publications 5 and 6, the proposed design solutions would lead to a negative EVR, which,without rebound effects, could even be classified as impact-positive.

1.11 Recommendations for further research

This mixed method research project, applying an action research case study approach where in each case (part of) the EVC approach is applied in order to explore its generic potential for accelerating the transition in different contexts and system complexities, has provided indications that the EVR based approach has potential to serve as a promising approach for designers.

Whilst the observations on the overall applicability of the EVC approach lead to a rather stimulating conclusion, an important limitation that even though the EVC approach has been applied to real-world cases, it has not been possible to collect evidence on actual business model viability of the proposed design interventions. Further research is recommended to investigate whether large scale application of the EVC approach would lead to actual substitution of unsustainable products in the market.

Another important limitation of the selected research design is that for most cases it cannot be known whether, without the design interventions, the search for sustainable solutions would have led to other solutions, and whether those potential other solutions would have a higher EVR or actually might have a lower EVR. However, e.g. in publication 3 a preliminary indication was found that with application of environmentally focused design approaches, the design choices in some cases led to sub-optimal design solutions in terms of eco-efficient value creation.

Another limitation of this research approach is that there might be many companies already applying the EVC approach, without defining their approach as an EVC approach. At least one observation points in this direction in publication 3. Further research is recommended to investigate whether there are more design approaches practiced in the business context that are similar to the EVC approach, and subsequently analyse whether these companies are outperforming their competition as well as whether their success is enabled by regulatory development.

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Part II: Publications

This section contains the 6 research papers developed and published during this research project.[*]

Publication 1: Two LCA based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable

Publication 2: Innovation in product and services in the shipping retrofit industry: A case study of ballast water treatment systems

Publication 3: Evaluating the sustainability of Vietnamese products: the potential of 'designed in Vietnam' for Vietnamese vs. Dutch markets

Publication 4: Combined analyses of costs, market value and eco-costs in circular business models: eco-efficient value creation in remanufacturing

Publication 5: Insulation or Smart Temperature Control for Domestic Heating: A Combined Analysis of the Costs, the Eco-Costs, the Customer Perceived Value, and the Rebound Effect of Energy Saving

Publication 6: Eco-Efficient Value Creation of Residential Street Lighting Systems by Simultaneously Analysing the Value, the Costs and the Eco-Costs during the Design and Engineering Phase

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Publication 1

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Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism more sustainable

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ABSTRACT

There is a need for metrics to analyse complex business models in the circular economy. Life cycle assessment (LCA) currently is the best defined system to analyse the environmental aspects, and is capable to analyse circular systems, Product Service Systems, and systems for recycling. However LCA falls short of analysis of the added value of business models. Since new sustainable business models are part of the transition towards a circular economy, there is a need for combined analyses of value and eco-burden.

This paper applies the LCA-based Eco-costs Value Ratio (EVR) Model to analyse potential negative environmental effects of business initiatives on a system level, and to provide a theoretical approach to the design of sustainable business models by means of a three dimensional approach of costs, eco-costs and market value. Two methods are applied for analysis and design: Eco-efficient Value Creation (EVR benchmarking) and the Circular Transition Framework (describing stakeholder activities which are required for the transition towards sustainable business models).

The practical case of the analysis, design and implementation of a business model for sustainable water recreation in Friesland (a province in the Netherlands) is used to validate the usefulness of these two LCA-based methods.

The conclusion is that the approach of Eco-efficient Value Creation helps to avoid many pitfalls of the design of circular business models (e.g. having a positive result on product level, but having a negative effect on societal level; having a positive effect on the environment but having insufficient customer perceived value to overcome fierce market competition). The Circular Transition Framework reveals pitfalls and opportunities in implementation (e.g. the coordination between business models and governmental policies).

1. Introduction

1.1. The transition towards a circular economy

The quest for a sustainable society is the quest for solutions in the so called “circular economy”. The notion that materials in the “techno sphere” must be recycled, toxic emissions must be eradicated, fossil based energy must be replaced by renewable energy, and that materials from the “bio sphere” provide new opportunities for innovations, is not new. New is, however, the focus on the *transition* from the old, linear and unsustainable systems towards new, circular, systems. Essential for such a transition is that new business models must be developed to support this transition. These business models must have extra added value (in comparison to the market competition) combined with lower eco-burden (less resource depletion as well as less environmental pollution).

Our expansive economic system is putting enormous stress on the planet's carrying capacity. Global environmental concerns have led to the emergence of the green economy, which extrapolates to the concept of circular economy (Mathews, 2011). Opposing unsustainable “business as usual”, which is generally characterized as being linear in nature, the circular economy approach focuses on closing loops (economically) and thereby on reducing environmental impacts.

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The issue in this paper is not the general philosophy of the circular economy as such, but its practical implementation. Literature on the general philosophy is abundantly available for the Chinese state controlled economy (Su et al., 2013, (Yuan et al., 2008)), but not for new circular business models in the Western free market economy. However, there are two leading reports of the Ellen MacArthur Foundation (written with the help of McKinsey) on the business opportunities in our Western economies (Ellen MacArthur Foundation, 2013). In these reports general guidance is given for circular business model development, but a lot still has to be learnt in practice about design and implementation.

This paper discusses two approaches which are in line with the principles of the circular economy, since they are not only focussed on the environmental aspects of product systems, but also on the business aspects of the required transition: the approach of Sustainable Product Service Systems, and the approach of the Ecocosts/Value Ratio (EVR) with two design methods: Eco-efficient Value Creation and the method of the Circular Transition Framework.

The approach of Product Service Systems is focussed on new business models which fulfil the functional needs of the customer in innovative ways by adding services to products. This approach is summarised in Section 1.2.

The approach of the Ecocosts/Value Ratio, in short EVR, is LCA based (ISO 14044, 2006) (EU Joint Research Centre, 2010). This comprehensive approach is developed to analyse the sustainability of products, services, and their business models. Eco-efficient Value Creation is the part of the EVR which has its focus on a two-dimensional analysis and design of the eco-burden and the market value of a system. This method has recently been published in this journal for the case of sustainable product design (Mestre and Vogtländer, 2013). Eco-efficient value creation is explained in Section 2.1, and is applied in Section 3 to complex systems, with a regional water tourist system as an example. The Circular Transition Framework, part of the EVR as well, describes the transition pathways on the level of activities with added value (Section 2.2). This framework was recently introduced in this journal (Rivas-Hermann et al., 2014) for the case of a simple Product Service System, and is used in this paper to analyse the implementation of a complex regional water tourist system (Section 3.4).

1.2. Bundling of products and services a panacea for the circular economy?

Bundling of products and services results in a so-called Product Service System (PSS). It is common practice in modern business development to boost the sales of a product. Examples are adding financial services to a product (e.g. leasing or borrowing related with the sales of cars), adding maintenance services to the product (e.g. free maintenance for the first years), or adding convenience (e.g. collecting cars at home for repair and maintenance and bringing them back). The Ellen MacArthur Foundation (2013) highlights the financial PSS as a means of creating new business models in the circular economy ("*high-end washing machines would become accessible for most households if they were leased instead of sold*" (Vol. 1, p. 9)), where these machines have a lower energy demand and a longer lifespan than the low-end machines. Especially the absence of ownership ("dematerialization"), facilitated by IT services, is appealing to environmentalists (sharing or pooling of products).

The concept of PSS, however, is not a panacea for making our society more sustainable, as shown by many European research projects on the subject (Bartolomeo et al., 2003) (Tukker, 2004) (Tukker and Tischner, 2006) (Tukker, 2015). Tukker indicates that the only type of Sustainable PSS is the 'result-oriented' type where a function can be fulfilled in a less polluting way (e.g. videoconferencing to replace conventional meetings). White et al. (1999) already stated: ”*It is clear that the simplest and most optimistic view — a service economy is inherently clean economy — is insufficient and incorrect … […] … Instead, the service economy is better characterized as a value-added layer resting upon a material-intensive, industrial economy.*" (p. 1). White et al. conclude that, even though growth in services might be less environmentally damaging than growth in manufacturing: *"If services are to produce a greener economy, it will be because they change the ways in which products are made, used and disposed of — or because services, in some cases, supplant products altogether."* (p. 1).

One may conclude that a PSS can support the transition to a circular economy, but new business models must be implemented with care.

The reason for a lot of confusion about PSS is its complexity related to changes in customer behaviour, boundary limits, and 'rebound effects' (explained in Section 2.1.2). The EVR model (Section 2) unravels this issue, and the case study (Section 3) is an example of such complexity. To give some food for thought, two examples are given below.

Example 1. The gut feeling that sharing a product results in less materials depletion is in most of the cases wrong, which can be seen by making the analyses *cradle-to-grave* instead of *cradle-to-gate*. When two families have a car and drive 25,000 km per year, and the life span of the car is 250,000 km, they will need two cars per 10 years, regardless whether they share the cars or not. There is also no difference between the case that both families buy a new car and use it until the end, the case were family A buys two times a new car during the period and sells them to family B, and the case that both families share the first car and have to buy a second car for the second period. There are product types in our modern society which are discarded way before they are worn out or broken, such as clothing and mobile phones. These product are, however, not very suitable for shared use, therefore PSS is not a solution. Sustainable solutions for such products are reuse (2nd hand circuit), recycling, and change in customer behaviour. Only a few niche markets (e.g. electrical hand drills at home) are suitable for pooling. But even then, the disadvantage is that the users save money, leading to a 'rebound effect' which mitigates the environmental advantage (Vogtländer et al., 2014).

Example 2. An example of a successful car sharing business is the Dutch company Greenwheels (https://www.greenwheels.com/nl-en/Home/Private/Home), accessed August 2014). This company adds 'clean' rental services to 'dirty' cars (what is to be considered as 'clean' and 'dirty' is defined in Section 2.1). In terms of consumer behaviour, the Greenwheels PSS has two opposed system effects for two different customer segments (A and B):

A) Consumers who used to own a car, now use a combination of public transport and shared automobiles provided by Greenwheels, resulting in a reduction in eco-burden for transport. The main reason for this change in behaviour is that, when you invest in a car you are inclined to use it, whereas when you pay per kilometre you are inclined to avoid the costs of driving extra kilometres;
B) Consumers who did not own a car, now move partly away from using public transport because they have access to a 'private' car without the need to invest in one, resulting in an increase in the overall eco-burden for transport.

Since generally over 80% of the environmental impact of such products is generated in the use phase by the combustion of fuel, the environmental impact reduction of sharing the physical product is insignificant at best. Depending on consumer behaviour, it remains questionable whether the amount of use of cars for mobility on a system level is reduced: it is likely that such a PSS stimulates the use of cars on system level, rather than reducing it (Vogtländer et al., 2014; Meijkamp, 2000). "*In fact, product sharing, without the appropriate protections or contractual provisions, could make the individual user less concerned about maintenance, creating what economists call moral hazard, and potentially increasing use-phase environmental burdens or reducing product lifespan*." (Lifset, 2000) (p. 1–2).

The conclusion is that a PSS must be designed with great care, since it might seem beneficial for the environment, but might increase the environmental burden as well (e.g. Agrawal et al., 2012). When leasing is applied to increase market share of a 'dirty' product, it is damaging our environment, however, when leasing is applied to increase market share of a 'clean' product, it is beneficial. When products save energy in the use phase, but require higher upfront investment (e.g. an electrical car), leasing is an important component in the business model.

In order to objectively assess and improve sustainable innovations and avoid unforeseen environmental impacts, quantitative assessment tools are required (De Pauw et al., 2014). A powerful tool to analyse a PSS is the model of the EVR. In this model, a product or service has three dimensions which are kept strictly apart from each other: the costs, the eco-costs, and the (market) value, which is explained in the next section.

2. The methods

2.1. *Eco-efficient value creation and the model of the eco-costs/value ratio*

2.1.1. *Eco-costs and market value*

Eco-costs is a so-called 'single indicator' in LCA. It is a measure to express the amount of environmental burden of a product on the basis of prevention of that burden: the costs which should be made to reduce the environmental pollution and materials depletion in our world to a level which is in line with the carrying capacity of our earth (the 'no effect level'). The eco-costs should be regarded as hidden obligations, also called 'external costs' in environmental economics (European Commission, 2003).

The eco-costs have been introduced in this journal (Vogtländer et al., 2002) and in the International Journal of LCA (Vogtländer et al., 2001), and has been updated in 2007 and 2012 (see for a comprehensive description www.ecocostvalue.com, accessed August 2014).

The market value equals the price in a simple EVR analysis, which is a reasonable assumption for most consumer products in our Western market economy. For the case in this paper, however, we have to zoom in to the level of the consumer, revealing a more complex issue: the perception of the individual buyer. We have to understand the relationship between the value, price and cost of successful offerings, see Fig. 1. For definitions see Table 1.

Table 1
A summary of important concepts used in this paper.

EVR	The Eco-costs/Value ratio
Eco-costs	A prevention based single indicator for environmental impacts (€)
Value	The sum of the perceived product- & service-quality, and the image (€)
Price	The price at which these offerings are sold in the current market (€)
WTP	Willingness to Pay (€)
Customer Perceived Value	The expected use and fun of a product and/or service after the purchase (€)
Surplus Value	The difference between the price and the customer perceived value (€)
Eco-efficient Value Creation	The overall aim of application of the EVR Model (the double objective)
Double Objective	Lowering of the eco-burden of a product and/or service and at the same time enhancing the value
'clean' product and/or service	EVR < 0.04
'dirty' product and/or service	EVR > 0.4

In Fig. 1, the difference between the costs and the price is the profit margin for the seller, and the difference between the price and the (customer perceived) value constitutes the 'surplus value'. The higher the surplus value, the more desirable the offering is.

For a commodity product, the price and the value are (nearly) the same (there is hardly any surplus value). The price of a luxury product, however, can be considerably lower than the customer perceived value for the individual customer (the individual surplus value can be rather high). In the case of business innovation, the value can only be determined with some form of consumer research: e.g. WTP inquiries.

Design engineers are commonly faced with this issue, since their activities are directed towards value creation. They use their knowledge, experience and intuition to determine whether their solution creates sufficient customer perceived value at feasible costs, leading to an offering that generates profit for producers at a fair price for consumers. This is why design engineers easily adopt the concept of Eco-efficient Value creation, as stated in Mestre and Vogtländer (2013): "*It is the talent of the designer that creates the value of the product*" (p. 13).

The customer perceived value (resulting in a WTP) is related to the perception of the product by an individual buyer at the moment of purchase (i.e. the expected fun and use after the purchase) and in the use phase thereafter (which can lead to either increased

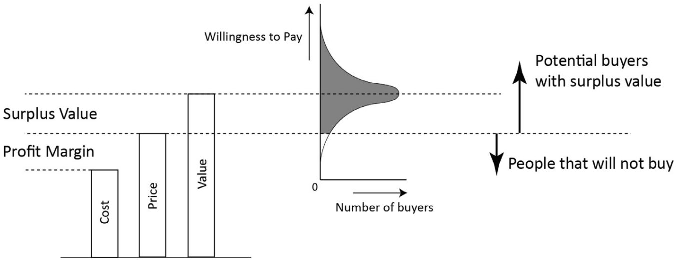

Fig. 1. The relation between costs of production, the price at point of sale, and the customer perceived value of a successful offering (Vogtländer et al., 2014): only buyers that perceive surplus value will consider buying the offering.

satisfaction or dissatisfaction) (Gale, 1994). For some potential buyers in the market the surplus value is positive, for some it is negative (these people do not buy the offering), as depicted with the Gauss curve in Fig. 1. The customer perceived value is determined by the physical and functional product qualities (tangible as well as non-tangible), the service, and the image. Therefore, it is not possible to improve the Ecocosts/Value Ratio just by setting a higher market price, since this will affect the number of buyers: improvement of the EVR requires a higher customer perceived value in order to maximize the surplus value of the offerings.

For a further explanation of Eco-efficient Value Creation, we first need to explain some essential aspects of the EVR model.

2.1.2. The EVR model

The model of the Eco-costs/Value Ratio (EVR) is developed to analyse the required delinking of the economy and the ecology on a product level as well as on a system level: the EVR is a single indicator for sustainability. The basic idea is to combine the 'value chain' of Porter with the ecological consequences this value chain has in terms of eco-costs.

The idea is based on the fact that every step in the value chain adds costs, eco-costs and value to the total system: optimal sustainable design has the lowest Eco-costs/Value Ratio for the total system from cradle to grave. For a circular business model, the situation is slightly more complex than for a linear product chain: at the 'end-of-waste' a new value chain starts, adding value by recycling the materials flow and closing the loop.

The advantage of a service is that the Eco-costs/Value Ratio is low relative to a product, since a service tends to have a lower materials/labour ratio than a product.

The EVR model links the production side of the environmental problem (i.e. make products with lower eco-costs) to the consumer side (i.e. give environmentally sustainable products a higher relative value so that consumers will buy it).

It must be noted that many surveys of customer behaviour in Europe show that the majority of people agree that the environment is important. However, people are not prepared to pay more for the fact that a product is environmentally more sustainable. Therefore, the required added value must be created in other aspects: product quality, service, and/or image (branding), where the environment plays a secondary role, next to health, nature, design, and other 'feel good' aspects (Mestre and Vogtländer, 2013).

A circular business model can have quite an impact on the level of a society. Hence it is insufficient to analyse a system only on the level of the product chain from cradle-to-gate, as it is illustrated in the case of the water recreation system in Section 3. It is therefore important to explain what the meaning is of the Eco-costs/Value Ratio on the level of groups of people. Fig. 2 explains the strategic issue of delinking of ecology and economy on the level the European Union.

Fig. 2 shows the eco-costs/price ratio of products on the Y-axis. This ratio has been calculated for 478 product categories. The X-axis shows the cumulative expenditures (prices in euro) of the products and services within these 478 product categories of the citizens in 25 EU countries (EU 28 excluding Bulgaria, Romania and Croatia). The products and services are ranked on the basis of the eco-costs/price ratio (low ratios left, high ratios right). The data is calculated from the EIPRO (environmental impact of products) study of the EU (JRC, 2006). The area under the curve is proportional to the total eco-costs of 25 EU countries; hence the system level goal is to reduce the area under the curve. There are two strategies to achieve this:

- forcing the industry to reduce the eco-costs of their products (this will shift the curve down)

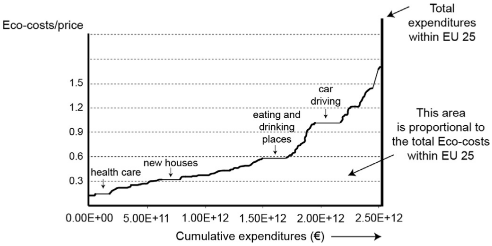

Fig. 2. The EVR and the total expenditures of all consumers in EU25, (EU Joint Research Centre, 2006), re-calculated (Vogtländer et al., 2014).

- trying to influence the buying behaviour (preference) of the consumers, by designing and producing products with low eco-costs that are considered to be more attractive. The result will be less expenditures at the right side of the curve and more expenditures at the left side of the curve (this will shift the middle part of the curve to the right).

Note that simple savings do not work: people tend to spend what they earn (the net lending/borrowing ratio is below 5% in most countries (Eurostat, Eurostat, 2009; Chawla and Wannell, 2005)). In environmental economics this is referred to as the 'rebound effect'[1]: when people save money, they will spend that money again. Some examples: when the fuel efficiency of cars is enhanced, people tend to drive more (Small and Van Dender, 2005); when light bulbs are made more efficient, people tend to apply light bulbs in their gardens (Saunders and Tsao, 2012). Therefore the essence of the EVR model is that people must spend their money on products with low eco-costs by giving these products a high value (price) to avoid the rebound effect.

The question of what is, and what is not environmentally sustainable, can be answered by means of the EVR and the EIPRO study. The average ecocosts per euro spent (EVR) for the EU is 0.4. We call a product 'dirty' when the EVR is higher than 0.4. A 'clean' product is defined by the target – a reduction factor of 4 (Von Weiszäcker et al., 1998) or a factor 10 (Hinterberger and Schmidt-Bleek, 1999) – resulting in an EVR of 0.1 to 0.04 respectively. In this paper a product is referred to as "clean" when it has an EVR lower than 0.04.

The question is how designers of products, services, and circular business models can contribute to the aim of decoupling ecology and economy. The solution is Eco-efficient Value Creation which is explained in the next section.

2.1.3. EVR benchmarking and eco-efficient value creation

The EVR model can be applied to compare existing products where their value (the price) is known. Some simple examples in the field of food packaging show that the 'brown bag paradigm of environmentalists' (= minimising the eco-burden of packaging) does not result in the best solution for sustainability (Wever and Vogtländer, 2013). This study focuses on the comparison of small food containers with a similar primary function, but a difference in quality (customer perceived value). The example of two water bottle designs – one with a normal cap and one with a 'sports-cap'-shows the strength of the EVR model in benchmarking: it clearly illustrates that, even though a 'sports-cap' design generates slightly

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[1] http://en.wikipedia.org/wiki/Rebound_effect_(conservation), last accessed January 14th, 2015.

more environmental impact, it might well be the better option due to its higher price: The EVR of the bottle with 'sports-cap' is better (= lower). Moreover, consumers might experience an increased inclination to re-use the bottle with the 'sports-cap' because of its convenience. If consumers re-use the 'sports-cap' design, they support the transition to a circular economy.

Such mechanisms underline the importance of design as a value-adding activity for the relationship between environmental impacts, customer perceived value and consumer behaviour. The 'sports-cap' design can achieve higher environmental gains on system level than the conventional design with the lowest eco-costs, because of its higher value.

The EVR and Eco-efficient Value Creation can also be applied to new product development: Mestre and Vogtländer (2013) showed this recently in this journal, applying it to high-end design products made out of cork.

The need for the pursuit of the 'double objective' (lower eco-costs and at the same time higher value, as depicted in Fig. 3) for product design and business model design is threefold:

- Modern people tend to buy innovations only when the innovations have a higher value than the existing offerings: it does not make sense to try to implement offerings which will not be bought
- The higher price prevents the 'rebound effect': lowering the EVR is key to environmental sustainability at the level of regions or even at the level of the EU, see Fig. 2.
- The higher price is required to cover the extra production costs of environmentally sustainable products (note that a higher price is only accepted by the customer when the functionality and/or quality is higher)

The most successful design strategies to achieve the 'double objective' are depicted in Fig. 4. In general the best design strategy is:

- to increase value where value is high (more marketing for a better image, more quality and service, and a longer life span) to get a higher market price
- to decrease the eco-costs where the eco-costs are high (a shift to: more labour, more bio-based materials, more recycling, more renewable energy, less transport)

The importance of the end-of-life solution is clearly depicted in Fig. 4. Landfill reduces the value of the total system, and leads to higher eco-costs. Recycling (as well as re-use and remanufacturing) results in an added value combined with lower eco-costs ('end-of-life credits' in LCA). Fig. 4 clearly shows that the transformation towards a circular economy fulfils the 'double objective' of 'eco-efficient value creation'. However, it also shows that designing a sustainable circular system needs to address more than circularity only: other aspects such as cleaner production, minimal transport and optimal marketing play an important role as well.

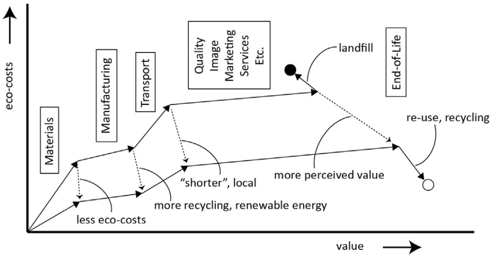

Fig. 4. Design strategies to enhance the EVR of a product (for products with a negligible eco-burden in the use phase).

2.2. The Circular Transition Framework

In order to deal with the complexity of the design of circular business models and their introduction, a Circular Transition Framework has been developed. It describes the different system levels, the stakeholder networks and value creation within these networks, as well as the related effects of regulatory drivers (See Fig. 5). This framework has been introduced in this journal (Rivas-Hermann et al., 2014) and in (Vogtländer et al., 2014). The framework describes the product life cycle in four stages: production, marketing, operation and end-of life. The main stakeholders in the PSS are represented on four different systems levels, derived from the Multi-Level Design Model (Joore, 2010):

The Product-Technology level refers to tangible products. The use of a product is considered a product-service system, if the ownership of the product resides with other stakeholders than the end-user.

The Services and Infrastructure level refers to infrastructure systems and services that are inextricably linked to the products of the product-technology level.

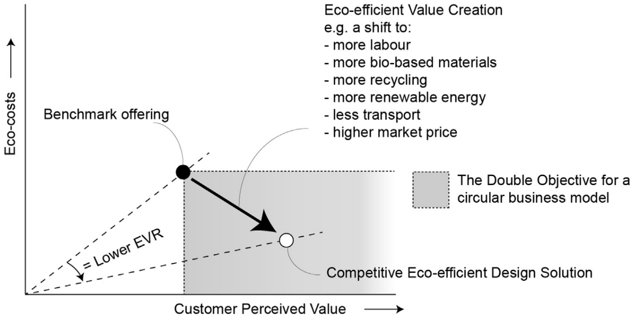

Fig. 3. The double objective of eco-efficient value creation. The objective is to increase the customer perceived value, and at the same time reduce the environmental impacts (Vogtländer et al., 2014).

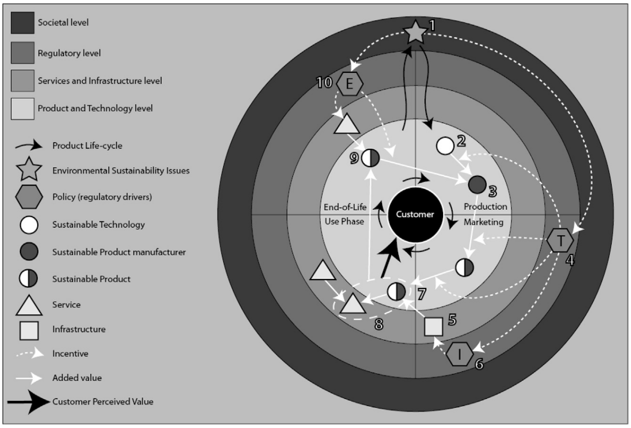

Fig. 5. The Circular Transition Framework for business innovation towards a circular economy.

The Regulation and Subsidies level is related to the contribution of authorities (local, regional and governmental). For the design and implementation of a complex circular business system, it is important to realize that regulations (laws, subsidies, taxation) are often indispensable elements to support and facilitate environmentally sustainable innovations. It is important to consider that regulations on this level are likely to have a broader impact than only on the business model under study. Since the introduction of such a complex system takes several years, it is quite important that the government is a reliable stakeholder for the long term.

The Societal System level is the highest level in the framework. A circular business model has an interaction with the world around it. There are third parties (stakeholders) who benefit from a business innovation; however, there are also third parties who will feel that their current conventional business is attacked by the new business model. The management of the introduction of a circular business system should analyse these outside forces in order to take the appropriate actions. These outside forces of course also include the environment.

The symbols in the framework are explained by a general example.

- The raison d'être of a new circular business model is the desire in society to become more sustainable (star 1)
- Entrepreneurial companies develop new sustainable technologies (circle 2)
- Product manufacturers develop innovative products with the new technologies (circle 3)
- It often appears that the new product cannot be sold without tax reductions (hexagon “T” (4))
- In complex cases infrastructure is needed (e.g. database systems, communication systems, electric grids, see square 5)
- The required infrastructure might be subsidised (hexagon 6)
- The new products are distributed in the consumer market in existing systems (7)
- In the use phase, the product + services might be leased or rented to the consumer (PSS bundle (8)) and the increased customer perceived value is delivered.
- At the end-of-life the product is returned to the manufacturer (or a specialised recycling company) to be dismantled and recycled (9)
- The government might regulate the recycling activity, closing the loop (hexagon “E”)
- The society is happy (or not) with the new business system, which affects further governmental support or which triggers new developments (star 1)

3. The case

3.1. The aim: more water tourists with less regional pollution

Within the EU, much attention is paid to inland waterways and tourism. The EU has developed many regulatory drivers for inland waterways to support optimal benefits of the so-called “single market”, sometimes with limited success (EP, 2009). The single market represents free trade and optimal economic benefits for all 28 member states. There is however no mention of the concept of circular economy in these regulatory drivers, contrary to the example of the Chinese government which has adopted the circular economy as one of its main pillars for future development.

Where tourism products (“holiday packages”) usually have a rather significant contribution from indirect environmental impacts mainly originating from transport (Filimonau et al., 2013), water recreation poses an interesting case, since with these tourism products the accommodation is its own (relatively inefficient) means of transport.

An interesting case of creating a sustainable business model in the circular economy, is the case of environmentally sustainable water tourism in the province of Friesland in the northern part of the Netherlands (with its main area the ‘Friese Meren’ or Frisian Lake District).

This area has had a stable number of water recreation tourists over the last decennium: approx. 1.2 million overnight stays in marinas in Friesland per year (Toerdata Noord, 2011b), however in recent years, water recreants and their individual expenditures are in decline (Toerdata Noord, 2009).

The question is what can be done to expand the regional tourist industry, and at the same time reduce the regional pollution of the lakes, reed lands, and surrounding canals.

In a sense, this is the double design objective at a regional scale: higher value of the existing product service systems (e.g. rental of family boats in combination with the ‘experience’ of the regional

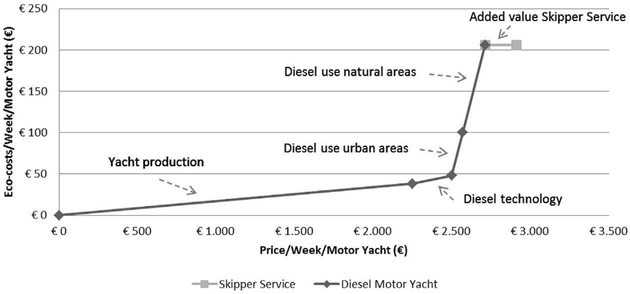

Fig. 6. The value and the eco-costs of one week motor yacht rental in Friesland Lake District.[2]

nature and the regional hospitality industry), combined with less (regional) pollution caused by these tourists.

To achieve this double objective, the Province of Friesland has started the following projects:

- the development and introduction of a ‘water navigation system’, which is an internet information system on waterways, lakes, reed lands, and other natural areas of interest, social activities in villages, and advertisements of local shops, restaurants, museums
- restriction of access to wet areas where nature has to be protected (electric and hybrid boats are allowed, diesel and petrol boats are forbidden);
- subsidies for the introduction of a vast grid of charging points for electric vessels in marinas and beyond;
- subsidies for conversion of diesel propulsion systems of rental vessels to (hybrid-) electric propulsion systems
- and subsidies for on-board solar panels

The Delft University of Technology is involved in the water navigation project. Here it was realized that changing the propulsion system from diesel to electric is the first important step, but a lot can be gained as well by a sustainable redesign of the vessels itself, aiming at lower environmental impact and higher value.

3.2. *The water navigation system: added service to delight tourists*

The basic idea of the Water Navigation System is that many tourists are relative strangers in the region. As they are travelling around they need actual information on the area where they are, such as water depth, opening times of bridges, information on marinas; natural areas (with descriptions of the wildlife and pictures of the landscapes); practical information on villages, such as restaurants, bars, shops (with opening times); places to visit such as museums with opening times and other information; local concerts, festivals, fairs, town markets, etc.

With the aid of such an information system, tourists can instantly plan their activities, better suited to their needs and personal interests. When tourists have a good experience during the holiday, and they are delighted, there is a higher chance they will come back and tell it at home to other people, which will result in more tourists in the region.

As such, the extra activities of one tourist within such a PSS do not generate a lot of extra eco-burden, compared to the eco-burden of the yacht and the diesel used during one week holiday, as shown in Fig. 6.

Fig. 6 shows that the eco-costs of the yacht are relatively small in comparison to the eco-costs of the diesel. The eco-costs of the water navigation IT service itself are negligible, as well as the direct value (the price), since visitors are likely to expect that IT services are offered free-of-charge.

The interesting issue about such a service is that the indirect value of the service can be rather high in terms of the value of the total bundle of the PSS: the ‘experience’ of a special trip through nature, a visit to a museum, or even an evening in a restaurant, can make or break the holiday. The character of this type of extra value is that it is not paid for in advance, since it is not expected at the moment of purchase of a boat holiday. It is a ‘delight quality’ (Gale, 1994), first introduced by (Kano et al., 1984).

Hence delight quality can only be measured at the end of the holiday. Delight quality enhances the surplus value by positively influencing the customer perceived value after the moment of purchase (Bartl et al., 2013), increasing the future WTP for the PSS: *consumers* experiencing delight exhibit higher levels of behavioural outcomes, such as loyalty and purchase intentions (Chitturi et al., 2008). It generates 'repeat customers', and that is exactly the aim of the province of Friesland.

The effect on the regional environment, however, is far from positive: The total motor yacht rental market in the region is estimated at 800 boats (based on Toerdata Noord, 2011a) which are rented for approximately 19,35 weeks per year on average (Toerdata Noord, 2011b), resulting in 800 × 19.35 = 15.480 ‘boat weeks’. The total of related eco-costs is 15.480 × € 206 = € 3.188.880,-. Under the assumption that the water navigation application creates 20% more repeat buyers, the eco-costs in the region will become 20% more, i.e. € 637.776,- (of which more than 50% is estimated to be emitted in natural areas during the use phase, as shown in Fig 6).

The conclusion is that, if this water navigation service has its economic effect, it will be unsustainable in terms of environmental impact on a system level. The regional calculation is depicted in Fig. 7.

The white arrow in Fig. 7 shows that the water navigation service causes a higher eco-burden in the region due to the increase of tourists. This is caused by the fact that the product (the motor yacht) is unsustainable, and remains unsustainable after the service is added, in combination with the fact that the service stimulates the use of the unsustainable product. The challenge to make this PSS sustainable is to redesign the yacht, as well as its propulsion

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[2] http://www.linssenboatingholidays.com/tl_files/lbh/content/dokumente/LBH_Preisliste.pdf, last accessed January 14th, 2015.

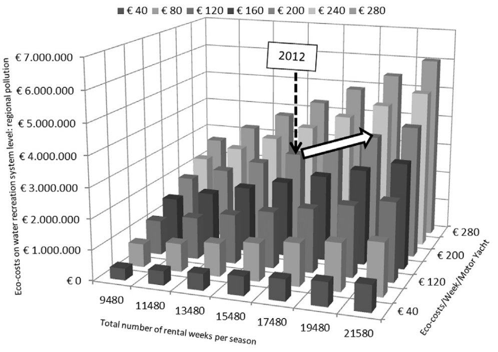

Fig. 7. The regional effect of the water recreation service in the Friesland Lake District.

system from diesel powered to electric. The latter is extra important, because it diminishes the pollution in the natural areas.

3.3. From diesel powered to electric propulsion

For the standard yacht, two alternative solutions are depicted in Fig. 8:

- A hybrid system which is available for this type of yacht, i.e. an electric motor in series with the diesel motor, with enough lead-acid batteries for 3 h at cruising speed (22 kW)
- An electric system (without diesel motor), with enough lead-acid batteries for 8 h at cruising speed (22 kW)

For the hybrid system in Fig. 8, the assumption has been made that 50% of the required energy in a week is delivered by the national power grid (UCTE electricity mix) or windmill parks, and the other 50% is delivered through diesel. For the full electric system, the assumption is made that 100% of the energy is generated at a windmill park or the national grid, charging the boats at night.

Fig. 8 shows that hybrid and full electric systems for yachts are considerably better for the environment than diesel propulsion systems, especially when the electrical power comes from a windmill park: the eco-costs of using such a yacht for a week can be less than half of the eco-costs of using a diesel yacht.

However, the hybrid system has one major problem in practice: nobody seems to be prepared to pay the 20% higher price: there are only few hybrid rental yachts in the region, which are subsidized by the Province of Friesland to approach the price level of diesel yachts. At that price level tourists are happy repeat buyers, but at a higher price level the vast majority of tourists is not prepared to acquire sustainable offerings even though they regard environmental sustainability as important. Apparently, the customer perceived value (the WTP) for the vast majority of tourists is lower than the required price, as depicted in Fig. 9 (contrary to how it should be, as depicted in Fig. 1).

The question is now what can be done to enhance the willingness to pay for this sustainable innovation. The solution is shown at another little region in the Netherlands: the Nieuwkoopse Plassen. This is a lake with extensive reed lands, which are forbidden for diesel boats. There is a flourishing electric boat rental, since the tourists are willing to pay for the experience in nature, which is only accessible by these electrical boats. The same applies to a Dutch region called ‘De Biesbosch’.

The Province of Frieslandxe “Province of Friesland” is planning to extend the protected areas as well. This will affect the competitiveness of hybrid and electric boats (in comparison with diesel boats) as depicted with the arrows in Fig. 10.

Arrow 1 in Fig. 10 represents the tentative decline in surplus value for diesel yacht rental due to restrictions on diesel yachts in natural areas. Arrow 2 depicts the expected decline in surplus value and environmental impacts associated with the introduction of

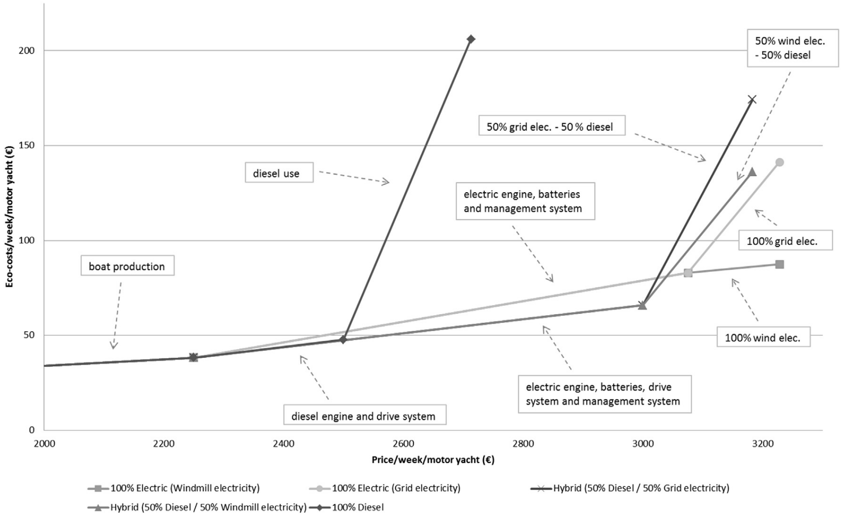

Fig. 8. The value and the eco-costs of one week boat rental for three types of propulsion systems (55 kW max., 22 kW oper.).

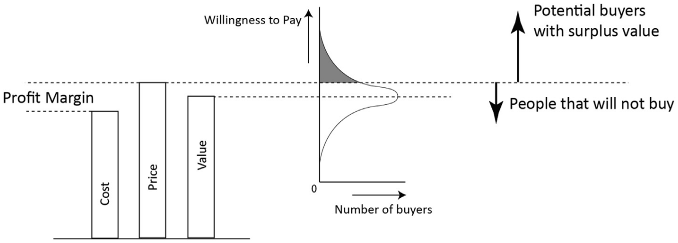

Fig. 9. The problem of a (hybrid) electric boat: the price is higher than the WTP.

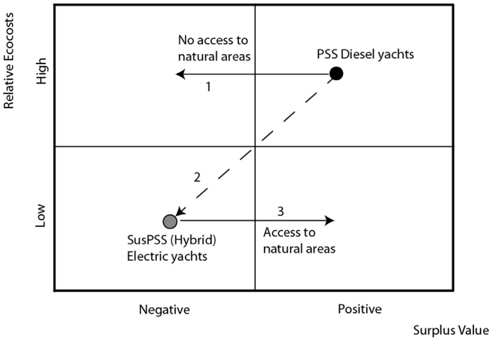

Fig. 10. Restricted access to natural areas will decrease the surplus value of diesel yachts and increase the surplus value of (hybrid)electric yachts.

hybrid/electric yachts due to their higher price. Arrow 3 represents the tentative increase in surplus value for hybrid or electric yachts related to the restrictions for diesel yachts entering natural areas in the region.

This means that the feasibility of hybrid or electric yachts in the rental business is improved, when the Province of Friesland introduces restrictions for diesel yachts which can be used in the marketing of hybrid and electric yachts. Note that marketing and communication is required to underline the advantage of having electric propulsion to enter protected natural areas: tourist must be made aware of it before they rent a yacht.

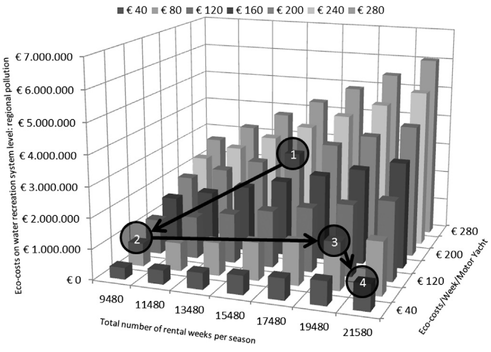

Fig. 11. Tentative effect of the introduction of electric or hybrid boats, in combination with protected natural areas.

The combined business model of water recreation in Friesland fulfils the double objective of eco-efficient value creation: It combines more tourists in the region, attracted by the protected natural areas, with less regional pollution caused by these tourists. This double objective is depicted as the steps 1 through 4 in Fig. 11.

Point 1 in Fig. 11 represents the current situation: all boat rentals are diesel. Point 2 depicts a tentative decline of tourists when diesel is replaced by electric or hybrid. Point 3 depicts a tentative growing number of tourists when large protected natural areas are introduced (accompanied by the appropriate marketing and communication, including the water navigation application). Point 4 in Fig 11 is the ultimate goal: replacing the current steel vessels by vessels made from materials which are more sustainable, such as softwood which has been made durable by non-toxic modification. Especially when on product level its new design also creates surplus value, point 4 is an excellent starting point for further development of sustainable tourism.

Note: the calculations in this section are based on the eco-costs as single indicator for the LCAs. To test the sensitivity of the choice of single indicator, the calculations have also been made for carbon footprint, see Table 2. These calculations show that the shape of the lines in Fig. 8 is not different for the other single indicator, and that the main conclusion is the same.

3.4. The Circular Transition Framework for a circular water recreation system

The activities required for the transition to sustainable water recreation in Friesland are depicted in the Circular Transition Framework in Fig. 12.

Table 2
The calculated environmental impacts expressed in two different indicators: eco-costs and carbon footprint[a].

Environmental impact per boat-week	Eco-costs (€)	Carbon footprint (kg. CO_2 equiv.)
Yacht production	€ 38.22	91.59
Yacht production + Diesel system	€ 47.78	114.09
Yacht production + Hybrid system	€ 65.81	172.40
Yacht production + Electric system	€ 82.88	234.78
Diesel yacht + Use phase 100% Diesel	€ 206.01	584.49
Hybrid yacht + Use phase 50% Diesel, 50% Grid elec.	€ 174.15	562.63
Hybrid yacht + Use phase 50% Diesel, 50% Wind elec.	€ 147.21	412.61
100% Electric yacht + Use phase Grid elec.	€ 141.33	544.86
100% Electric yacht + Use phase Wind elec.	€ 87.44	244.81

[a] http://ecocostsvalue.com/EVR/img/Appendix A 3.pdf.

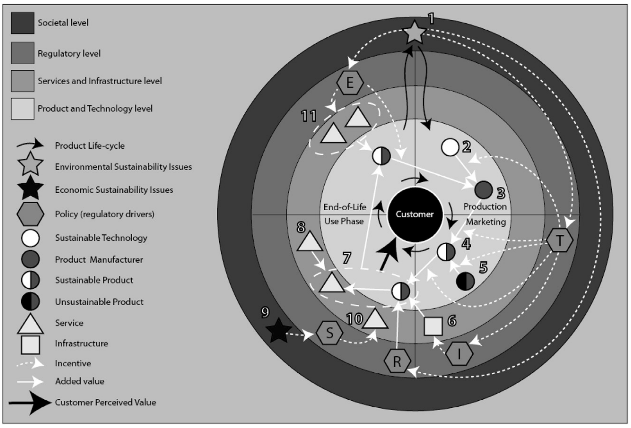

Fig. 12. The Circular Transition Framework for the case of motor yacht rental in the province of Friesland, The Netherlands.

The increased demand for environmentally sustainable water recreation (star 1) has spurred the development of (hybrid) electric drive technology (circle 2) for the production of motor yachts (circle 3). The local government realized that (hybrid) electric yachts were too expensive to obtain a large market share, and therefore initiated regulatory drivers. This policy (Hexagon “T”) is firstly aimed at increasing the surplus value by reducing the costs of (hybrid) electric drive technology through subsidies (4) and conversion of conventional boats (circle 5). The required charging infrastructure (Square 6) needs to be expanded (Hexagon “I”). Further value is added to the sustainable yachts through the restricted access of conventional diesel boats in certain areas of natural beauty (Hexagon “R”). The marketing of the sustainable yacht rental offering (PSS bundle 7) further enhances the customer perceived value. During the operation phase, the sustainable rental fleet is serviced by marine service providers (triangle 8). A recent decline in water recreation tourists (star 9) has initiated the regional and European government (Hexagon “S”) to subsidize an increase in value of the region for water recreants. This regulatory driver supports the development of the water navigation service (triangle 10). The water navigation service adds value to the water recreation system as a whole, which increases the number of water recreants and their expenditures. At the end-of-life, the products are recycled by the end-of-life service providers (PSS bundle 11), which require regulatory support (Hexagon “E”).

4. Discussion

This paper is about the *implementation* of complex circular business systems through *value creation*, rather than simply calculating the eco-burden of products and services (LCA). The two LCA-based methods are developed for design and implementation of circular business models. Although the principles of Eco-efficient Value Creation are quite straightforward, its application seems to be quite complex since it requires the integration of two quite different skills: thorough understanding of modern marketing as it is applied in successful business innovation to boost sales of a product or service, as well as a thorough understanding of sustainable design practice, qualitative (‘EVR thinking’) as well as quantitative (the application of LCA). The design of a business model such as the regional water recreation system in Friesland is even more complex since political skills and knowledge of legislative issues are required.

Applying the three-dimensional EVR approach shows that sustainable products which are too expensive (the WTP is lower than the production costs) can be marketed in a new business model, especially when the high initial investment can be earned back in the use phase. Operational lease creates the right PSS approach for such cases. The marketing of electric cars and hybrid plug-ins (e.g. the Opel Ampera by GM, and the Twizy, Zoe, Kangoo and Fluence by Renault) are practical examples. Note that these cars do not only suffer from a high initial investment, they have also a rather low perceived value because potential customers mistrust the promised lifespan of the batteries. In such cases the right solution is a PSS offering (operational lease) which transfers this risk to the lease company.

In many cases, the design of a business model is more complex, since two levels of PSS have to be integrated: the product level and the regional level. On a product level a PSS may seem rather harmless, where on regional level it may be highly unsustainable. On the other hand: governmental regulations on regional level, and building regional infrastructure, are often indispensable to enhance the relative market value of a sustainable business model.

In the case of the water recreation system of Friesland it seems that such an integration of product level and regional level is being shaped in the right way, although the implementation of this complex sustainable business model remains far from straightforward. One of the major issues in implementation is the fact that it requires a long term commitment from the stakeholders involved: the government as well as the companies in the stakeholder network, as depicted in the Circular Transition Framework. The key to a successful sustainable business model is thus to lower the eco-burden of its *product*, and to enhance its surplus value by adding *services, regulations and infrastructure while reducing cost through subsidies or tax reduction*.

For the design of regional recreational business models, where part of the customer perceived value resides with the quality of nature, an interesting opportunity is identified: restrictive local regulations for unsustainable transport systems. This leads to a better EVR: the environmental impacts will be reduced significantly per unit of service, whilst people are willing to pay more to get access, since they experience an increase in natural value in these areas. Part of the challenge for recreational business model design is therefore to form a stakeholder network that conjointly pursues the transition from the use of relatively unsustainable products, to the use of relatively sustainable products within the recreational region. Applying a combination of the two methods used in this paper, with a particular focus on enhancing the perceived value for tourists, will increase the feasibility of sustainable business models. In this case, moving away from fossil energy-based systems to renewable energy, in combination with enhancing the WTP (in order to cover the higher costs related to such a transition) is a significant step in the transition to a circular economy.

In other countries we see similar successful policies with regard to sustainable tourism.

An example of the successful influence of regulations as a management strategy is the increasing number of marine reservations in California,[3] where activities such as commercial fishing are banned. Such a policy allows the recovery of coral reefs, whilst simultaneously providing a nursery for marine life, creating value for both fishermen as well as e.g. divers, stimulating the local economy and environment (e.g. Murray et al., 1999).

Another example is the restricted access for cars to holiday destinations such as Saas Fee (CH), where only specialized electric transport is allowed in the town. Such regulations lead to a significant increase in value for visitors (Holding, 2001).

Adding value by imposing restrictions has a relationship with the prestige of the customer as well. At the entrance of some parking places in Dutch cities, parking bays are restricted to hybrid and electrical vehicles only. This prerogative for the owners of these cars gives them extra value in terms of prestige and comfort. Another example in the automotive industry is the restriction of CO_2 emissions by cars in Europe. Car owners are proud of driving in cars with innovative, high quality standards of technology (Volkswagen, Mercedes, BWM), hence the CO_2 restriction is converted in extra perceived value. The same phenomenon is observed in the Dutch building industry: strict restrictions on the maximum energy required for heating has forced the industry to implement innovations which give the owners more comfort as well as standing (the owners are proud of the new, high standard technologies).

The main limitation of the two methods applied in this paper is that these do not include social interactions within the local communities involved. In practice this might have significant influence on the feasibility of new business models. Further research should be aimed at inclusion of social factors in the two methods.

5. Conclusions

The advantage of the method of Eco-efficient Value Creation is that the designer of a system is guided in a wider perspective than costs and subsidies alone.

The EVR Model has been shown to be useful for the analysis, design and implementation of a sustainable water recreation system in the regional context of the province of Friesland. The addition of the water navigation service to the water recreation system has its positive economic effect, but is unsustainable in terms of environmental impact on a system level: it generates an increase in use of the 'dirty' diesel motor yachts. As shown in Fig. 8, the significant environmental impacts generated by water recreation system reside in the use phase: the use of diesel.

To avoid further environmental deterioration, the water recreation service must be converted to a sustainable business model through the introduction of sustainable yachts, using renewable energy for propulsion and applying sustainable materials. In this analysis, it is shown that replacing the diesel technology in rental motor yachts with electric propulsion (which results in an overall eco-costs reduction of over 50%) is essential to convert the business model into a sustainable solution. However, this is only feasible if new electrical infrastructure networks are implemented to enable the use of windmill power (e.g. charging poles connected to the grid). If this is achieved, the EVR of a boat-week will be $(87.44/3228 =)\ 0.027 < 0.04$, enabling classification as a sustainable solution (Section 2.1.2).

Without other (external) measures, the WTP for these environmentally sustainable solutions is unlikely to be high enough to counteract the higher price associated with such offerings. Therefore, external measures are required to enhance the WTP for environmentally sustainable solutions. In this case, the implementation of regulations for exclusion of diesel propulsion in certain natural areas has been shown to simultaneously decrease the WTP for these offerings, and enhance the WTP for the offerings in the new sustainable business model.

The Circular Transition Framework has been useful for structuring the complex management of stakeholder activities within the regional business model. Incorporating the EVR approach in a holistic manner has led to a comprehensive overview of how environmental sustainability can be improved on a societal level, by using regulatory drivers for relative enhancement of the value of the regional business model for sustainable offerings.

Acknowledgement and further research

Following up the research presented in this paper, other applications of the EVR approach and the Circular Transition Framework are studied for other business cases. In parallel, the possibilities for inducing an integrated EVR Industrial Design method will be explored.

Part of the study has been funded by the EU Interreg IV A program: Netzwerk Toekomst. From www.deskipper.eu, accessed 28-02-013, as part of a bigger sustainable PSS: "… *integration* with as many *products* and *services* in an *innovative* and *sustainable* manner will be pursued …"(project goal description, 2009). For Interreg IV A see www.deutschland-nederland.eu, accessed 28-02-2013.

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Innovation in product and services in the shipping retrofit industry: a case study of ballast water treatment systems

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ABSTRACT

Eco-innovation research pays increasing attention to business models and their contribution to the diffusion of environmental technology into socio-technical systems. The extent to which a business model hampers or promotes certain types of eco-innovations remains an open question. In order to shed light on this issue, the authors develop a conceptual framework to show how a specific type of business model (Product-Service Systems) could be applied to the context of the maritime industry. With a focus on the Danish maritime industry, the case study addresses two questions: *Which* business models are being used to develop, install and service the ballast water treatment technology? And, *How can these business models add value to the ballast water treatment systems in the market?* The case shows that different business models are applied depending on whether the installation is on new or retrofitted vessels. Both installation and operation stages of ballast water treatment systems provide opportunities for collaboration among stakeholders. Based on the Eco-costs/Value Ratio model, the authors perform an analysis of on-board and port-based ballast water treatment systems with the aim to propose a possible product-service system. These results suggest that port-based systems have the highest potential for eco-efficient value creation and a possible product-service system can be designed for this kind of technology. The article highlights the point that authorities need to improve regulations to stimulate port-based ballast water treatment systems rather than on-board ballast management systems.

1. Introduction

Ballast water is essential for ship operations. Unladen ships require ballast water to keep stability and trim; fully-laden ships need it to keep an appropriate trim during rough seas (Goncalves and Gagnon, 2012). More than 150 000 metric tons of fresh/sea water can be pumped in or out of ballast tanks in one operation and that water may include living organisms (Dunstan and Bax, 2008; Ruiz et al., 1997). Due to these large volumes of water being transported from place to place, there is a risk that many different species are transported and are viable at the destination waters (Ruiz et al., 1997). These species are usually called invasive, non-indigenous or alien species and the broad definition “includes any species reported to have become established outside its native range” (Molnar et al., 2008). Ballast water on ships is considered as the most important vector in dispersing these invasive species throughout the world, although the dispersion risk highly depends on the vessel's type and route (Seebens et al., 2013). Alien invasive species may have economic, ecological and health impacts on marine and estuarine ecosystems. Ruiz et al. (1997) provide the example of the zebra mussel's invasion in the Great Lakes, which beyond being an ecological problem led to costs of between 1,8 – 3,4 billion US dollars by the year 2000. Cholera is an example of a disease indirectly caused by ballast water, as the *Vibrio cholera* pathogen can travel in ballast water (Ruiz et al., 1997).

To control the spread of invasive species, the Ballast Water Convention was approved by the International Maritime Organization- Marine Environment Protection Committee (IMO-MEPC) in 2004. By April 2014, the convention is pending ratification by

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some countries – it will enter into force twelve months after the ratification of countries representing 35% of the world's merchant shipping tonnage. Meanwhile, individual countries, ports or regions have put in place local rules to prevent invasive species distribution from ballast water discharge. A significant event took place on March 23, 2012, when the United States Coast Guard (USCG) published stricter rules to prevent untreated ballast water discharge in U.S. coasts. These international and national regulations generally focus on three strategies to manage ballast water, namely, ballast water exchange, installing ballast water treatment systems (BWTS) or a combination of both. Ballast water exchange implies flushing the ballast water tanks and refilling them with saltwater in mid-ocean (i.e., more than 200 nautical miles from the shore). This water exchange reduces the number of viable fresh water organisms in the ballast tanks due to the salinity (Briski et al., 2013). Ballast water exchange is not always possible; the major constraints being geographical (i.e., some shipping routes do not operate in mid-ocean). Therefore, BWTS represent a second alternative to reduce the number of organisms to low risk levels for the ecosystem and human health. The requirement is that ships need to install a technology that is able to clean all ballast water before it is released into the harbour. Some prototypes of port-based systems receive the ballast water from the vessel instead of having to install a treatment unit on board (King and Hagan, 2013). Existing on-board or port-based treatment technologies combine mechanical (filtration, separation) and biological steps (sterilization through UV, Ozone) (Goncalves and Gagnon, 2012; Veldhuis et al., 2006).

Currently, IMO has provided final type-approval to thirty-tree on board BWTS, while forty-nine systems received basic approval (IMO, May, 2014). This legislation will create a significant market for new BWTS. According to King et al. (2012), the market size includes 68 000 vessels whose owners require the installation of on-board BWTS before 2020. King et al. (2010) estimated a market value in the range of US $50 to $74 billion between 2011 and 2016.

Environmental technology such as BWTS is perceived to be a key sector for future economic growth at the EU level. The possibility of positioning the member states as world leaders in key areas of green technology development is explicitly stated in the EU 2020 green growth strategy (European Commission, 2010). Some member states, such as Denmark, consider the maritime industry as a key sector for growth and have taken action to try and enter the BWTS market. Environmental technology for the maritime industry is mentioned in the national eco-innovation strategy (MST, 2010). The Danish Partnership for Ballast Water Technologies was formed with the participation of public and private actors to find cost-effective opportunities of compliance once the convention is put into force (Danish Shipowners' Association, 2013). The Danish maritime industry recognised this market opportunity and set up companies such as DESMI Ocean Guard A/S, to develop BWTS (Filtration industry analyst, 2009).

However, the maritime industry is globalised, and any market for BWTS will also be globalised (Köhler, 2014). Current data on orders for new ships shows that Europe as a whole only has 6% of the global orders (Clarkson Research Services, 2013). However, BWTS may also be installed as a retrofit during a docking period. In this case, the decision about where to retrofit will be partly determined by the location of the ship at the time being, with the implication that ships on EU trade routes could be cheapest to refit in EU shipyards. This would give, e.g., Danish ship-repair yards and equipment suppliers a competitive advantage for part of the retrofit market. Since on-board BWTS are specialized equipment, the provision of maintenance services to ship operators could also be a significant market.

An important question for the Danish ship-repair yards and equipment suppliers is which business model will lead to profitable involvement in the BWTS markets. There is, however, only a limited selection of literature on business dynamics in the marine industry. Hameri and Paatela (2005) consider the dynamics of supply networks including the case of shipbuilding as a case of an industry where the structure of supply networks has changed. They find that from the end of the 1970s, shipyards changed from producing all the systems at the shipyard to a multi-layered supply network, where the specialist firms in, e.g., industrial kitchens or computer services also have other customers and are less dependent on the vagaries of the shipbuilding market. 90% of the end product value is now produced by the supplier network (Hameri and Paatela, 2005). For a country such as Denmark, with a small shipyard sector but a strong reputation in ship technologies, the provision of services around BWTS installation and operation might provide the best market prospects.

This suggests that the Danish shipyard sector as a highly integrated and specialized network of suppliers has the potential to use the so-called Product-Service System (PSS) as a basis of its business models. The accepted definition of a PSS is: *"A system of products, services, supporting networks and infrastructure that is designed to be: competitive, satisfy customer needs and have a lower environmental impact than traditional business models"*, e.g., Mont (2001) and ELIMA (2005).

BWTS developments' overall intention is to reduce environmental impacts by drastically reducing the risk of invasive species spreading due to shipping. The required integrated offering delivered by a complex multi-stakeholder network mean that BWT technology is fully compatible with the application of Product-Service Systems (PSS). Therefore, the authors applied the PSS literature to the case of eco-innovation in the shipbuilding industry and expanded the PSS concept to explicitly consider supply networks in an industry where these relationships are complex. The results of Hameri and Paatela (2005) described above show that the shipbuilding industry already has a complex supplier network, which is therefore capable of applying a PSS approach. The results also show that the shipbuilding industry has changed its balance between OEMs and suppliers, which indicates that the industry is also capable of further changing its structure to adopt a PSS approach.

In this article, the authors address two research questions:

- Which business models are being used to develop, install and service the BWTS?
- How can these business models add value to the BWTS market?

Section 2 summarizes the analytical framework as well as the hypothesis. Section 3 presents the methods. Section 4 presents the case study. A discussion is presented in Section 5. Conclusions and suggestions for further research are presented in Section 6.

2. Product-service systems and the maritime industry

An emphasis on service provision rather than equipment manufacture suggests that the PSS concept could provide a suitable conceptual approach to this study. PSS has received attention as a suitable model for sustainable innovation (Boons and Lüdeke-Freund, 2013). On argument is that the division between manufacturing industries and service providers has become blurred (Baines et al., 2007; Pawar et al., 2009). In particular, many firms now view services as a source of added value and it has come to dominate the operations of firms which were traditionally considered as manufacturers. Baines et al. (2007) argue that product manufacturers and service providers have moved closer together in their structures to generate added value, a trend also identified by Wong (2004). The concept is that what is sold is not the product, but the use value which the customer derives from a product and its associated services. This involves a continuing relationship with the customer and provides a continuing source of added value for the PSS provider. An important feature is that the asset ownership is not transferred to the user, but the PSS provider contracts the asset to provide a service. In general, this involves selecting the equipment, monitoring performance and providing servicing. An example of such an arrangement could be the provision of transport services.

A manufacturer could traditionally build and sell e.g. a diesel engine, but in a PSS, a (network of) firm(s) could build the engine, install it in a ship but also monitor and maintain it while the ship is operating.

Tukker (2004) identifies at least eight different PSS types in three categories:

1. Product-oriented PSS, where the product is sold but also with an after-sales service contract,
2. Use-oriented PSS where the product is rented or leased to the user together with after-sales services,
3. Result-oriented PSS where a performance or capability is sold (functionality/function/result) (e.g., a level of power provision instead of "an engine" or "a comfortable climate" instead of "air-conditioning" and a specified availability over a specified length of time). Here, the PSS provider offers a customised mix of products and services and the user pays the amount of delivered functionality.

Ceschin (2013) shows how firms have successfully introduced PSS into markets for eco-innovations. It is found that factors for success could be clustered into four groups: the implementation of experiments in a niche, the establishment of a broad network of actors, the development of a shared PSS vision, and the implementation of learning processes. In a market such as BWTS where a demand is already being established, it is the last three factors that form the major challenges to successful market development.

When engaging in innovation towards PSS business models, new producer–customer relationships are required. Pawar et al. (2009) describe a case in which an aero-engine manufacturer sells power. Their service guarantees a certain number of flying hours and minimises maintenance (Johnstone et al., 2009). They conclude that a PSS provider must create value through the combined design of a product, the service provided and the organisation to provide the service. They identify three stages: defining value, designing value, and delivering value. They argue that this will require that the gap between production and marketing is removed and that resources and capabilities which are not internal to a manufacturer are present. Thus, the collaboration with other partners may be necessary.

2.1. Service and product provision in the international maritime industry

The maritime industry system connects a complex network of subsidiaries, suppliers and customers (Hameri and Paatela, 2005). Fig. 1 adapts Dicken's (2011) production circuit to illustrate connections between inputs, service provision, distribution, and consumption in the maritime industry. Shipping lines are responsible for providing transport services, while shipowners may be subsuppliers to these shipping lines or can sell transport services themselves. Both own or lease different kinds of vessels, which are subsequently used for transport purposes. Vessels are the main assets that are upgraded – either by maintenance or by new additions to the fleet (Lun et al., 2010).

Shipping lines require new equipment to improve the performance of their fleet. Maritime equipment manufacturers and shipyards provide ship owners or shipping lines with a variety of maintenance and installation services. These "conventional" services may range from retrofitting—upgrading existing vessels with new or improved equipment—to new builds (Hall et al., 2011). Alliances among maritime system actors are common: equipment manufacturers become suppliers to shipyards, while at the same time shipyards are suppliers to shipping lines or shipowners. Geographical proximity may influence these alliances, i.e., maritime clusters (Viederyte, 2013). However, in globalized industries,

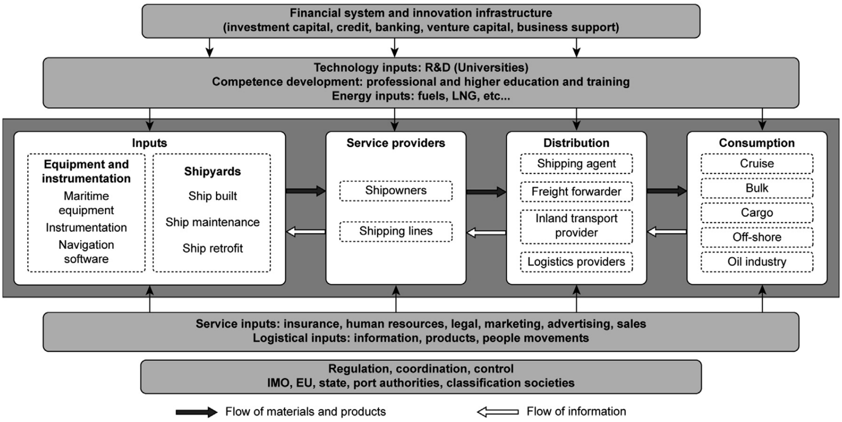

Fig. 1. A proposed model of circuits of materials, products and information in the Danish shipping industry. Different actors are involved in supply and demand aspects of environmental maritime technology.
Adapted from: (Dicken, 2011; DMA, 2006; Fremont, 2009).

such as shipping, equipment suppliers can be located anywhere in the world (Dicken, 2011).

Distribution agents are intermediaries between customers requiring freight transport and service providers. Examples of distribution agents are freight forwarders, inland transport providers or logistics providers. Shipping firms are also moving into this part of the market (Fremont, 2009). Companies requiring transport services may be users in different ways. Fig. 1 groups them into passenger and ferry transport (including cruise ships), bulk, cargo, off-shore services, and oil and gas industry.

The shipping system is complemented by a second tier of actors which provide competences or service inputs directly needed by the industry. This second tier is represented by the boxes located above and beneath the central square in Fig. 1: Technology inputs, competence development, and energy provision. Similarly, other advanced services can be placed here such as insurance, legal advice, and advertising (Hall et al., 2011).

In a third tier, Fig. 1 presents the financial system and the regulatory framework. In industry, financing is characterized by an important circulation of capital, which in turn is required for investments in equipment and fleet (De Monie et al., 2011). Regulation sets the standards for the different activities taking place within the system. At an international level, this is done through the IMO or the EU (for European waters). These international agencies approve conventions and directives that each nation state must translate into national legislation. It is the task of the port authorities to enforce the different conventions. Similarly, classification societies certify that all vessels comply with safety standards (Mensah, 2007).

As shown by Fig. 1, the maritime industry is characterised by a highly complex market structure, which has traditionally used a variety of contractual relationships between shipbuilders, shipowners and charterers who buy the transport use value of a ship, and hence can be placed in the use-oriented PSS category. An example of such a PSS is the use of bareboat charters, where a shipbuilder builds a ship and then leases it to a charterer, who then operates the ship. Another arrangement is time chartering, where a shipowner leases a vessel to a charterer for a fixed time period. The operation of the vessel may be undertaken by the shipowner or the charterer, and in current markets, firms also exist which specialise in ship management only. Hence, contractual arrangements in two directions can be identified: the application of PSS structures with elements of combined production and on-going services and in contrast, the division of shipping into specialist single activities.

These arrangements apply to a complete ship and the transport service that it provides. Modern ships have a wide range of specialist machinery, which the crew cannot repair on board. Therefore, specialist firms are contracted to maintain and repair equipment in addition to production and installation. This is already the case of engines, where specialist manufacturers are not only contracted to service and repair engines, but also provide consultancy services in the design of machinery arrangements for ships. Another example is lifeboats, where a specialist firm builds the lifeboat and is also contracted to inspect and maintain the lifeboat during the operational life of a ship. Other examples in ships are ramps, lifts and also cranes, where the manufacturer builds and installs a relatively complex piece of equipment and is then contracted to maintain the equipment throughout the life cycle of the ship. A PSS can also be applied to electronic equipment such as radar or electronic control systems.

Therefore, the maritime industry is one in which PSS are already well-known and institutional arrangements between shipbuilders, subcontractors, shipowners, and charterers are already developed. This means that new specialist firms who wish to enter the market for ballast water treatment equipment and services do not have to face major institutional and organizational barriers to providing ballast water treatment PSS.

2.2. Hypothesis and proposed analytical framework

The analytical framework in Fig. 2 illustrates the authors' hypothesis: “Current business models contain elements of PSS in the market niche of BWTS and these elements could be a basis for increasing value in the offering of integrated services and products to the market”. The framework, divided in four quadrants, describes the product life cycle in four stages (Scheepens et al., Forthcoming): production, installation, operation and end-of-life (it is interesting to note that the case study did not reveal attention to the end-of-life stage of BWTS). The main actors in this hypothetical Danish BWTS PSS are represented in circles (technology and manufacturing firms) and triangles (service companies) at four different systems levels which are derived from the Multilevel Design Model (Joore, 2010). The customer is placed centrally in the framework. In accordance with the PSS theory, the potential relation between these actors is included: The white arrows represent the value added to the product during its life cycle (black arrows).

In accordance with the case study, the environmental issues associated with untreated ballast water discharge, placed within the societal system level, are the incentive for policymakers such as the IMO at the socio-technical system level to develop regulations addressing these issues. These regulations have spurred the development of mainly on-board BWTS technology and products, placed at the product-technology system level. Based on the case study presented in Section 4, marine consultants and shipyards (represented by two triangles in the installation phase), flying squads and other contractors (represented by two triangles in the operation phase) are the BWTS service providers at the Product-Service System level. “Flying squads” are specialized staff from external maritime service firms that could travel around the world to service vessels. The End-of-life phase has not been mentioned by the stakeholders in BWTS, therefore it is assumed that this phase in the product life cycle is not taken into account during current developments of BWTS.

Since it is assumed that the equipment and installations for BWTS currently in development will last the full life cycle of the ship – e.g. 26 years in average for container ships (World Shipping Council, 2014) – the environmental impacts of the end-of-life phase are likely to be insignificant compared to the production – and use – phases of the BWTS. This is mainly due to the BWTS energy use over a lifespan of 26 years. In Europe, it is likely that a large share of the BWTS (as part of the ship) waste materials are recycled (Ahuja et al., 2011), assuming that most of the components are manufactured using (high grade) metals and plastics. This is also the case in the automobile sector, where due to regulatory drivers up to 95% of the materials in cars are to be recycled in 2015 in Europe (Dalmijn and Jong, 2007). When regulatory drivers such as the IMO guidelines on ship recycling are applied to BWTS, the environmental impact over the full BWTS life cycle is reduced. Recycling has reduced environmental impacts compared to raw materials mining and processing; in LCA, the recycling of, e.g., metals yields environmental impact credits, where, e.g., landfill adds to the environmental impacts of the system (Vogtländer, 2012). However, performing a LCA of the BWTS is outside the scope of this paper.

What is more important in the context of this paper is that, during current design and development processes of BWTS, the end-of-life stage of the products/PSS appears not to be considered at all. Assuming that this is confirmed in future LCA studies on BWTS, this should not result in massive environmental sustainability issues. Nonetheless, considering the end-of-life stage during

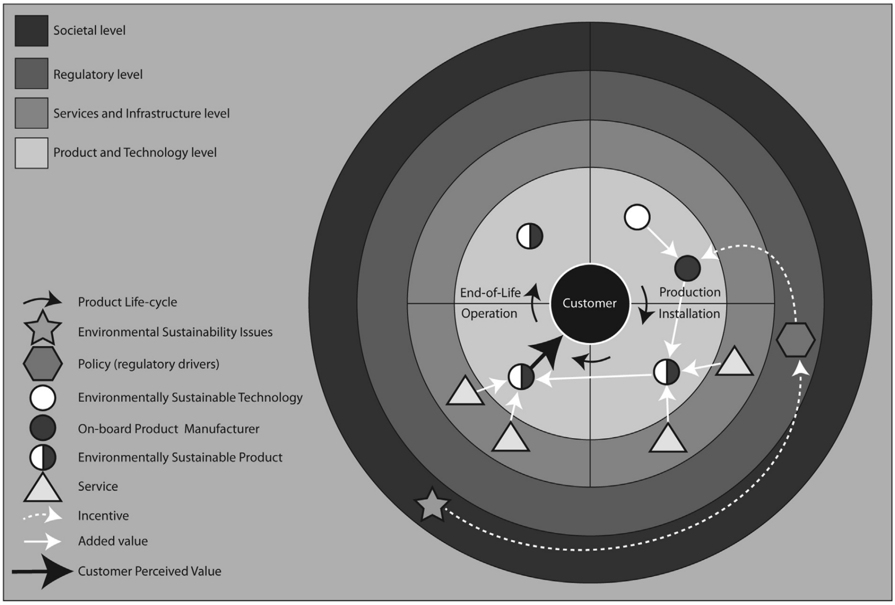

Fig. 2. A conceptual framework of PSS for ballast water treatment systems within the multi-level design model.

design and development is an important recommendation from an LCA perspective to current and future BWTS designers, developers, installers, maintenance providers, manufacturers, and above all, policy makers.

3. Methods

The authors have considered a single-case study design to structure the results. To select the case study, the authors followed an information-oriented strategy, which is one category of selection described by Flyvbjerg (2006). In an information-oriented strategy, "cases are selected on the basis of expectations about their information content". The authors expected to present a critical case, which according to Flyvbjerg (2006) allows "deductions of the type 'if it is (not) valid for this case, then it applies to all (no) cases". The authors agree with Flyvbjerg (2006) that "context dependent case studies" —e.g., generalizable under certain conditions — are also valid means of achieving knowledge. The selection of a critical case had the purpose to increase the possibilities of generalization from a single case.

3.1. Case study and selection criteria

In Section 2.1, the authors explained that the ship repair market is globalized and therefore it is challenging to set national boundaries when analysing business models. In addition, collaboration and trust building among firms have been highlighted as important factors in generating business models leading to PSS (Mougaard et al., 2013). This endeavour of collaboration and trust building is facilitated by interaction and networking (Mougaard et al., 2013). The authors have considered business models leading to the retrofitting and building of new ships with BWTS by Danish firms as a critical case of study. The first reason is that Denmark counts with an active shipping cluster with the representation of all actors presented in Fig. 1 (DMA, 2006). Second, in Demark there is a political commitment to support the shipping industry as a key area of economic growth at the national level and in some regions (Danish Government, 2012; Region Nordjylland, 2014). An important element in these strategies is to support cluster collaboration between national maritime equipment manufacturers and suppliers (Sornn-Friese, 2007). Third, some of the most important actors in the shipping/maritime innovation system have started collaborative network initiatives to develop and prototype environmental technologies, but also network initiatives to consider alternative business models which involve the combination of products and services (Hsuan et al., 2012; Schack, 2009).

Following the research questions and the analytical framework presented in Section 2.2, the authors have considered the case study as the business models for the production/development, installation and maintenance/operation of BWTS within Denmark. In the analysis, focus was on three units: BWTS manufacturers (suppliers of equipment and instrumentation), maritime service companies (shipyards and consultants) and shipping companies (demand). The authors did not limit the case study to a specific BWTS technology and manufacturer despite thirty-three systems with final type-approval by IMO (and many more being developed). There were practical reasons for this. First, it appeared that the shipyards and maritime service companies are able to work with different providers of BWTS. Second, shipowners are free to install any of the systems currently in the market if approved by IMO. Thus, the case study focused on a general rather than a specific business model of BWTS. However, since it was not possible to interview all Danish BWTS manufacturers, shipyards, and shipping companies, the authors developed a set of criteria for selecting these interviewees and ensuring representativeness. These selection criteria are expanded on Section 3.2.

3.2. Data collection

Empirical evidence was collected between February 2012 and February 2013 through in-depth interviews, document review and participant observation. The authors carried out seven in-depth interviews as shown in Appendix A. Judgement sampling was performed to select these interviewees (Marshall and Rossman, 2006). An initial overview of the actors involved in the Danish BWTS innovation system was performed at the outset (as explained in Section 2.1 and illustrated in Fig. 1). As shown in Appendix A, the authors selected key representatives from different types of stakeholders involved in this innovation system to include in the sample. The sample of interviewees included one global shipping company and the shipowners' association, two BWTS manufacturers, one shipyard, one maritime equipment branch organisation, and a maritime service firm (135 employees). These interviewees were acquainted with business models involved in BWTS and were active participants in several networks of business development in the shipping industry. Although two other Scandinavian BWTS manufacturers were contacted, they did not accept to participate in the study. A summary presents the interviewees' positions within the organisation, see Appendix A. A semi-structured interview guide was prepared before the meetings. The purpose of this data collection method was to guide the conversation while leaving the interviewee free to provide longer answers (Rubin and Rubin, 2012). Appendix B shows a general template of the interview guide.

A document review complemented the interviews. This document review differed from the literature review presented in Section 2. The main difference was the kind of documentation and the sources. As Table 1 summarizes, the documents were of different categories (i.e., commercial brochures, websites and international law). To select the document source, the authors first mapped actors in the innovation system of BWTS as presented in Section 2.2. From this map of actors, the authors considered important documentation which was collected from key organizations as shown in Table 1. A first criterion of selection was to triangulate the information arising from the interviews, for example, to complement specific data about the technology, dates, regulations, etc. A second criterion was that some stakeholders were not interviewed; either they did not give permission to include the interviews in the article or they had no time for interviews. Through a document review, it was possible to include information about their roles in the BWTS business models.

Table 1
Stakeholder and document type used as source for empirical material.

Document source	Document type
International Maritime Organization (IMO)	Ballast water convention
	Environmental protection committee documentation (e.g. minutes from meetings, available through the IMODOCs website)
	BWTS technologies approval requirements and status
BWTS Manufacturers interviewed	Technical documentation and websites
Danish Maritime magazines	Newsletters
International green technology maritime magazines	
Danish Branch organizations	Position papers, technical studies
Consultants	Product catalogue
	Commercial presentations
Specialized conferences and seminars on ballast water treatment technology and regulation	Presentations

A third method was participant observation. The authors formed an insider/outsider team (Louis and Bartunek, 1992). This method claims that a better analysis of an organization's affair can be achieved when combining the experience of insiders with the critical eyes of outsiders (Bartunek, 2007). One of the authors was a researcher in the Maritime Centre for Operations and Development (MARCOD). This centre provides support to maritime SMEs on product and market development with a strong focus on environmental Technologies. As an insider, this author co-organized a seminar on “Business opportunities with ballast water treatment technologies” in March 2013. During the event, around 50 practitioners from BWTS manufacturing firms, shipyards or maritime consultants[3] shared their experiences on business models involving ballast water systems. A consultant also facilitated a brainstorm on possible services that could be associated with these business models. As a researcher in MARCOD, the author also attended two practitioner events in November 2013: the second Copenhagen international ballast water conference; and the Danish seminar on marine product service systems organized by the PROTEUS consortium (Hsuan et al., 2012). Both these events were an opportunity to understand different perspectives from the business models involved in the current ballast water treatment technologies and to identify interviewees. The authors have included some of the reflexions from these seminars as part of the case study.

4. Ballast water treatment systems business models in Denmark

The findings from the case study are grouped into the following three categories (Fig. 3):

- Market context and system development
- Installation new build/retrofit
- Operation

4.1. Market context and system development

For maritime service firms, the current context will determine the future growth in the market of ballast water treatment technologies. The installation of ballast water treatment systems has begun, even though the ballast water convention is not ratified by the minimum number of IMO member states required. However, the installation of systems is proceeding at a very low rate and the market growth is small. This is the result of shipowners' interest in avoiding large investments before January 1, 2014. The IMO convention does not require the retrofitting of ships before that date. For this reason, most systems are currently installed on new builds, and few are installed on retrofitted vessels:

> *“I think we haven't really started the retrofitting yet, because we don't have the Convention in place. The convention was agreed in IMO in 2004, but we still need 30% of the world fleet to sign on, before it is entered into force. It will be enforced twelve months after the ratification. So, that's why we still, I mean, our members will not go and retrofit before they are totally sure about the future*

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[3] The presentations of MARCOD's events are available at http://www.marcod.dk/arrangementer/konferencemateriale/38-materiale-fra-konference-om-for-retningsmuligheder-inden-for-ballastvand.

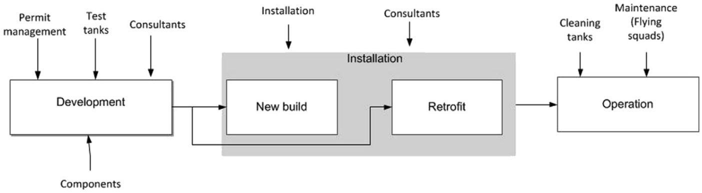

Fig. 3. A linear model of BWTS production and service flows. The model comprises three main parts: development, installation and operation. The different products and services that can be provided are listed as arrows in the model.

> *regulation. Despite the fact that the convention was agreed upon in 2004, we are still discussing amendments to the convention, so as part of that discussion we are actually working on changing the implementation dates for the existing ships. If you have a big tanker or bunker, you will first have to install equipment in 2019 or 2020. Then you are not going to do anything. We have a lot of members who will be in that situation. We see installations on new buildings (as I see it), but we don't see many retrofits" (Interview 3).*

Despite this apparent inertia from a shipowner's perspective, while the negotiations are going on at the IMO, shipowners are very active in their networks. There are on-going assessments of different technologies and service partnerships with suppliers. An example is the Danish partnership for ballast water. The partnership organizes match-making meetings and specialised seminars to seek cost-efficient ways to comply with the regulations:

> *"No, we are more into meetings and conferences at the moment. We had a meeting about land-based solutions last time, we co-organized it together with MAERSK, DFDS and Danish Ports, and then there have been other projects as well. The projects may be supported by the [Environmental Ministry], and they have a call right now. We wait to see which projects they will support and then people will start discussions. So far, no technology development or demonstration projects" (Interview 3)*

Manufacturers react to this situation in three ways: manufacturing a few units with local resources and suppliers, getting the permits to commercialize BWTS ahead of the competition, and looking into innovative systems. Until the convention is enforced, most activities are centred on securing the right system permits (IMO and USCG). Similarly, the production of the systems is at very low rates, mostly with local manufacturing (e.g. in Denmark) with most suppliers of components among local firms (e.g. UV lamps or steel components). The manufacturers have, however, acknowledged that this may not be sustainable when the demand increases considerably.

The Danish maritime branch organization (Danish Maritime) considers it to be preferable to support Danish R&D companies to look into second generation ballast treatment systems. The main reason is the large offer of first generation systems already in the market looking for permits (e.g., currently 26 with Type I approval at the IMO). Many of these systems are developed by South Korean and Japanese firms with strong connections with shipyards in Southeast Asia. A couple of Danish companies are developing "second generation BWTS". These second generation systems will be developed for direct use on vessels and not as land-based technologies adapted to the vessels (Interview 4). An example of such land-based systems is port-based ballast water treatment. In a first principle of operation, "ballast water is treated at the port of departure and discharged at the destination without further treatment". A second option is when "ballast water is taken in without treatment and treated immediately before discharge at the destination" (COWI, 2012). An advantage of port-based systems is that shipowners will not have to invest in installation, maintenance or retrofitting (COWI, 2012).

4.2. Installation

Installations can take place in two ways: in new builds and by retrofitting older vessels with ballast water treatment technology. Different business models are involved in these markets. Shipowners decide that new builds are to be delivered with the BWTS because it is easier to install the system during the construction than it is in a later retrofit (Interview 3). The date when the convention will enter into force is still uncertain. However, from the manufacturers' perspective, the market share for installation of BWTS in new builds was small in 2012:

> *"What we are seeing is that 2012 has been a year with very low activity in the new building market. Very few new builds have been contracted. What you can say is that in the [BWTS] market is very weak for new buildings right now" (Interview 6).*

Most new builds are produced in Southeast Asian shipping yards (mainly China and South Korea), with a close relation between shipowners and shipyards in terms of related services and products. Therefore, there are fewer opportunities for external service firms. The BWTS manufacturers receive an order from the shipyard, and what the shipyard needs is the system delivered in components. The shipyard then installs it, and does all the pipe work, electrical installations, etc.:

> *"When it comes to new builds, strictly speaking, the customer is the shipyard. But of course, the shipowner has also something to say, on which system to put on their vessels" (interview 6)*

In the retrofit market, more opportunities exist for collaboration between manufacturers, shipyards and other maritime service firms. For BWTS manufacturers, these opportunities exist and they are continuously looking for options of collaboration with maritime equipment installing firms. Part of this collaboration is focused on the early stages of engineering assessments (calculations, detail drawings, etc.). Then, another firm can install the system on board. All these additional services should be reflected in the quotation handed to the shipowner:

> "*Sometimes the shipowner will ask you to make a complete retrofit. For example [the shipowner] will ask: "What is the price to equip my vessel with this system?" Design, installation and delivery will be a total price for that delivery. We can work with the business*

> *model that we take the responsibility of everything, but then we will need to carry joint projects in collaboration with some others. But we cannot take out the whole responsibility. In other cases, we will remain, we just send the components to the dock, and we have done our part. It depends on the shipowner, on the shipyard, what they agree"* (interview 6)

This manufacturer-centred business model could change to a shipyard-centred model (similar to the new builds explained above). Depending on the complexity of the installation, the ship must be taken out of operation for some weeks and be serviced in a dry dock. Because this entails loss of revenue, it is an important business decision from the ship operator perspective. The shipowners may already have planned a refit at a given shipyard. In that case, the BWTS installation can be an extra task for the servicing shipyard on top of a normal service stop and the shipyard will only require the system and the technical details from the manufacturer. In Denmark, a shipyard has already installed four BWTS with this business model. The vessels had a Norwegian BWTS installed at the request of the shipowner.

Previous to the installation, calculations must be performed by an external naval architect. These calculations assess the exact location of the different modular components of the systems within the vessel. The owner approves, involving close communication with the BWTS manufacturer. Then, the installation follows as a normal part of a refit by the shipyard staff. This involves making the foundations, pipe work and electrical connections (interview 5). From a shipyard perspective, it is the shipowner who decides which system goes in the vessel, and there is no imperative to require a binding agreement with a specific BWTS supplier.

In any case, manufacturers and shipyards agree that the shipowner will have the last word on where the installation is to be undertaken. Some variables that come into play are where the vessel usually sails, what are the comparative prices of shipyards, etc. Manufacturers have considered this as problematic; they want to compete globally with other companies in Asia (for example).

Ways to tackle this are either by sending a specialist from the BWTS manufacturer to supervise the installation or by hiring other companies which have already installed the BWTS system that has been chosen. It is, however, important to have close supervision along the whole installation because "you can never teach a yard in total to do everything, that will be difficult and definitively not all yards [will be able to be trained as fast]. Maybe, some few yards will be trained on location or something like that" (Interview 6).

4.3. After sales and operation

The operation phase of BWTS provides some opportunities for the integration of product and services into one package. One reason is that shipowners focus their business on transport, and would welcome integrated solutions that will outsource the maintenance of ballast water treatment technology to the supplier (Interview 2). Although no formal PSS is already in place with this profile, the possibility is being considered by manufacturing and service firms:

> *"I think that the big players will do it themselves. But there may be opportunities in relation to the smaller companies if they could make a package so to speak. If they can say we can make sure that it can be installed and it will be working and perhaps there is a possibility" (Interview 3).*

The possibility is already being considered by one of the Danish BWTS suppliers:

> *"We will do it ourselves with our network. Likewise with the automobile shop, they don't want to earn money with the new cars but with repairs" (Interview 6).*

In practice, this could be translated into some partnerships in different harbours in the world, but also agreements with "flying squads". The idea is for the shipowner to purchase a "package" once the shipowner pays for the BWTS. Manufacturers consider the following requirements to set such service agreements:

> *"One thing which is important when you look at these … it has to be a company with certain size and experience within the industry and also very used to working globally, because we don't expect that the majority of our systems will fit in Danish repair yards or something like that. It will be global, because the shipowner will take their ships in docks where they have agreements or where it is already trading and so on. It is really global. You really need to team-up with companies that already have experience with this and are used to having people working in Asia, middle-East" (Interview 6).*

Shipyards, on the other hand, are less likely to get involved in these maintenance agreements on a long-term basis:

> *"The service is the responsibility of the [BWTS] manufacturer. They do that where the vessel is,we don't service the BWTS within the vessel because that is the manufacturer" (Interview 5).*

The reason is that, from a shipyard perspective, the tasks of the shipyard are best narrowed down to the installation. More technical and precise maintenance –not requiring a long stay in the shipyard – is a manufacturer's commitment:

> *"As a shipyard, we are not promoting a maker. But if someone comes to us tomorrow, an owner, they don't have an idea what to use. We will recommend this system. But one thing is what we know about installing it and another thing is working with it on the day-to-day basis. We don't know if it is easy. But we don't interfere with the choice" (Interview 5)*

5. Discussion

The research questions will be elaborated based on the results presented in Section 4.

In relation to the first question considering which business models are being used to develop, install and service the BWTS; it can be said that different business models also operate in segregated phases of the BWTS life cycle: manufacturing, installation and operation. Manufacturing is characterised by a relatively small demand of BWTS (since the convention is not yet entered into force). The business model is organized by manufacturers with mostly local manufacturing of a few demonstration units. Installation and operation also have differentiated business models. In the installation phase, the shipyards play a major role by coordinating what is installed on board of a new or retrofitted ship. Shipyards become hubs of collaboration between shipowners, manufacturers and contractors. The business model in the operation phase of BWTS is more relevant to manufacturers and service companies than to shipyards. Manufacturers avoid a strong fixed dependency on a single shipyard that may limit the manufacturers' ability to make extensive contacts worldwide. The capability of maritime service firms to provide prompt responses through, e.g., flying squads gains a large relevance here. Once the ballast water convention is put into force and the demand of BWTS and services increases dramatically, manufacturers may well lack the staff to service the industry.

The case study results did not show that the business models in these three phases can be defined as a result-oriented PSS. A characteristic result-oriented PSS will be that in which shipowners pay by the volume of water treated and not by the BWTS, with the actors (manufacturers, shipyards and contractors) selling the product-service system to the shipowners. In the case, however, BWTS are still considered as a product; shipowners pay separately by installation and for a possible after sales service.

The second part of the hypothesis proposes that current business models have the potential to generate value through a possible PSS. The second research question deals with this issue in more detail by explaining how these business models can add value to the BWTS market. The case highlighted the importance of rethinking the concept of BWTS, which should be seen less as a product and more as a system of services that could be built around BWTS products. In particular during the operation stage, shipowners may be interested in paying per volume of treated ballast water, while concentrating their energies on their transport business. In this way, BWTS consortia could propose complete packages of installation, service and monitoring, enabling shipowners to outsource the entire process required to comply with the proposed regulation and its potential future follow-ups. This PSS concept should be designed by a consortium to deliver the required value for the shipowner whilst minimizing the environmental impacts associated with ballast water discharge in order to maintain and improve the competitiveness of the offering. The main question is thus how to design a PSS concept that achieves competitive value for customers of BWTS, whilst minimizing the environmental impacts. In the long term, the BWTS is also expected to yield competitive value for the PSS consortium, since future regulation compliance is ensured through continuous environmental impact reduction innovation. Tukker (2004) argues that when moving from product-oriented PSS towards result-oriented PSS (moving towards a service economy) the potential for environmental impact reduction and perceived value for the customer increase.

This coincides with the eco-efficient value creation (EVC) theory (Vogtländer et al., 2013) in which the Eco-costs/Value Ratio (EVR) model is suggested as having the potential to support eco-efficient value creation (EVC). The aim of EVC is to design solutions that increase the customer-perceived value whilst reducing the relative environmental impacts. Simultaneously creating customer perceived value for environmentally sustainable offerings ensures market penetration. Therefore a qualitative EVR analysis is performed for designing a sustainable PSS concept for BWTS in terms of EVC.

In general, two types of BWTS can be discerned: on-board BWTS where the ballast water is treated on-board before discharge and port-based BWTS where the untreated water is discharged into BW processing facilities in a port. It appears that the main business focus is on on-board BWTS, since many ports do not have a BW discharge system and the treatment facilities required for a port-based system. However, a port-based treatment facility has several advantages in terms of eco-efficient value creation:

- The ships themselves do not need to be (re)fitted with complex BWTS, reducing the investment costs for shipowners.
- A lower relative energy consumption of the ship during operation: more goods can be transported since less room and weight are required for the BWTS.
- The BWTS is used much more frequently in a port-based system than on a ship: The BWTS processes ballast water of every ship coming into the dock, whereas an on-board system only processes its own ballast water. This should result in cost reduction for the shipowners, due to a more efficient operation of the BWTS.
- The measure is implemented at the place where the problem occurs: in the ports of destination.
- Expensive maintenance such as flying squads is no longer necessary for servicing the BWTS during operation.

These advantages both potentially increase the value perceived by the customer as well as the eco-efficiency of the operation of the service. Hence from an EVR design perspective, the port-based type BWTS PSS has the highest potential for EVC. Of course, there are several issues with such a PSS concept, as yet seemingly left unaddressed by individual companies or PSS consortia:

- No standards are set (yet) by the IMO regulation on the type of connection between ship BWTS and ports.
- Such a PSS would only work well if every port had such a system installed. PSS consortia should investigate whether it would be possible to install port-based BWTS in the necessary ports in order to be able to offer a BWTS service to shipowners wanting to comply with the IMO regulation.
- Substantial investments are required to fit ports with such systems, but on the other hand, this could provide a unique competitive edge compared to on-board BWTS offerings. Although indications have been found that port-based systems tend to be more expensive (COWI, 2012; King and Hagan, 2013), costs such as the so-called flying squads have not been taken into account in these analyses. Therefore, it still remains questionable whether such port-based systems really turn out to be more expensive: *"The estimated cost of the on-board treatment seems somewhat lower than the calculated treatment cost of the best case; however, that needs to be investigated further, taking all conditions into account, to reach a more solid base for comparison between the concepts."* (COWI, 2012). In terms of customer perceived value (for shipowners) and eco-efficiency, port-based systems are preferred over on-board systems.

Therefore two possible venues can be defined for PSS consortia wanting to achieve EVC:

- Push the IMO regulation directed at shipowners to ports experiencing the problems of BW discharge
- Or invest heavily in port-based systems for ports experiencing BW discharge issues, potentially giving the consortium a competitive edge over on-board BWTS manufacturers and consortia.

Both venues should result in a more service-based economy, creating competitive value for customers of BWTS whilst minimizing the environmental impacts associated with BW discharge. The proposed framework for port-based systems as an alternative to on-board systems is depicted in Fig. 4.

The framework as presented in Fig. 4 shows that the customer (shipowner) now also has the possibility to completely outsource the responsibility for compliance with, in this case, the IMO regulations. The consortium would be able to offer different configurations of products and services, payable by the amount of, in this case, ballast water treated. This means that there is no transfer of ownership of the products; therefore the responsibility of operation lies with the consortium. This has several benefits for the customer as well as the environment: End-of-life re-use, component re-use, remanufacturing and recycling are made easier, the product quality is enhanced, and less effort and risk are required of

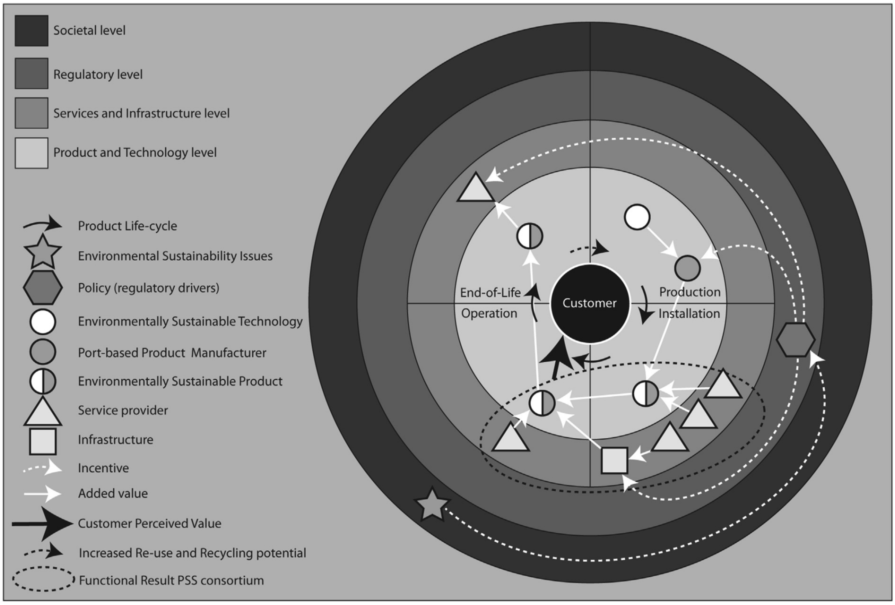

Fig. 4. Proposed Functional Result PSS conceptual framework for port-based BWTS.

the customer to maintain operation. Port-based systems will also be beneficial to maritime service firms in the PSS consortia. These firms are usually hired by shipyards to carry out activities linked to the installation or maintenance of on-board systems. However, the operation of port-based systems can become an extra market for maritime service firms.

Despite these advantages of port-based systems, on-board systems are diffusing at higher rates in the international shipping industry. Since many ports do not have port-based and port-serviced BW facilities (infrastructure), and many ships will need to comply with IMO regulations, in the short term, on-board systems are the most applicable solution. Then the ships can sail to any port and discharge their BW after it has been treated on the ship. This underlines the importance of an adequate regulation development: in order to stimulate, e.g., port-based BWTS systems development and implementation, additional or different regulations are required, such as subsidizing port-based BWT facilities.

The case study material shows that Danish firms are actively engaged in developing their presence in the market for BWTS. They are dependent on relationships with operators and shipyards in Scandinavia and globally. They are applying the PSS concept for BWTS service provision to some extent, but have not yet fully developed the market potential through the PSS approach.

6. Conclusions and future research

This article has looked at business models for the case of BWTS in Denmark, using the PSS framework. This is a new market, created by international regulation from the IMO on ballast water management. Ballast water discharges have been recognised as an important environmental impact from shipping. This section first summarizes the main practical and theoretical implications, and then it provides suggestions for further research.

The article has three major practical implications: First, the case of Denmark shows that a western European maritime sector is entering into the market for BWTS. In spite of the East Asian domination of the shipbuilding industry, Western European specialist firms are still competing for equipment supply and service provision in a market which has been estimated to have a potential value of US $50 to $74 billion between 2011 and 2016 (King et al., 2010).

Second, the installation phase is driven by the shipowners' needs of installation and geographical service. The operational phase provides new opportunities for links between manufacturers and maritime service companies. Packages of products and services are especially welcomed by shipowners in this phase. While there are elements of a combined installation and service approach, the full potential of a PSS has not yet been exploited.

Finally, the EVR model has been found to be a valuable tool for developing future business strategies for eco-efficient value creation in BWTS. It provides direction for innovation on a product and PSS level, as well as for business strategies and regulation development. The model also indicates that the regulation could be refined towards stimulating port-based BWTS, instead of onboard BWTS.

The major theoretical contribution of the article has been to extend the PSS framework with the eco-efficient value creation (EVC) theory, using a qualitative Eco-costs/Value Ratio model approach. The case of BWTS in Denmark extends the literature on PSS through the consideration of the maritime industry, an example of a complex OEM-supplier structure with the business dynamics of a new market that is being created through environmental regulation. This extension of the PSS approach is generalizable to other industries with similarly complex OEM-supplier structures, where new eco-technologies are being developed for the product. Two examples of this are the development of fuel cells and batteries in the automobile industry (Köhler et al., 2013). The in-depth case study of BWTS shows that the ballast water regulation is certainly the main factor behind the development of BWTS. This is therefore an example supporting the perception that environmental regulation is often the cause of eco-innovation (Köhler et al., 2013; Walz and Köhler, 2014). However, the regulation itself explains little about the emerging service and product-service combinations in the industry. These were identified through the case study analysis as being based on current business structures in the shipbuilding industry. In the case study, current business structures provided more opportunities for new entrants (e.g., small and medium-sized maritime service enterprises). It is not possible to draw general conclusions about the most suitable product and service combinations in eco-innovations. A case specific analysis of the combination of industrial production structures and the particular environmental regulation is necessary to determine the potential for new production structures using PSS.

Future research could be, in the first place, firm-centred perspectives which explore, for example, which capabilities are necessary to implement or develop the links between manufacturers and maritime service companies. Another research avenue for future development could highlight the impact of the regulation in the implementation of sustainable business practices. Thereby, it is essential to further investigate the feasibility of port-based BWTS versus on-board BWTS. Finally, the current business models and regulatory drivers do not consider the end-of-life phase. It would be useful to explore how the end-of-life of BWTS is expected to be handled by manufacturers and service providers in a business-as-usual and a PSS model.

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Appendix A. Interviews to build evidence on the contextual conditions

Table A-1
List of interviews.

#	Date	Type of organization/relevance to the case	Interviewee position within the organisation	Duration of the interview (minutes)	Purpose in the research	Where was the interview performed?
1	February 2012	Maritime service company/ The company provides contracting services in its yard but also through “flying squads”. Actively involved in local and national networks. Partnership with a BWTS manufacturer.	Chief technical officer	60	Section 4.3	Company's headquarters, Frederikshavn, Denmark
2	October 2012	Scandinavian-based global Shipping company/ Shipping company with 5700 employees worldwide Car-carrier and Roro vessels as main business area	Fleet manager responsible for a BWTS comparison assessment	*	Section 4.1	Aalborg
3	February 2013	Shipowners' Association/ Industry branch for the Danish shipowners. Co-Coordinator of the partnership with ballast water (Along with the Nature Agency)	Consultant; Partnership spokesperson attached to Danish Shipowners' Association	30	Section 4.1	Copenhagen
4	February 2013	Danish Maritime/ Branch organisation for maritime equipment suppliers Coordinator of Retrofit project/member of the PROTEUS consortium/MARCOD network and many other initiatives	Business consultant; project leader for retrofit project	58	Section 4.1	Copenhagen
5	February 2013	Shipyard Active shipyard with 230 employees; local hub for sub-contractors; have installed several BWTS to Scandinavian customers	CEO	30	Section 4.3	Frederikshavn
6	February 2013	BWTS manufacturer Danish manufacturer with IMO approval	CEO	52	Section 4.2	Nørresundby, Aalborg
7	March 2013	BWTS manufacturer American BWTS manufacturer but with business relations with Danish shipowners and shipyards	CTO/Country representative	40	Section 4.2	Frederikshavn, subsidiary of American BWTS manufacturer

* Communication with this source was through email.

Appendix B. Template of semi-structured interview guide

Semi-structured interview guide with shipping liners/shipowners

1) Firm's and IMO ballast water convention (Interviews with shipping liners/shipowners)
    a. Firm's strategy for compliance
    b. Systems suiting firm's needs
    c. Collaboration with manufacturers and authorities
2) Ballast water treatment system (interviews with equipment suppliers)
    a. Background of its development
    b. Relation with the Danish partnership for ballast water
3) Ballast water treatment systems
    a. Installation
    b. After sale service
    c. Consultants/ship architecture design
    d. Spare parts

4) New services
   a. Retrofitting
   b. Collaboration with shipyards
   c. Opportunities for suppliers

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Publication 3

Evaluating the sustainability of Vietnamese products: the potential of ‘designed in Vietnam’ for Vietnamese vs. Dutch markets

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Abstract: Future Living Studio (FLS) is a temporary design studio concept that aims to explore and embed sustainable design approaches in the Vietnamese product design context. Each studio brings together local and visiting designers to develop collections of environmentally sustainable products with participating local companies. These products act as reference products and inspiration for demonstrating the potential of sustainable design in Vietnam. From 2011 to 2013, three studios were deployed in Vietnam where nine local designers, nine visiting designers, and 9+ local production companies took part. The aim of this paper is to assess how sustainable the products developed in three editions of FLS are, by analysing their environmental impacts and their competitive value on domestic versus Western European export markets. The increasingly popular eco-costs/value ratio (EVR) model is used to give a portrayal of the environmental and economic sustainability of the products developed, based on a ‘willingness to pay’ (WtP) assessment that supplements the life cycle assessment (LCA) approach.

Keywords: design for sustainability methodology; eco-cost/value ratio; EVR assessment; designed in Vietnam; competitive value through sustainable innovation; LCA; willingness to pay survey; Future Living Studio; Vietnamese designers; bamboo furniture design; cross-cultural collaboration and learning; emerging Vietnamese domestic market; Western European export markets; strategic design approach; temporary studio.

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Arnost Eduard Scheepens is a PhD candidate at the TU Delft since 2010 at the Design for Sustainability section. He completed his Master's thesis on the rebicycle-project. This project was aimed at investigating the inception of 100% environmentally sustainable product. His PhD topic is on exploring applications of the eco-cost/value ratio to promote economic and environmental sustainability across products and product-service systems. He and Shauna Jin contributed equally to this work as co-first authors.

1 Introduction

The need to further environmental sustainability with regard to production, consumption and, in the long-term, economic growth, is a pressing topic from both the perspective of emerging and developed markets. The emerging economy, Vietnam, is a country with a growing domestic market (Andrew and Yali, 2012) and is a large producer for Western European markets (Breu et al., 2012). Thus, addressing sustainable design and production issues in Vietnam has the potential to influence sustainability on both domestic and export markets.

Vietnamese producers have production experience but have limited knowledge and experience on how to add value to their products through, e.g., design, sustainability, or marketing considerations (Breu et al., 2012; Reubens, 2013). The design discipline is still nascent in Vietnam; currently there are only two design schools offering product design education to a population of 88 million people. In comparison, the Netherlands has more than ten product design programs offered at various colleges and universities serving a population of 16 million people.

Changes in every day practice are the first step to trigger larger, socio-technical transitions (Shove et al., 2008). Thus, the change process to sustainable design and production practices will involve mobilisation of the whole value chain involving designers, producers, potential users, and outside design knowledge (Jin et al., 2011). The Future Living Studios (FLSs) attempt to help Vietnamese design industries leapfrog environmentally unsustainable design and production scenarios.

Sustainable production must necessarily further sustainable consumption: sustainable products should be sold in place of unsustainable alternative offerings to achieve actual relative environmental impact reduction. However, no scientific evidence has been found that proves that people are willing to pay for environmental sustainability in their products and services. Observing markets and customer preferences, specific problems are the higher prices customers must pay for environmentally sustainable offerings and that customers perceive these products as lower in value; this inhibits environmentally sustainable offerings from becoming widespread in their respective markets. This problem has been identified in Western European markets, and regulatory support appears to be critical for achieving market penetration of environmentally sustainable products and services (Rivas-Hermann et al., 2014). This is especially important, since consumers do not act on 'informed choice' to choose sustainable products. Instead they are becoming further removed from the environmental impacts of unsustainable consumption (Thorpe, 2010).

Similarly, in Vietnam environmental impacts are becoming more pressing as the Vietnamese economy continues to grow. The World Bank calculates that Vietnam loses

5.5% of its GDP annually to pollution and energy waste, not including the money spent to address community health problems linked to pollution (WWF Vietnam, 2010). When, if at all, would Vietnamese consumers be willing to pay for environmentally sustainable products? Could design help achieve this goal as a value adding activity?

In the following sections, details about the FLSs' approach, goals, and outcomes are presented. Thereafter, the eco-cost/value ratio (EVR) model is introduced, with an explanation of how the model is applied to the selected product designs. The findings for Vietnamese versus Dutch markets are compared in order to determine best practices and provide guidance for further sustainable product innovation (SPIN).

2 Future living studio

FLS is a temporary design studio concept that uses cross-cultural collaboration to promote mutual learning on SPIN potentials in Vietnam (Jin et al., 2012). The studios develop strategic partnerships between designers, companies and support organisations, spreading outward to involve potential users and markets to the greater network. Since 2011, three studios have been conducted in Vietnam and the concept has been expanded to Cambodia in 2014 (see http://www.futurelivingstudio.com for more information about the project).

Table 1 A summary of the three studios conducted in Vietnam

Studio	*Producers*	*Market*	*Location/dates*
1	A bamboo furniture producer, a terra cotta producer linked to a craft village, and a kitchen cabinet producer.	A collection for eco-island tourism in Vietnam for the domestic-tourist market.	HCMC, VN August 2011–February 2012
2	A bamboo furniture producer, a hardwood furniture producer, and a water hyacinth furniture producer.	A collection for young Vietnamese families for the domestic market.	HCMC, VN September 2012–January 2013
3	A bamboo furniture producer and a rattan furniture producer.	A collection for green working for domestic-export markets, starting from domestic offices.	Hanoi, VN February 2013–July 2013

Each studio brings together three Vietnamese designers, three visiting designers, and 2–3 Vietnamese producers with different material capacities to develop a collection of environmentally sustainable products (3+ per company) under a unifying theme; the themes address sustainability between a mix of local, export, and hybrid markets (see Table 1). The designers worked in teams with companies to explore sustainability potentials in Vietnam by:

- learning-by-doing together in a new product development (NPD) process with Vietnamese SME producers from their production and material capacity
- cross-pollinating their diverse knowledge and experiences

The resulting physical designs were tangible artefacts that demonstrated and started discussions on sustainable design in Vietnam from the material and production expertise of Vietnamese producers. The products embodied a range of ideas for sustainable design in Vietnam using local materials, production capacity, and market potential. Making these ideas tangible in products was critical for demonstrating the potential of sustainable design in Vietnam especially to companies, users, and the greater network (Jin et al. 2014b).

2.1 Process

Each studio lasted 3 months with the whole team, combined with 1–2 months of preparation and follow-up before and after the studios (see Figure 1). Three months was deemed the minimum time needed to undergo the whole NPD cycle, and the maximum time on the ground that international designers were willing to accept without limiting the size of the application pool. During the studios, each design team went through complete NPD cycles including design phases following the standard design model used at the Delft University of Technology (Buijs and Valkenbrug, 2005):

1. *Preparation* (1–2 months): the management team recruits participants and sets up a physical studio space. Recruited Vietnamese designers help with getting the project started. The design team members read the design for sustainability (D4S) manual in preparation for the project's start.
2. *Orientation* (2 weeks): the project officially launches with the arrival of the visiting designers. The management team facilitates activities to get the project started on the right foot such as site visits, kick-off meetings, orientation, and training activities. The participants are familiarised with the project: strategic design brief, resources, and expectations. The design team gains familiarity with each other and the participating producers.
3. *Research* (2 weeks): the design team conducts research on the producers, materials, and potential users/markets. At the end of the research phase, the strategic design brief is reformulated and deepened into specific briefs regarding user/market, producers, and materials. These briefs are presented to the producers and management team for feedback.
4. *Ideation* (2 weeks): the design team generates, analyses, and develops ideas expanding on the briefs developed in the research phase. At the end of the phase, the ideas are presented to the producers and management team for feedback.
5. *Concept development* (2 weeks): the design team develops ideas into concepts, refining their concepts through models, and paper prototyping. At the end of the phase, the concepts are presented to the producers and management team for feedback.
6. *Prototyping* (3 weeks): the design team works between the studio and factories to develop first prototypes based off of the concepts selected from the last phase. In this phase, they co-design intensively with producers.
7. *Finalising* (2 weeks): the prototypes are evaluated, tested, and refined through a second round of prototyping. They are readied for exhibition.

8 *Follow-up and exhibition* (1–2 months): the management and local team follow-up to document and disseminate the project process and outcomes through reports, exhibition, presentations, etc.

In each design phase, several company visits were made to discuss and work on evolving deliverables. In addition, at least one outreach and dissemination activity was held to connect to the greater community of designers, companies, and potential customers.

Figure 1 Images showing the FLS process; vision development, team work, ideation, sketches, co-design with producers, dissemination, user testing, and exhibition (from left to right, top to bottom) (see online version for colours)

2.2 *Participants*

The designers in the studio were selected for their interest and open-mindedness toward exploring sustainable design and cross-cultural collaboration. They were also selected for their ability to work in English, and to represent a diversity of backgrounds: education, work experience, disciplinary (within design), and cultural. The Vietnamese designers were educated at the Ho Chi Minh University of Architecture (at the time the only program offering product design education in Vietnam) in product design (5) and architecture (1) and at the Hanoi Architectural University as interior designers (3). The visiting designers came from diverse educational and industry experience backgrounds: Australia (1), France (1), Germany (2), Italy (1), Netherlands (2), and the USA (2).

Producers were selected for the attitude and interest of the management towards sustainability, in-house production capacity, natural material, and proximity to the studios. The companies represented had complementary material capabilities (see Table 1). Most produce commodity products that are indistinguishable from competitors, but two companies had started developing their own brand. All were looking to improve their design capacity and to expand their customer base in domestic or in export markets.

2.3 *Defining sustainability in the studios*

FLS is part of the SPIN Project funded by the SWITCH-Asia project to promote environmentally sustainable design and production in Vietnam, Cambodia, and Laos through training and consultancy work. The main methodology of SPIN is the D4S methodology that embeds a life cycle approach to environmental sustainability in the product design process (see http://www.spin-asia.org and http://d4s-de.org for more information about the funding project and its methodology).

In the studios, D4S was used as a starting point for introducing concepts of environmental sustainability to the team. The teams were given a strategic design brief to connect environmentally sustainable design to added value design and sustainability aspects such as: cultural, social, or economic sustainability. Diverse understandings were brought from the designers themselves, who came from different disciplines and backgrounds. Additionally other complementary and competing sustainability approaches were introduced to the designers through training and discussion, i.e., the David Report, and UNIDO sustainability checklist to show a plurality of sustainable design approaches available (David Report, 2009; Reubens, 2013). These approaches highlight not only environmental sustainability but also social, cultural, and economic sustainability aspects.

2.4 Resulting collections

The studios resulted in more than 30 designs ranging from alpha to beta prototypes, including chairs, tables, lamps, storage, etc., for home, office, and tourism applications. The products in each studio were exhibited in Vietnam at two trade fairs (Lifestyle 2012 and VIFA Home Fair) and at the Goethe Institute in Hanoi. The goal of the exhibitions was to start a dialogue on sustainability through the project and products as a part of a larger change process connecting sustainable design and consumption.

Initial market responses from the exhibitions and showroom suggest that the products are attractive for both local and export markets. For the local market, the collection concept was new to Vietnam. The Vietnamese recognised the designs as ‘new’ for their context, and people were initially drawn to the exhibitions by the novelty aspects of the collections or specific designs. The designs elicited feedback that showed preferences by the domestic or export markets for functionality, material combinations, or aesthetics. Certain designs were more appreciated by some markets and less by others.

The studios used the learning and probing approach to develop future Vietnamese sustainable design consumers by exposing them to the prototypes and designs in progress through exhibition and outreach (Lynn et al., 1996; Hellman, 2007). Visitors gleaned aspects about sustainability by learning about the project, collection, and products. Through feedback and discussion, visitors were acquainted with the sustainability story about the collection. They could interrogate sustainability from the physical products. Some products embodied new functionality for the Vietnamese context such as the need to store clothing in an ‘open’ versus closed wardrobe in tropical climates.

The goal of the exhibitions was to start a dialogue on sustainability through the FLS products as a part of a larger change process to further sustainability considerations in the local context. However, in this stage, it has been difficult to objectively assess the FLS products on their actual market value and environmental sustainability, for both the domestic and Western markets. Therefore, the EVR model is applied to the FLS products in order to explore these issues.

2.5 Assessing the sustainability of the FLS products

The aim of this paper is to reflect on the combined environmental and economic sustainability of the product designs that were the outcomes of the FLS studios, and to discuss potential for further improvement. The following research questions have been formulated:

1. To what extent has the FLS approach been successful in developing products with high environmental sustainability?

2. How are FLS products valued in each market? Are FLS products valued higher in Western markets than in domestic markets?

3. What is the viability of FLS products for both markets? Is the perceived value of FLS products high enough to justify export to Western markets?

4. According to the results, what are the next steps to improve the environmental and economic sustainability of these products?

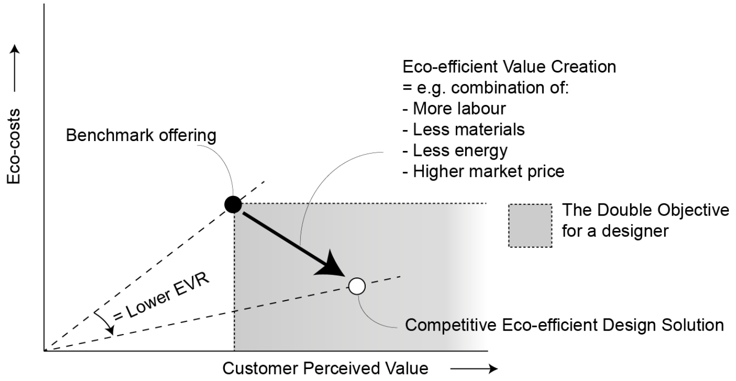
The first hypothesis is that the products will perform well in terms of environmental impacts for production, as a result of the FLS approach. The second hypothesis is that the products will perform well in terms of value on Western export markets compared to Vietnamese markets, because Dutch consumers are expected to appreciate the ‘design value’ of bamboo material more than Vietnamese consumers. In Vietnam, bamboo is considered a romantic but low-value material, but in Europe it is an interesting material and has the potential to compete economically as an alternative to wood (Van Der Lugt, 2008). The third hypothesis is that at least some FLS products are high-value enough to justify transport from Vietnam to Europe, although exporting bamboo to Western markets significantly increases the environmental impacts (Vogtländer et al., 2010).

3 The EVR model

As part of eco-efficient value creation theory (Vogtländer et al., 2013), the EVR model decouples economic value and environmental impacts. The model is created with the main objective of assessing and communicating the sustainability of products (Vogtländer, 2001). By de-linking the value and environmental impacts of products, services or product service systems (PSS), ‘EVR thinking’ provides (strategic) design decision-making with the necessary tools to achieve solutions that have low environmental impacts with high value for its respective markets (Mestre and Vogtländer, 2013; Rivas-Hermann et al., 2014). It stresses the need to innovate towards the eco-efficient value creation solution space called the double objective: the aim of the EVR model is to support designers to design products with a low EVR.

Figure 2 shows the relationship between eco-costs and customer perceived value and the double objective for designers to design product offerings that have higher environmental sustainability, and higher customer perceived value. A relatively low E/V ratio implies that the amount of environmental impacts is low compared to the value of the offering leading to a low environmental impact per euro spent. The EVR is calculated by integrating environmental assessment of offerings with their value-proposition: the relation between costs, market price and customer perceived value, which is further explained below.

Figure 2 Eco-costs/value ratio model



3.1 Eco-costs

Life cycle assessment (LCA) aims to quantify the environmental impacts of products over the whole product lifecycle of production, distribution, use, and end-of-life (Iso, 2006; Joint Research Centre European Commission, 2010). LCA quantifies the environmental impacts of selected products against benchmarks that are comparable in functionality and quality (as much as possible). In the EVR model, fast-track LCA methodology is used to calculate the environmental impacts of products and services. Fast-track LCA refers to the LCA methodology developed for designers, business managers and policy makers (Vogtländer, 2010). It was developed to enable non-environmental-specialists to perform fast and practical LCA calculations.

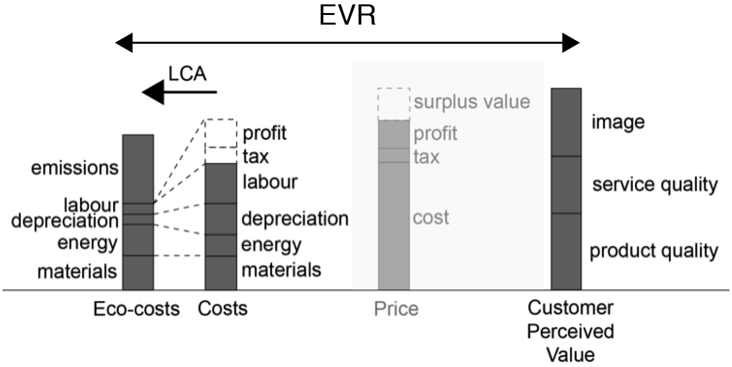
Following the EVR model, the calculated environmental impacts in this paper are expressed in eco-costs[1] as a prevention based, single indicator (Vogtländer, 2002).

3.2 Value

The value component of the EVR model is based on the concept of customer perceived value (Gale, 1994). The model circumvents the need to quantify multi-variable concepts such as quality, functionality, and image by using the market price for products available in the market, or willingness to pay (WtP) for new products as a measure for customer perceived value. For a full understanding of the EVR model, it is necessary to understand the relationship between cost, price and value of products from an EVR perspective.

Figure 3 depicts how the costs of a product relate to the price and customer perceived value. Costs including profit and tax constitute the price, where the difference between price and customer perceived value is the surplus value. Hence, surplus value can be seen as a measure for the attractiveness of an offering. Where LCA in itself only takes the environmental impacts into account, EVR also incorporates the value created by the product or service.

Figure 3 The EVR perspective on costs, price and value combined with the LCA approach



Consideration of EVR in the design phase can enable designers prevent the two pitfalls of ‘sustainable products’:

1 sustainable products have less ‘surplus value’ due to, e.g., higher production costs compared to competing, non-sustainable products

2 sustainable products tend to be perceived as having lower value.

This explains why many ‘sustainable’ products are often not successful on their respective markets: the offerings are considered too expensive relative to their perceived value. Or in other words, ‘sustainable products’ tend to lack surplus value.

Until now, the EVR model has been applied to products, services and PSS in Western contexts (Rivas-Hermann et al., 2014; Mestre and Vogtländer, 2013; Wever and Vogtländer, 2013). In this study, the EVR model is used as an evaluation tool to evaluate the FLS products on domestic and western markets, and as a prescriptive design tool to suggest opportunity areas to improve the designs and the studio setup.

4 Method

Two bamboo products per studio were selected for evaluation. Bamboo was chosen because it is a material FLS consistently worked with across each studio. In terms of sustainability, bamboo is a promising material. It is cheap, low in Eco-cost, abundant, and renewable. It also has potential design value for Western markets (van Der Lugt, 2008). The FLS products were selected to represent designs from both the local and international sides of the design collaboration. The six products represent a range from alpha to beta prototypes. At the time of project completion, no products were yet market ready.

For each FLS design, an IKEA benchmark was selected that has a similar functionality (see Figure 4). IKEA was chosen as a benchmark because it is an example of a highly successful international company with a strong commitment to sustainability (Strand, 2008). IKEA could also represent an aspirational furniture brand for emerging Vietnamese consumer groups. There are a few ‘pre-IKEA’ retailers in Vietnam with similar product offerings [see *UMA* (http://www.uma.vn) or *Index Living Mall* (http://www.indexlivingmall.com) for example].

Figure 4 Selected bamboo products per studio and IKEA benchmarks (see online version for colours)

4.1 LCA data collection

The eco-costs are calculated through a fast-track LCA by making estimations and assumptions about the production processes of each design including the production, transport, use, and end-of-life stages. Scenarios for each of these stages were developed to estimate the likely influence of local contexts.

Information about FLS products is integrated into the LCA calculations to represent which products were designed to be flat-packed for transportation. Comparable substitutions are made for processes or materials that are not available in the eco-cost database. It is assumed that FLS products are less optimised for transportation compared to IKEA.

A highly optimised supply chain is assumed in the calculation of eco-costs for IKEA products. IKEA products are modelled as ‘flat packable’ with materials sourced from the same geographical region (for the Dutch market materials are sourced from Germany and Eastern Europe; for the Vietnamese market materials are sourced from China). Information is collected from the IKEA website about each product’s dimensions, weight, and volume.

4.2 WtP survey

In order to calculate the EVR of each product, the LCA data is supplemented with WtP data, because the market price of the FLS products is unknown, i.e., the FLS products have not been introduced to the market yet. WtP data was collected through two online surveys in Vietnamese (see Figure 5) and English. Respondents were asked two control questions in addition to the WtP question for each of the 12 products (six FLS and six IKEA benchmarks):

- How much you would be willing to pay for this product? (WtP)

- How much you think the product would retail for in a shop?
- Indicate how much you like the product on a scale of 1–7 (‘hate it!’ to ‘love it!’).

Each product was presented with a functional title, e.g., ‘multi-functional rack’ and a picture. No additional product story was included explaining the products further. The functional titles used for each FLS product and IKEA benchmark are indicated in Figure 4.

Figure 5 Screenshot of online VN WtP survey (see online version for colours)

Khảo sát về mong muốn của khách hàng đối với sản phẩm nội thất

Bản khảo sát này là một phần hợp tác giữa các chương trình nghiên cứu cấp tiến sĩ của trường Đại học Công nghệ Delft - Hà Lan và dự án Future Living Studios tại Việt Nam.

* Required

Giới thiệu chung về bản khảo sát

Bản khảo sát này giúp xây dựng một phần đánh giá tính bền vững về mặt kinh tế và môi trường của các sản phẩm nội thất.

Dưới đây là những câu hỏi được đặt ra cho bạn nhằm đánh giá các sản phẩm dựa trên:
1) Khoản tiền mà bạn sẵn sàng trả cho sản phẩm này
2) Khoản tiền mà bạn nghĩ sản phẩm sẽ được bán lẻ trong cửa hàng với giá đó.
3) Mức độ bạn thích sản phẩm đến đâu

* Xin vui lòng trả lời tất cả các câu hỏi bằng tiền đồng Việt Nam (Ví dụ: 1500000 đồng)

Kệ/chia ngăn

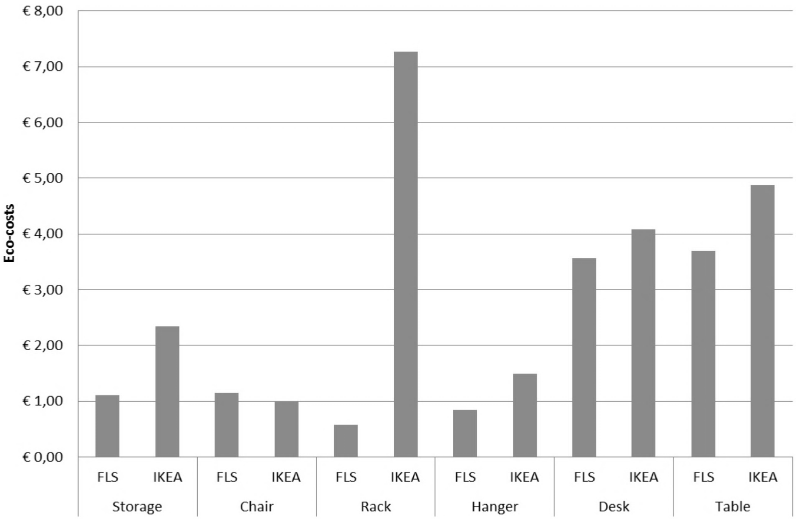
Surveys were distributed online in Vietnam and the Netherlands. The Dutch market was chosen as a representative market for Western Europe. Data was collected between April and May 2014. All values were converted to euros for the comparison.

5 Results

5.1 *Eco-costs*

The eco-costs comparison between FLS products and selected IKEA benchmarks shows that the FLS approach is successful in achieving a lower environmental impact as a result of furniture production. See Appendix A for the complete results of the fast track LCA analysis. Figure 6 shows that the FLS products have lower eco-costs for production due to the use of local, naturally renewable materials: bamboo, waste materials (i.e., rubber wood), and re-used material (i.e., re-purposed doors). The only exception is the FLS chair, which has a slightly higher eco-cost for production; this difference is caused by the use of PUR foam and dyed cotton for the cushions where the IKEA chair is made entirely from naturally renewable material (modelled as Scots Pine). Analysis of the IKEA products shows that the eco-costs of using materials such as steel (e.g., IKEA rack) significantly contributed to the total production eco-costs, justifying the initial focus of FLS on local, natural materials.

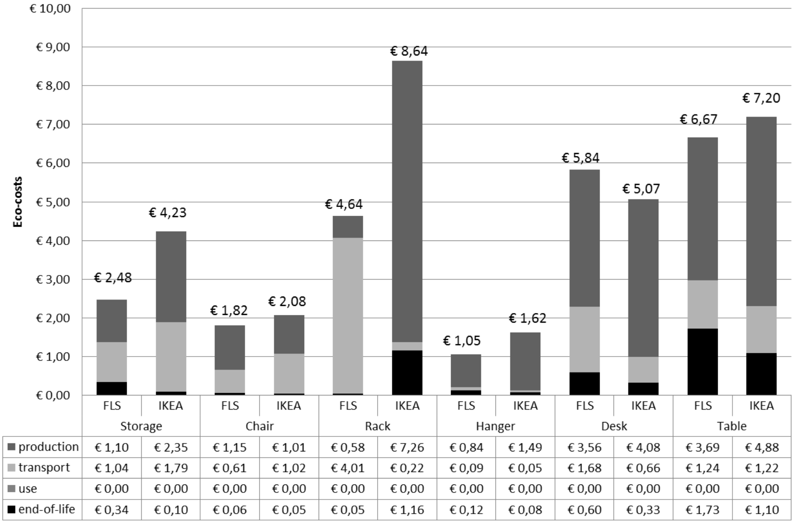
Figure 6 Eco-costs comparison for FLS vs. IKEA production per product category



However, taking the full life-cycle into account (production, transport, use, and end-of-life), a slightly different picture emerges based on the transport and end-of-life scenario for Vietnam (Figure 7). The FLS products have lower eco-costs compared to the IKEA benchmarks if they are produced and sold in Vietnam, with the exception of the desk due to the tempered glass top, rubber tires, and large transport volume. Despite the material use and logistical complexity of IKEA's products and supply chains, the lifecycle eco-costs are still comparable to the FLS products (less than factor 2). The opposite picture emerges when selling the products for the Dutch market.

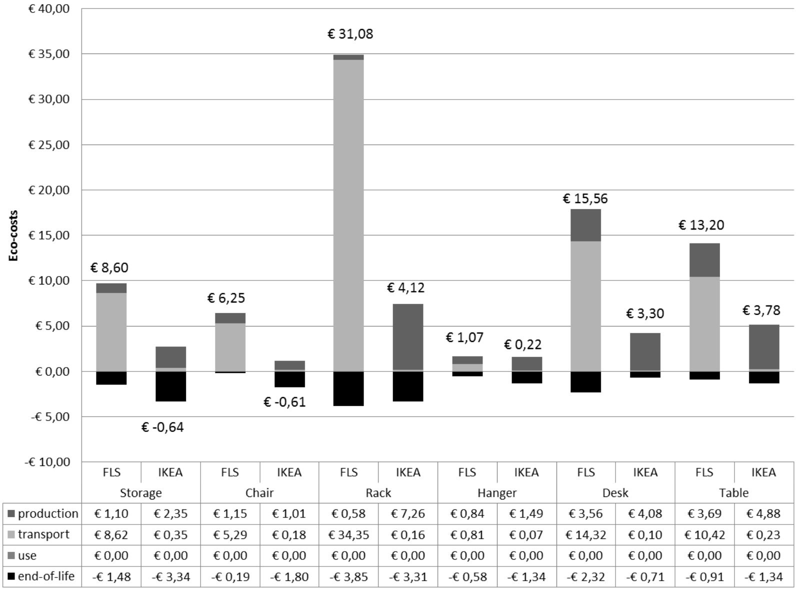
Figure 8 shows that all IKEA benchmarks have lower eco-costs compared to FLS products when sold on Dutch markets; the bulk of the eco-costs of FLS products are accumulated during the transportation phase. In comparison, the IKEA products generate the most eco-costs during production: some IKEA products result in negative eco-costs, explained by the use of local, naturally renewable materials with a negative eco-cost for production and end-of-life when the materials are burnt for energy production to accrue 'credits' (Vogtländer et al, 2014). These combined credits are higher than the eco-costs for transport and production, and generate negative eco-costs for the IKEA chair and storage benchmarks.

Figure 7 FLS product vs. IKEA benchmarks for the Vietnamese market



	Storage		Chair		Rack		Hanger		Desk		Table	
	FLS	IKEA	FLS	IKEA	FLS	IKEA	FLS	IKEA	FLS	IKEA	FLS	IKEA
■ production	€ 1,10	€ 2,35	€ 1,15	€ 1,01	€ 0,58	€ 7,26	€ 0,84	€ 1,49	€ 3,56	€ 4,08	€ 3,69	€ 4,88
■ transport	€ 1,04	€ 1,79	€ 0,61	€ 1,02	€ 4,01	€ 0,22	€ 0,09	€ 0,05	€ 1,68	€ 0,66	€ 1,24	€ 1,22
■ use	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00
■ end-of-life	€ 0,34	€ 0,10	€ 0,06	€ 0,05	€ 0,05	€ 1,16	€ 0,12	€ 0,08	€ 0,60	€ 0,33	€ 1,73	€ 1,10

Figure 8 FLS product vs. IKEA benchmarks for the Dutch market

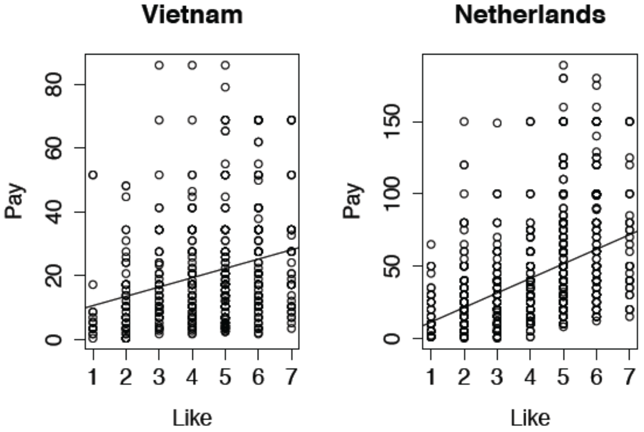


	Storage		Chair		Rack		Hanger		Desk		Table	
	FLS	IKEA	FLS	IKEA	FLS	IKEA	FLS	IKEA	FLS	IKEA	FLS	IKEA
■ production	€ 1,10	€ 2,35	€ 1,15	€ 1,01	€ 0,58	€ 7,26	€ 0,84	€ 1,49	€ 3,56	€ 4,08	€ 3,69	€ 4,88
■ transport	€ 8,62	€ 0,35	€ 5,29	€ 0,18	€ 34,35	€ 0,16	€ 0,81	€ 0,07	€ 14,32	€ 0,10	€ 10,42	€ 0,23
■ use	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00	€ 0,00
■ end-of-life	-€ 1,48	-€ 3,34	-€ 0,19	-€ 1,80	-€ 3,85	-€ 3,31	-€ 0,58	-€ 1,34	-€ 2,32	-€ 0,71	-€ 0,91	-€ 1,34

5.2 Value

The survey resulted in 47 Vietnamese and 88 Dutch respondents. To assess the quality of the surveys, a positive relationship was confirmed between how much a customer likes (LIKE) a product to their WtP in both markets, both including and ignoring outliers (2.5% >= outliers >= 97.5%). A positive relationship was confirmed based on the correlation shown Figure 9.

Figure 9 Graphs showing LIKE predictive of WtP for NL without outliers included



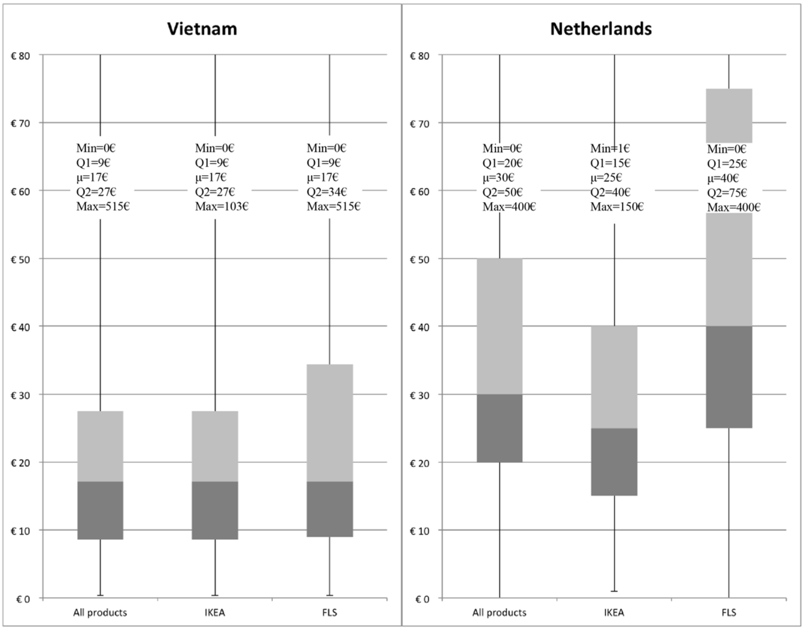
Comparing market level differences, the statistical analysis shows that the Vietnamese are willing to pay significantly more for all products as a proportion of their income when compared to Dutch respondents (Table 2 [1]). However, controlling for income and using absolute values, Dutch are willing to pay significantly more than Vietnamese respondents (Table 2 [2, 4]). These findings are also reflected in the box and whisker plots of WtP showing differences for the Vietnamese and Dutch market (Figure 10). The graphs show where 75% of WtP results lie for all of the products and for each company. The mean and range of the results for WtP_{NL} is higher than WtP_{VN}.

Table 2 Impact of country on WtP – significant differences are highlighted per cell with the country that was willing to pay more printed in the cell

DV: WtP	WtP_{all}			WtP_{FLS}		
	[1]	*[2]*	*[3]*	*[4]*	*[5]*	*[6]*
	% income	*Absolute*	*Absolute*	*% income*	*Absolute*	*Absolute*
Vietnam	VN***	NL***	NL***	VN***	NL***	NL***
Vietnam *income			VN°			VN°

Notes: ***p < 0.001, *p < 0.05, °p < 0.1, absolute values were converted to euros; see Table 8 in Appendix B for full results of the statistical analysis.

Figure 10 Mean WtP graphs showing country level differences for VN and NL



Notes: Box 25th and 75th percentiles; bars = min values (max values not shown).
Vietnamese incomes converted to euros.

Examining FLS products, the results are the same. The Dutch are willing to pay more in absolute values and controlling for income (Table 2 [5, 6]); the Vietnamese are willing to pay more as a proportion of their income (Table 2 [4]).

Regarding brand preferences, the Vietnamese like IKEA significantly more than the Dutch (Table 3 [5, 6], Table 4 [1, 2]). For the Vietnamese market, income is predictive of WtP (Table 5 [3]); for the Dutch market, income is not predictive of WtP (Table 5 [6]).

Table 3 Impact of Country on LIKE - significant differences are highlighted per cell and the country that liked the products more is printed in the cell

DV: LIKE	*$LIKE_{all}$*		*$LIKE_{FLS}$*		*$LIKE_{IKEA}$*	
	[1]	*[2]*	*[3]*	*[4]*	*[5]*	*[6]*
Vietnam	VN***	VN***		NL°	VN***	VN***
Income				NL°		
Vietnam *income		NL°				NL*

Notes: ***p < 0.001, *p < 0.05, °p < 0.1, values were converted to euros; see Table 9 in Appendix B for full results of the statistical analysis.

Table 4 Impact of company on $LIKE_{country}$, significant differences are highlighted per cell and the country that liked the products more is printed in the cell

DV: $LIKE_{country}$	*$LIKE_{VN}$*		*$LIKE_{NL}$*	
	[1]	*[2]*	*[3]*	*[4]*
Std.	Absolute	Absolute	Absolute	Absolute
IKEA		IKEA°	FLS***	FLS***
Income				FLS*
Ikea*income				

Notes: ***p < 0.001, *p < 0.05, °p < 0.1, values were converted to euros; see Table 10 in Appendix B for full results of the statistical analysis.

Table 5 Impact of company on $WtP_{country}$ – significant differences are highlighted and the brand with higher WtP is printed in the cell

DV: $WtP_{country}$	*WtP_{VN}*			*WtP_{NL}*		
	[1]	*[2]*	*[3]*	*[4]*	*[5]*	*[6]*
Std.	% income	Absolute	Absolute	% income	Absolute	Absolute
IKEA				FLS***	FLS***	FLS***
Income			IKEA*			
Ikea *income						

Notes: ***p < 0.001, *p < 0.05, °p < 0.1, absolute values were converted to euros; see Table 11 in Appendix B for full results of the statistical analysis.

Table 6 Impact product type on $WtP_{Country}$ for all product categories compared to a chair

DV:	*WtP_{VN}*	*$LIKE_{VN}$*	*WtP_{NL}*	*$LIKE_{NL}$*
	[1]	*[2]*	*[3]*	*[4]*
IKEA			FLS*	
Coffee table (FLS)	Coffee table***	Coffee table*	Coffee table	
Desk (FLS)	Desk*	Chair°		
Hanger (FLS)	Chair**		Chair**	Hanger*
Rack (FLS)				
Storage (FLS)	Storage***			
IKEA*coffee table	FLS*	FLS***		
IKEA*desk	IKEA°	FLS*		
IKEA*hanger		FLS***		
IKEA*rack	IKEA***	IKEA**		
IKEA*storage	FLS***	FLS***	FLS*	

Notes: ***p < 0.001, **p < 0.01, *p < 0.05, °p < 0.1, absolute values were converted to euros; see Table 12 in Appendix B for full results of the statistical analysis.

Both Dutch and Vietnamese are willing to pay more for the FLS storage compared to the IKEA benchmark (Table 6 [1, 3]). The FLS product that is universally liked significantly over IKEA is the FLS coffee table (Table 6 [2, 4]). Figure 11 shows the density plots of WtP for IKEA and FLS products in VN and NL.

The Vietnamese do not show a preference for brand; they do not significantly like, nor are willing to pay more or less for IKEA products versus FLS products (Table 4 [1, 2] and Table 5 [1, 2]). The box and whisker graphs of the median, 25% and 75% values show that the median LIKE for FLS and IKEA products are the same, though the range of LIKE on lower percentile is larger for FLS products (Figure 12).

Figure 11 Density plot for WTP in VN and NL: FLS and IKEA products (outliers removed)

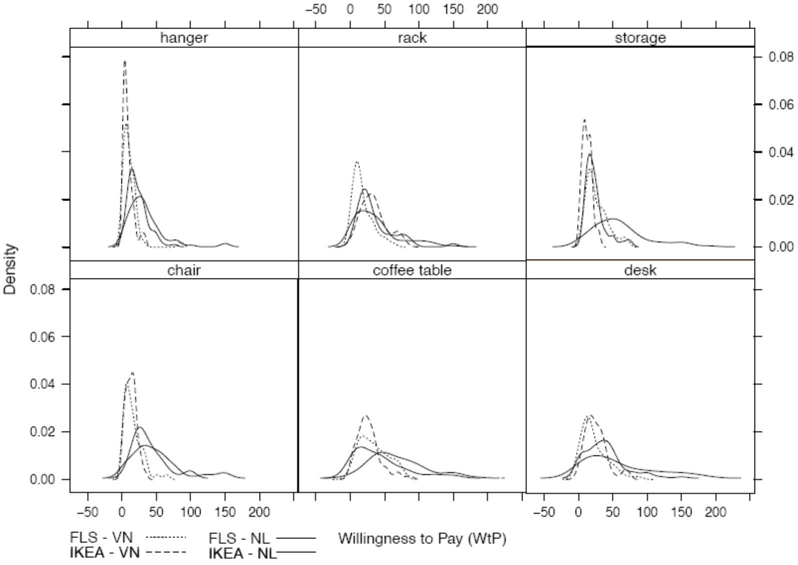
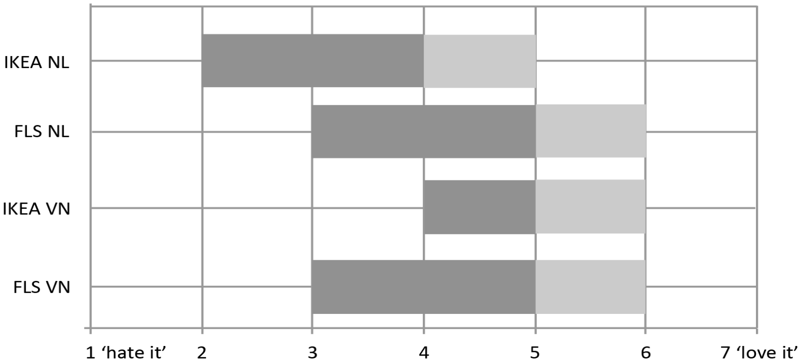
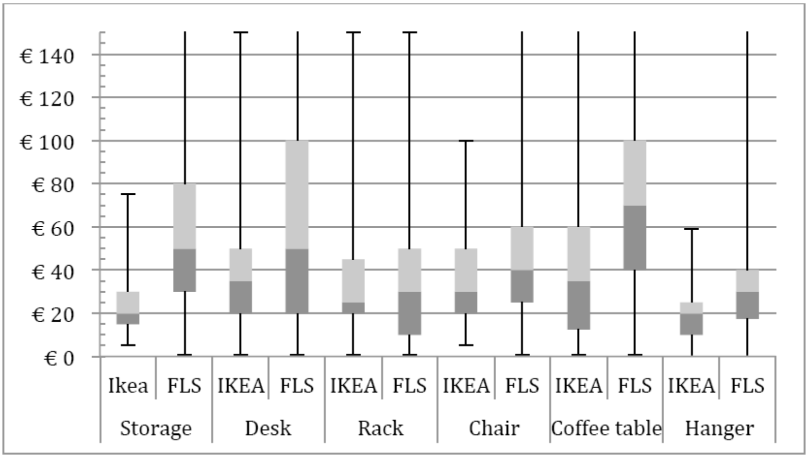


Figure 12 Median LIKE IKEA vs. FLS in VN and NL markets. Box 25th and 75th percentiles; min/max values = 1 and 7 res



Products that respondents are willing to pay significantly more for: IKEA rack, FLS storage (Table 6 [1]). Specific products that are marginally liked more compared to the other brand: IKEA desk, IKEA rack, and FLS coffee table (Table 6 [2]). Some IKEA products score higher than FLS products: rack and desk; some FLS products score higher than IKEA products: storage and coffee table.

Figure 13 Median WtP IKEA vs. FLS in the NL market for each product. Box 25th and 75th percentiles; bars = min values (max values not shown)



The results show that the Dutch significantly like and are willing to pay more for FLS products compared to IKEA products (Table 6 [4–6] and [3, 4]). The box and whisker graphs show that median Dutch like values for FLS products are one point higher (Figure 12).

Regarding specific products the FLS coffee table and storage significantly outperform IKEA benchmarks on WtP (Table 6 [3]). FLS coffee table, desk, hanger and storage are also significantly liked more than IKEA benchmarks (Table 6 [4]). Figure 13 shows that in the Netherlands, the range of the 25% to 75% and median WtP for FLS products is higher than for IKEA.

5.3 The EVRs

The EVR values are calculated by dividing the eco-costs by the median WtP values for each FLS product and the corresponding IKEA benchmark. Median values from the survey were chosen to represent WtP because they are not sensitive to outliers compared to average values; median represent the middle of the dataset. EVR results are shown in Table 7.

For the Vietnamese market, the FLS storage, chair, hanger and table score better in terms of EVR; they achieve a lower EVR than the IKEA benchmarks by generating sufficient WtP relative to the environmental impacts in the Vietnamese scenario.

Table 7 EVR values; highlighted cells indicating better EVR score

Product	EVR_{VN}	EVR_{NL}		
	FLS	*IKEA*	*FLS*	*IKEA*
Storage	0.11	0.35	0.17	–0.032
Chair	0.13	0.15	0.16	–0.020
Rack	0.39	0.25	1.04	0.17
Hanger	0.12	0.23	0.036	0.011
Desk	0.34	0.15	0.31	0.099
Table	0.20	0.30	0.19	0.11

For the Dutch market, the results show that the EVR's of all FLS products are higher than their IKEA benchmarks, indicating that currently it is not sustainable to export the FLS products to The Netherlands. Though Dutch customers are willing to pay more than the Vietnamese this does not make up for the increased environmental impacts from transport. The ratio of environmental impacts per euro spent is higher, suggesting that the FLS products are currently less sustainable on the Dutch market than the IKEA benchmarks.

6 Discussion

The first research question addressed the expected environmental sustainability of the FLS products. The results of the LCA show that the FLS products generate lower environmental impacts for production compared to IKEA benchmark products, with the exception of the chair. Generally, the focus of the FLS approach on using local natural materials and working with local production companies is successful for minimising environmental costs during the production phase of the products' life-cycles.

Taking full product life-cycles into account showed that products are more sustainable when they are produced and sold in the same region; FLS was more sustainable for the Vietnamese market, and IKEA was more sustainable for the Dutch market.

Optimising transportation results in eco-cost savings and corresponding EVR improvements. A counterintuitive finding is that eco-costs for the production of IKEA products were comparable with FLS products despite their use of mixed materials and complex global supply chain. Still, for the Vietnamese market, FLS products have lower environmental impacts, with one exception. Exporting the FLS products to the Netherlands generates higher environmental impacts than IKEA benchmarks. Therefore, from an LCA perspective, it is not environmentally sustainable to export FLS products to The Netherlands.

Answering the second research question showed that the Dutch value FLS higher than IKEA compared to Vietnamese counterparts who do not express a brand preference between IKEA and FLS. Dutch consumers are willing to pay more for the FLS products compared to Vietnamese consumers, and Dutch consumers like and are willing to pay significantly more for FLS products compared to IKEA products. For the Vietnamese market product preferences were observed on a product rather than brand level. Some products show potential for both markets.

Counter intuitively, the EVRs of the products show that the added value created through the FLS designs makes some products viable for the domestic market, but insufficient to justify transport to the Netherlands. The answer to the third question is that the additional Eco-costs for, e.g., transport, do not surpass value created by the FLS products in comparison to IKEA benchmarks.

IKEA is a good example of a company that produces sustainable products. The fact that they have optimised their production and supply chains means that it is no surprise that their products achieve low EVR values, and justifies the choice of IKEA as a benchmark for assessing the sustainability of FLS products.

The remainder of the discussion focuses on answering the fourth research question: what are the next steps to improve the EVR of the FLS products? Lowering the environmental impacts of the FLS products, especially transport, is one venue achieving a lower EVR. Another is to build off of the survey results and focus on the potential to add customer perceived value to the FLS products.

6.1 Adding value though branding and product stories

The addition of branding and product stories can improve the EVR of the FLS products by increasing customer perceived value in both markets. The products were presented as essentially commodity products in the survey and not as ‘designed’ products in a retail environment. Product stories and other marketing and branding aspects were left out to simplify comparison with IKEA benchmarks. This means that the full ‘value’ of the products that could be communicated or heightened by providing additional information was not represented in the survey. For future work, it would be interesting to evaluate the products including the branding and marketing material developed to see how their inclusion influence WtP and LIKE.

For both markets, there were two products with new functionality that could not be adequately explained through the product description or product photographs: the multi-functional rack and the chair. The rack reflects the need for open storage in tropical climates. The chair allows users to take a nap (inspired by after lunch naps in Vietnamese offices), lean, or stand to change position during work; this concept expands on ideas for green working. Respondents did not necessarily understand these new use scenarios. The rack performed poorly on the survey for both markets though it received good feedback from the export-oriented lifestyle fair. This shows the importance of product story and branding aspects (marketing, retail context, etc.) in helping potential buyers to assess the value of a product.

6.2 Viability of FLS products for the Dutch market

The results of the WtP survey for the Dutch market are straightforward: the Dutch valued the FLS products more than IKEA, though they were not necessarily developed with the Dutch market in mind. Currently, the Dutch were not willing to pay enough to offset eco-costs to make the FLS products more sustainable in comparison to IKEA in terms of EVR.

This result is not discouraging because the products were presented as commodity products without additional information that would raise the customer’s understanding of, and thus perceived value of the products. The unknown and unfamiliar bamboo material and FLS brand could mean that the Dutch were more cautious about reporting WtP information compared with familiar IKEA products. Another explanation is that Dutch consumers understand the IKEA brand almost as commodity products. If the FLS products had been compared to ‘design’ such as Piet Hein Eek, the results of WtP may have been higher due to the effect that sensitisation of the IKEA (commodity) versus Piet Hein Eek (design) brand would have effected. The fact that Dutch liked FLS products one point more than IKEA (Figure 12), and that the range of WtP is much broader than IKEA, speaks to the design value that is perceived by some respondents. Customer perceived value could be heightened by providing more product information or by targeting niche design or sustainability markets (Figure 13).

6.3 Viability of FLS products for the Vietnamese market: today and tomorrow

The WtP analysis shows that Vietnamese are insensitive to branding effects, and/or are unfamiliar with the two brands (as IKEA does not yet retail in Vietnam and FLS is an experimental project). Adding branding and marketing information can improve the WtP of the FLS products in the Vietnamese context, but probably only to a certain extent, limited by the purchasing power of consumers. The fact that IKEA is not valued higher than FLS is heartening because IKEA represents and aspirational brand in Vietnam (demonstrated by the ‘premium’ pre-IKEA stores). The similar valuation contradicts the initial expectation that domestic consumers would negatively perceive the bamboo materiality of the FLS products. The fact that they did not prefer IKEA is a positive result and one step in improving the customer perceived value of bamboo design in the eyes of the Vietnamese consumer. Some of the designs overcome the Vietnamese’s perception that bamboo is a cheap material demonstrated by their expressed preference for the FLS coffee table and storage.

As Vietnam and Vietnamese consumers continue to develop, the EVR of designed or sustainable products is likely to improve. EVR is not absolute in time, and the WtP can increase to reflect higher purchasing power. This trend is supported by the fact that export markets are shrinking and that domestic markets are growing. In Vietnam, the middle and affluent classes are projected to double to about 30 million in 10 years (BCG, 2013).

6.4 Multi-market perspective

The EVR results suggest that currently most FLS products are viable for the Vietnamese market, and could be made more viable for the Dutch market. The higher income and WtP of the Dutch, plus their brand preference towards FLS, means that the products can be viable if the Eco-costs are lowered, and/or the Value of the products is raised. As a prescriptive tool, EVR indicates how high the retail price should be set to offset eco-costs. By applying EVR to more than one market, designers have a higher chance of achieving environmental impact reduction per euro spent than comparing just one market context. Thoughtful application of the EVR model could achieve a system-wide reduction in environmental impacts by bringing in this new perspective.

The analysis showed differing user preferences across markets that cannot be captured by out-culture people. For example, the Vietnamese did not appreciate the FLS desk, but the coffee table was universally appreciated. This design approach could be complemented through considering complementary approaches such as systemic context variation to heighten intentional design for multiple end contexts (Crul et al., 2013). This perspective is especially valuable for emerging markets such as Vietnam, where user preferences are quickly evolving and changing (BCG, 2013).

6.5 The potential to integrate EVR thinking into FLS approach

Reflecting on the studios, there is an opportunity to improve the approach by including EVR thinking from the outset in the strategic design brief development. A criterion could be that the designed products must be more sustainable from the EVR perspective than benchmarks. In the future, EVR can be presented as a sustainability perspective that uses different metrics to reveal counter intuitive results about sustainability that can inform design decision-making. As we have shown, EVR can be used to check the concepts during the design process, to evaluate viability of products for different markets, and to set retail prices. These aspects can inform the design process and provide valuable feedback for companies looking to enter new or unknown markets.

7 Conclusions

The WtP analysis confirms that the FLS products have potential on the domestic market. Some of the products were able to overcome the Vietnamese consumers' perception of bamboo as a cheap material; this is part of a larger learning and probing process to understand and orient emerging consumer groups towards sustainable design issues of local production and consumption.

For the Western European markets, current eco-costs have to be lowered, and WtP raised to achieve an EVR similar or better than the IKEA benchmarks. There is potential to improve the marketing and communication aspects to raise the WtP. The LCA component suggests that the FLS approach should be expanded to focus more on optimising the other life-cycle stages such as transport in addition to the current production focus.

The EVR perspective adds a valuable perspective that environmentally sustainable products are not necessarily holistically sustainable when considering whether or not consumers are willing to pay a premium for environmental sustainability. Global companies such as IKEA are often accused of green-washing, but the EVR analysis shows that the design philosophy of IKEA is effective in achieving high-value products with relatively low Eco-costs. The total Eco-costs of IKEA products were comparable to FLS products that were developed with environmental sustainability in mind, despite their use of mixed materials and their complex supply chain.

Finally, novel contributions of this research are that it has demonstrated the potential for EVR application in new, 'emerging' contexts such as Vietnam. These findings have two main implications for business managers and policy makers in Vietnam. For both, EVR thinking can be applied to future projects holistically from the outset, and not only as an evaluation tool. For business managers, EVR adds holistic value to sustainability beyond environmental considerations that make considerations more tangible, such as its potential multi-market perspective. For policy makers, promoting the integration of EVR from start to finish could widen the scope of sustainable design from creating environmental value to creating multiple forms of value: social, cultural, and economic.

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Notes

1 See http://www.ecocostsvalue.com for more information on the EVR model and the eco-costs database for fast-track LCA.

2 Both authors contributed equally to this work as co-first authors.

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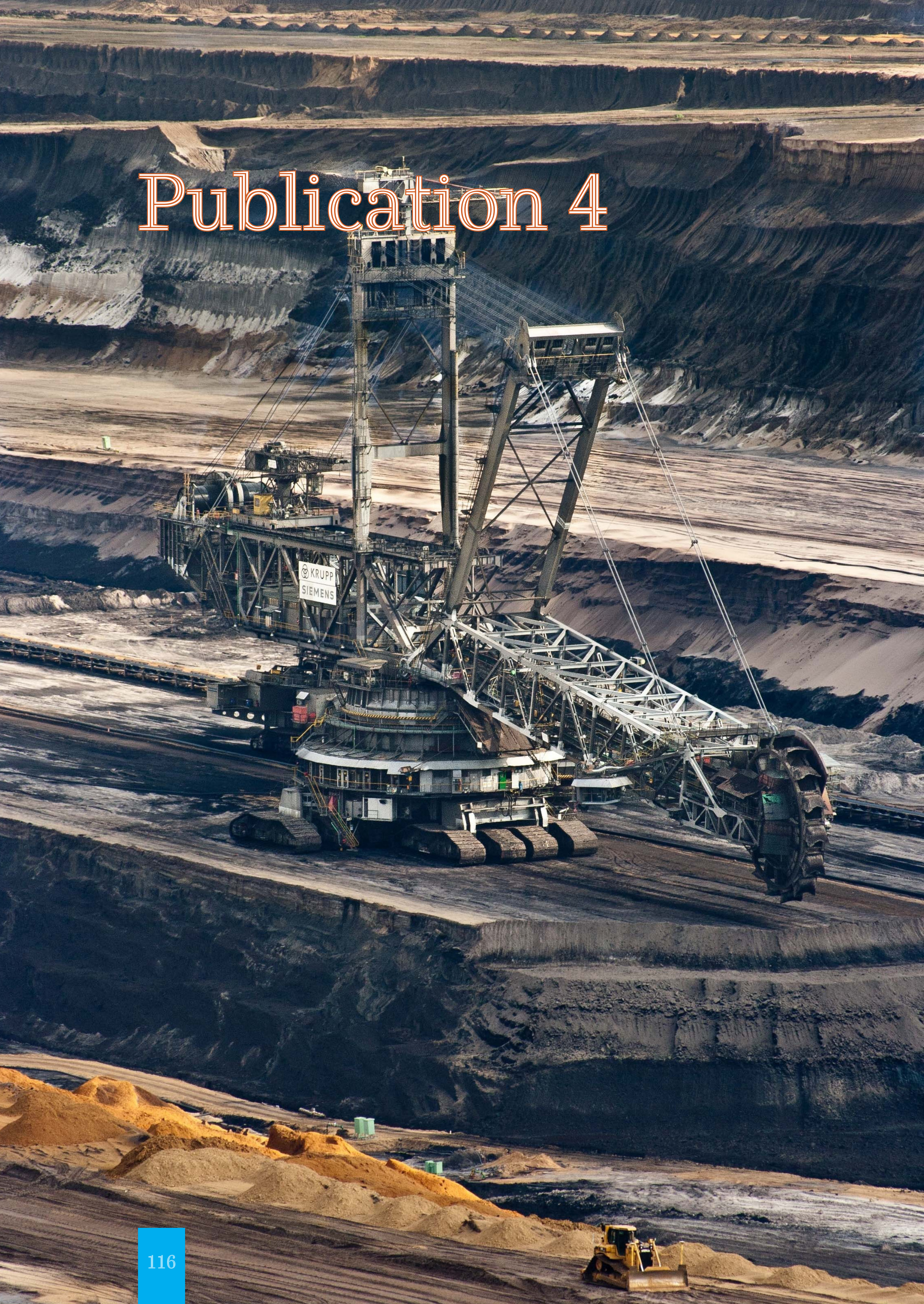

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RESEARCH

Combined analyses of costs, market value and eco-costs in circular business models: eco-efficient value creation in remanufacturing

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Abstract Eco-efficient Value Creation is a method to analyse innovative product and service design together with circular business strategies. The method is based on combined analyses of the costs, market value (perceived customer value) and eco-costs. This provides a prevention-based single indicator for 'external environmental costs' in LCA. The remanufacturing of products is an environmental and sustainable approach, in the circular economy, and can deliver lower eco-costs of materials depletion and pollution. From a business point of view, however, remanufacturing seems to be viable in B2B niche markets only. In consumer markets, remanufacturing is less common. The question is how can remanufacturing become a viable business solution for mainstream consumer markets. Traditional 'green' marketing approaches are not enough: green has a positive, but also negative connotations, so marketing approaches are complex. By using the Eco-efficient Value Creation method, marketing strategies for the roll-out of remanufacturing in mainstream consumer markets, can be revealed. This approach has led to the development of five aspects, which are key to innovative circular business models, for remanufacturing: (1) buyers differ from the buyers of the 'new product' (2)

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quality must be emphasised in all communications (3) risk must be taken away from the buyer (4) top level service is required to convince the buyer (5) a ‘green’ brand may support the remanufactured product image.

Keywords Eco-cost · Life cycle analysis · Reuse · Remanufacturing · Sustainability · Closed loop

Introduction

Remanufacturing is one of the promising business solutions in the future ‘circular economy’ [8, 15, 19, 27]. Although modern approaches of remanufacturing, as a successful business model, have existed since the end of World War II [17], it has recently attracted the attention of environmentalists, who propose that it is a way to slow down materials depletion and reduce CO2 emissions.

For products, all of which contain energy-intensive materials, remanufacturing can have significantly lower environmental impacts. Indeed, a large contribution towards total environmental impacts of products are related to the extraction and processing of materials derived from primary (virgin) stock materials. This is especially related to the use of scarce or critical materials [28]. Widespread remanufacturing would lower the environmental impact of society. To achieve this, there would need to be a significant increase in the market share of remanufactured products [19], [5, 23], [6, 3], [33].

Remanufacturing has been defined as: “*returning a used product to at least its original performance with a warranty that is equivalent to or better than that of the newly manufactured product”* [5]. The disadvantage of this definition is that it is not specific enough to all cases. An example is the return of new electronics products to the on-line store, because the buyer changed their mind (e.g. laptops, tablets an smartphones). These returned products are given a brief physical inspection and software test, and are boxed ‘as new’. Depending on which definition is used, this is ‘reuse’ or limited ‘refurbishing’. This growing business activity is a consequence of modern internet based sales and is not based in the concepts and ideas of the circular economy: it does not lead to a more sustainable society.

A more precise and meaningful definition of remanufacturing is: “*remanufacturing is an industrial process whereby products, referred to as cores, are restored to useful life. During this process the core passes through a number of remanufacturing steps, e.g. inspection, disassembly, part replacement/refurbishment, cleaning, reassembly, and testing to ensure it meets the desired product standards*” [34]. This definition clearly shows that the product is upgraded by a manufacturing process after its use-phase. In the electronics sector (along with some other sectors such as medical devices), this is also called “refurbishing”.

The database of the Boston University provides detailed and reliable data on the remanufacturing industry in the USA [18]. An in-depth market study was conducted by the [36]. This study reveals that the current remanufacturing markets are related to production of parts (“cores”) in the following business sectors: aerospace (aircraft components and subsystems), heavy duty and off-road equipment (HDOR) (e.g. Caterpillar), motor vehicle parts, IT parts (predominantly toner cartridges), medical devices (Single Use Devices), and tyres (for trucks and buses).

Not all products are suitable for remanufacturing. Eight criteria for remanufacturing are [10, 17]:

a. the product is durable
b. the product functionality can be recovered
c. the product design is standardised and modular
d. the value at end of life is high enough to prevent discarding
e. the cost to obtain the core is low if compared with the potential intrinsic value
f. the product's basic hardware technology is relatively stable over a period of time that exceeds the product life time
g. the consumer should be informed about the opportunity to return the core and about the availability of remanufactured products, in order to create an adequate supply and demand
h. the product is 'designed for disassembly'.

Despite optimistic analyses with regard to the circular economy [19], the market penetration of remanufacturing is still low. Table 1 shows that the core manufacturing business in the US is still in its 'classical' B2B markets of parts for durable products. In these classical remanufacturing markets, only 2% of the products are remanufactured.

Data from the UK shows similar remanufacturing market distributions. In the UK the remanufactured ink and toner cartridges is the largest market, followed by automotive, off-road equipment, and pumps and compressors [5]. In Europe as a whole, it is estimated that remanufacturing generates around €30bn in turnover and employs around 190,000 people. While substantial, the intensity (ratio of remanufacturing to manufacturing) is only 1.9%, which indicates ample room for improvement [8].

The technical engineering aspects (the production technology as well as the logistics) of remanufacturing are rather challenging [16], especially with regard to the fact that the costs must be kept low at a high product quality. Moreover, remanufactured products are perceived by consumers as 'second hand' with related performance risks, hence the 'Willingness to Pay' is lower than for a new product [22, 33], [13, 7]. Therefore, the profit margin is often squeezed between the low market price and the remanufacturing costs. For B2B markets, where parts are specified and tested, this perceived image problem is lower, since a test can show that the quality of a remanufactured product is equal to the new product.

For B2C markets, it is likely that this perceived image issue is the main reason that there are no high market shares of remanufactured products in consumer markets (apart from toner

Table 1 Remanufacturing good production in the USA, 2011 [36]

Sector, 2011 (ranked by production value)	Production volume (thousands $)	Market share (%)
Aerospace (parts of landing gears, engines, fuel systems)	13,045,513	2.6
HDOR equipment (heavy duty and off-road vehicles and parts)	7,770,586	3.8
Motor vehicle parts (starters, gear boxes, engines, differentials)	6,211,838	1.1
Machinery (valves, turbines, tools, textile machinery, compressors)	5,795,105	1.0
IT products (hardware components and printer cartridges)	2,681,603	0.4
Medical devices (imaging, medical pumps; Xray equipment)	1,463,313	0.5
Retreaded tires (for trucks, buses, HDOR equipment)	1,399,088	2.9
Consumer products (smart phones, electronics, household appliances)	659,175	0.1
All others	3,973,923	1.3
Total	43,000,144	2.0

cartridges), compared to the B2B markets. Another reason might be the short lifespan of many product types in the consumer markets: products become obsolete because new products offer more features, improved styling, and increased functionality [1, 43].

The aim of this paper is to explore what can be done to introduce remanufactured products into mainstream consumer markets more successfully, and which new circular business models are required to overcome the aforementioned problems. Business models like Product Service Systems, (PSS) might help [31, 26], but the key question is what kind of PSS has to be applied, in which business case, and why [35].

This paper investigates the following research question: *Under which conditions can remanufacturing lead to a business model, which is both environmentally and economically viable?*

The existing literature on remanufacturing, given in this introduction, highlights that much of the prior research has mainly been focussed on either the environmental or the economic aspects. A combined approach (required for the development of circular business models) is, however, lacking.

This paper provides a framework for such a combined approach.

In Section 2, Eco-efficient Value Creation strategies are explained, and this approach is applied to remanufacturing in consumer markets in Section 3. The discussion and conclusions are given in Section 4.

The method of eco-efficient value creation

The research question of this paper is addressed by applying the Eco-efficient Value Creation method in different contexts in order to understand the aspects behind a successful business model focused on remanufacturing. The model Eco-efficient Value Creation is characterised by a combined analyses of costs, market value and eco-costs. In this Section 2.1 a description of the meaning of eco-costs and several meanings of (market) value, as far as it is relevant for the analysis.

The two kind of options for product innovation strategies which evolve from the model will be explained in Section 2.2.

Eco-costs, costs, and market value

Eco-efficient Value Creation is a method, developed at the Delft University of Technology, to analyse products and services in order to design innovative products and circular business strategies. The method is based on combined analyses of the costs, the market value (the Customer Perceived Value) and the eco-costs (a prevention based single indicator for 'external environmental costs' in LCA). This method is part of the more comprehensive model of the Eco-costs/Value Ratio, EVR [41]. For definitions and concepts of value see Table 2.

Eco-costs is a measure to express the amount of environmental burden of a product on the basis of prevention of that burden: the costs which should be made to reduce the environmental pollution and materials depletion in our world to a level which is in line with the carrying capacity of our earth (the 'no effect level'). The eco-costs should be regarded as hidden obligations, also called 'external costs' in environmental economics.

Table 2 A summary of important concepts used in this paper [32]

EVR	The Eco-costs/Value Ratio
Eco-costs	A prevention based single indicator for environmental impacts (€)
Value	The sum of the perceived product- & service- quality, and the image (€)
Price	The price at which these offerings are sold in the current market (€)
WTP	Willingness to Pay (€)
Customer Perceived Value	The expected use and fun of a product and/or service after the purchase (€)
Surplus Value	The difference between the price and the Customer Perceived Value (€)
Eco-efficient Value Creation	The overall aim of application of the EVR Model (the double objective)
Double Objective	Lowering of the eco-burden of a product and/or service and at the same time enhancing the value

The eco-costs have been introduced in the International Journal of LCA [39], and the system has been updated in 2007 and 2012. For a summary description see: https://en.wikipedia.org/wiki/Eco-costs, accessed November 2016.

The eco-costs is the sum of 17 so called ‘midpoints’ (12 environmental and 5 social), as shown in Fig. 1.

The value in this analysis is the market value, i.e. the value in the eyes of the customer.

In a simple Eco-costs/Value Ratio analysis, the market value equals the price, which is a reasonable assumption for most consumer products in the Western market economy. For the case in this paper, however, one has to zoom in to the level of the consumer, revealing a more complex issue: the perception of the individual buyer. What has to be understood is the relationship between the value, price and cost of successful offerings, see Fig. 2. For definitions see Table 2.

In Fig. 2, the difference between the costs and the price is the profit margin for the seller, and the difference between the price and the value as perceived by the customer constitutes the ‘surplus value’. The higher the surplus value, the more desirable the offering.

For a commodity product, the price and the value are (nearly) the same (there is hardly any surplus value). The price of a luxury product, however, can be considerably lower than the Customer Perceived Value for the individual customer (the individual surplus value can be

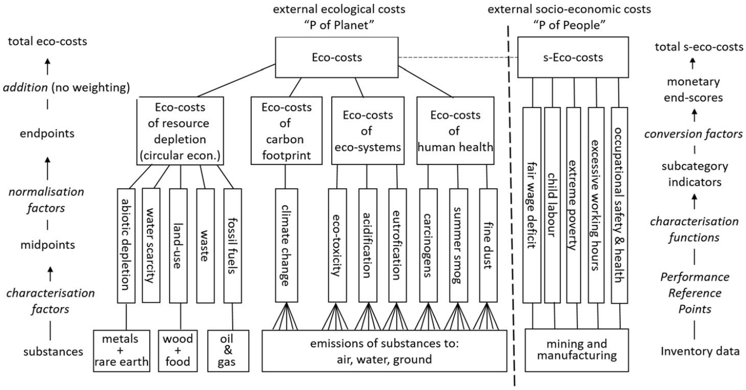

Fig. 1 The structure of the eco-costs 2012 [37]

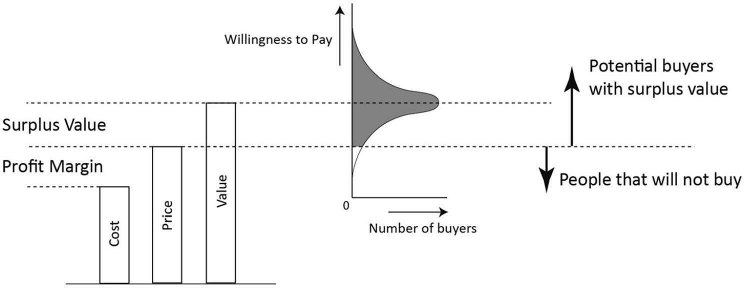

Fig. 2 The relation between costs of production, the price at point of sale, and the Willingness to Pay (WTP) of a successful offering. [32]: only buyers that perceive a surplus value will consider buying the offering

rather high). In the case of business innovation, the value can only be determined with some form of consumer research: e.g. WTP inquiries.

Entrepreneurs and product designers are commonly faced with this issue, since their activities are directed towards value creation. They use their knowledge, experience and intuition to determine whether their solution creates sufficient Customer Perceived Value at feasible costs, leading to an offering that generates profit for producers combined with a high value for consumers.

This Customer Perceived Value (resulting in a WTP) is related to the perception of the product by an individual buyer at the moment of purchase (i.e. the expected fun and use after the purchase) and in the use phase thereafter (which can lead to either increased satisfaction or dissatisfaction) [9]. For some potential buyers in the market the surplus value is positive, for some it is negative (these people do not buy the offering), as depicted with the Gauss curve in Fig. 2. The Customer Perceived Value is determined by the physical and functional product qualities (tangible as well as non-tangible), the service, and the image [11, 9].

Eco-efficient value creation: Two different sets of business strategies

The Eco-costs Value Ratio, EVR, combines eco-costs and market value to see whether a product will be successful in the future. The product should have a low environmental impact in its lifecycle (low eco-costs) and must have, at the same time, an attractive value for consumers (otherwise it is not successful in the market).

It is a trend in society that industrial 'free of charge' pollution, is no longer acceptable [41]. This can be seen in the stricter regulations put onto markets by countries (e.g. tradable emission rights, enforcement of best available technologies, eco-taxes, etc.). Eco-costs will then become part of the internal production costs. So eco-costs are not only a hidden obligation of a company towards the society, they are also a future risk of non-compliance with future governmental regulations.

The internalisation of eco-costs might pose a threat to a company, but it might also present an opportunity: when a cleaner product has a lower eco-burden than that of the competitor, the cleaner product can withstand stricter governmental regulations. So the characteristic of low eco-costs of a product is a competitive edge. This leads to the so-called 'double objective' (low eco-costs and high value at the same time) of Eco-efficient Value Creation in innovation and design. Examples of this two-dimensional design approach can be found in [20, 45, 46].

To analyse the short term and the long term market prospects of a product or service, each product can be positioned in the portfolio matrix of Fig. 3. The basic idea of the product portfolio matrix is the notion that a product or service is characterised by:

- its short term market potential: high value/costs ratio
- its long term market requirement: low eco-costs.

Most of the products in mainstream markets have a high quality/costs ratio, which provides the opportunity for the manufacturer to optimise profits: combining a good profit margin with many potential buyers, see Fig. 2 [42]. Most of these products, however, have rather high eco-costs as well. This is the "short term success, long term no market" quadrant 2. The long term risk of these products is the internalisation of the eco-costs [41]: it deteriorates the quality cost ratio, which shifts the product into quadrant 1: low quality/costs ratio, high pollution). This is sometimes a slow process, but in some cases it may happen quickly (e.g. TEPCO Japan, Hummer, Volkswagen diesel), when there is a sudden shift in public opinion, which deteriorates the Customer Perceived Value. Quadrant 1 is not a viable business area: it does not make sense to make low/no profit and pollute the world.

Many progressive main stream companies (e.g. BMW, Mercedes, Toyota, Unilever, Nike, Puma) are pro-active: they realise that the way to get out of quadrant 2 is 'greening' of their products. The aim is the "long term core product" quadrant 4.

Innovative green products are normally in quadrant 3 ("short term, no market"). They are generally introduced by Small and Medium Enterprises (SMEs) [4]. They suffer from a low quality/costs ratio, often because there is no economy of scale, and the benefit for the environment normally goes hand in hand with higher production costs [2]. The issue here is what to do to enhance the WTP of the customers, to enable a higher price at a high volume (see Fig. 2), in order to get into quadrant 4.

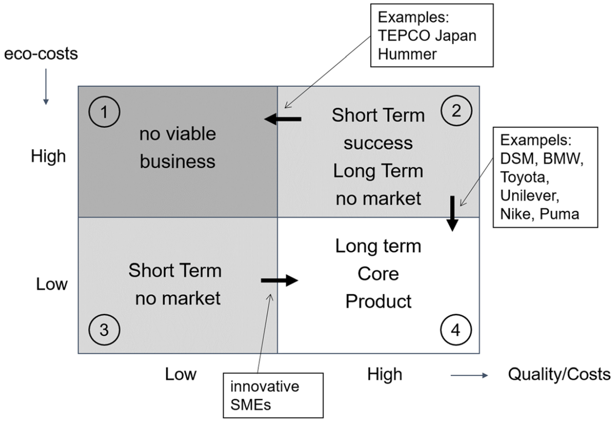

Fig. 3 The sustainable business strategy matrix

An important issue here is that the vast majority of people appear to be unwilling to pay more for the fact that a product is green [40, 38].

Successful business strategies for companies in quadrant 2 (main stream products of established multinationals) and the companies in quadrant 3 (SMEs with innovative products) are completely different:

A. main stream products (of multinationals) have to be redesigned for lower eco-costs, in order to make these products fit for future markets
B. green innovative products (of SMEs) need to get a higher Customer Perceived Value (WTP), in order to create a larger market

Ad. A. There are basically 3 highly successful redesign strategies for lowering of eco-costs of existing main stream products (the shift from quadrant 2 to quadrant 4):

- selection of less polluting materials (the effect of this design option has often been downplayed by environmentalists, but it appears highly effective in practice: a factor 4 is often achievable by shifting to bio-based materials or using advanced materials to improve performance)
- recycling of materials (by closed loop systems, or by application of materials from urban mining of post-consumer waste: in particular energy intensive materials such as metals)
- reduction of energy consumption in the use phase

Ad. B. The shift of (green) innovative products from quadrant 3 towards quadrant 4 is a bit more complex: it is about enhancing the Customer Perceived Value (WTP). Creating a sound Product Service System is often the key to do so. It seems an indispensable way to sell green and innovative products in main consumer markets. There are four general PSS strategies:

- Financing of the investment.
- Example: Electrical cars are more expensive than conventional cars, but have lower costs per kilometre in the use-phase; an operational lease contract takes away the hurdle of the initial investment for the car, and shifts that to the use-phase [32, 35]
- Enhancing convenience.
- Example: innovative products lack the wide distribution and service networks of mainstream products, since the market volume of new products is low; hence extra attention must be given to service (maintenance, repair, parts) by e.g. internet solutions and web-shops [32, 35]
- Enhancing image by means of social media.
- Example: In main stream markets it is possible to build a high value brand image via marketing activity, but for innovative products this strategy is too expensive because of the low volumes. Social media is a powerful alternative which is less expensive: users must feel that the product is something special, so they can be proud of it, and spread the message [11, 9], [14]. A high end brand image is required as well to attract investors (e.g. by crowd funding)
- Reducing risks.
- Last but not least: the negative side of innovative products is the risk of quality (e.g. Is the product reliable? What is market value after x years of use?). This risk is one of the major hurdles to buy innovative products. This hurdle can be mitigated by rental, operational lease, extra enhanced warranties, extra enhanced service [29].

The business strategies for eco-efficient value creation in product innovation, as has been described in this section, cannot be 100% copied to remanufacturing. However, there are a number of similarities, especially in the marketing strategies to bring products from quadrant 3 towards quadrant 4 (Fig. 3).

The aforementioned four marketing strategies for green and innovative products (financing, enhancing convenience and image, risk reduction) appear to be quite relevant for the remanufacturing business of mainstream consumer products [22, 33], [13, 7].

Furthermore, the low eco-costs for remanufactured products are difficult to sell. The theory of Eco-efficient Value Creation proposes here the approach of the 'double benefit' (as will be described in Section 3).

This paper will explore in the next Section 3, what the general theory of eco-efficient value creation means for the successful marketing of remanufactured products. Section 3 starts with "the problem": the main hurdles of introducing remanufactured products in consumer markets from a value perspective. Section 3.1, 3.2 and 3.3 will deal then with solutions for these hurdles.

Eco-efficient value creation in remanufacturing markets

Problems with the marketing of remanufactured products in mainstream consumer markets seem to be related to 3 major issues:

I. people seem unwilling to pay more for the fact that a remanufactured product is 'greener' than the original product [21, 38]
II. people perceive a quality risk related to remanufactured products [13, 21], [7]
III. people like to have the latest available functional features, and the newest designs (often the reason that people sell their product to buy a new one), so the market value of earlier product types is inherently lower

In the following 3 sections these 3 issues I, II and III are analysed, and consequences for business strategies are explored.

People do not pay more for green products

People *do not pay higher prices* (max 2–4%) for green products [13, 21], [38]. However, green brands have a competitive edge in attracting *more buyers*. This section describes this complex issue.

Ottman [25] was the first who described the opportunities and the pitfalls in green marketing. She introduced the notion of what we call the 'double benefit' for the buyer. Ottman distinguishes between the 'personal benefit' (e.g. comfort, looks, quality/price ratio) and the 'environmental benefit'. Ottman realised that most of the buyers regard the environment as important in the long term, however, they buy products at the point of sale on the basis of the personal benefit in the short term.

The environmental benefit seems to be more suitable to support the brand loyalty (creates 'repeat buyers'). The issue is that products must be marketed with a 'double benefit': a personal benefit as well as an environmental benefit. The marketing of German cars is an example of the use of this double benefit, e.g. BlueEFFICIENCY of Mercedes (efficiency is personal benefit, blue is environmental benefit), and EfficientDynamics of BMW ("environmentally friendly mobility and driving pleasure are anything but mutually exclusive")

This double benefit marketing is in line with the logic of two experiments at the Delft University of Technology.

In the first experiment, the buying behaviour of 3 small groups of people (business managers, consumers and environmentalists), was analysed. The group of consumers and the group of business managers appeared to select their products on the basis of quality and price. Only when there is no preference on the basis of quality and price, environmental issues become important as a final decision criterion. This phenomenon is called the 'double filter model' [40]. The conclusion of this experiment is that the environmental benefit does not support the price, but supports the market volume.

In the second experiment in 2012, a comprehensive questionnaire on buying behaviour of shoes, was sent to 600 s year bachelor students of the faculty of Industrial Design Engineering, of which 200 responded. This enquiry, which tested 8 variations in advertisements, revealed that a green (environmental benefit) product within a green brand, triggered a much lower buying intention than a product in a brand which were both not green, but both advertised personal benefit only [38]. This result was in line with other experiments with students, that revealed that 50% of the students have a negative connotation of 'green' with regard to the personal benefit: these students presume that a product is either more expensive or has less quality when it is green, or do not believe the green claims of the manufacturer. However, [38] reveals also that a product advertisement, with an accent on quality (personal benefit), within a green brand (environmental benefit), scores the highest buying intention: a double benefit strategy scores the best, see Table 3.

It is not expected that this pattern of buying intention of shoes will differ much from the buying intention of other consumer products with a strong correlation with the identity of the buyer, such as garments, smart phones, watches, and even cars. The conclusion for remanufactured products in consumer markets is that the high quality (personal benefit) of these products must be emphazised, to counteract the perceived risk of low quality [24]. Marketing in a green brand (environmental benefit) can support the competitive edge, to attract a maximum market share.

The perceived quality risk

The position of remanufactured products relative to the position of new products is depicted in Fig. 4. Although the value of a remanufactured product is higher than a second hand product (the buyer has less risk and gets a better quality), its perceived value (in consumer markets) is considerable lower than the perceived value of a new product.

The eco-costs, however, are considerably lower because of lowered use of primary raw materials.

The way to get the remanufactured product from quadrant 3 to quadrant 4 is to emphasise the high physical quality and add a PSS to the business model in order to:

Table 3 Buying intention for shoes on a 5-point Likert scale [38]

Buying intention (5-point scale)		Product	
		Environmental benefit	Personal benefit
Brand	Environmental benefit	1.95	2.45
	Personal benefit	2.36	2.29

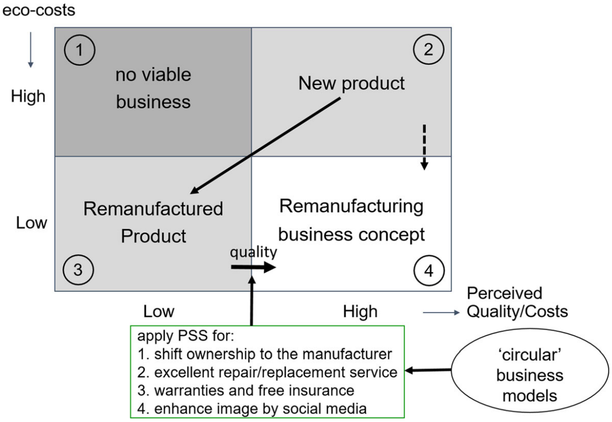

Fig. 4 The position of the remanufactured products and strategic actions to improve it

- Shift ownership to the manufacturer, so that user does not have the risk of unexpected repair costs and/or a low second hand price (leasing)
- take away the inconvenience of a repair by excellent service
- build-in warranties and insurance
- enhance image by social media to build a strong brand

This list is obviously fully in line with the list of Section 2.2. It should be the basis of the new circular business models.

A typical example of the combined analysis of eco-costs and perceived quality/cost ratio is shown in Fig. 5, the market of refurbished laptops in Europe.

Companies tend to depreciate the laptops they bought for their staff in 4 years to zero, hence the book value of a laptop is 25% after the third year. As an example we take the Macbook Pro 15 in. (Retina), price 2100 Euro new, so it is 525 Euro after 3 years. The battery life is 1000 cycles, or 4 years of 250 cycles per year (daily use of the laptop). For companies it is attractive to sell these laptops to a refurbishing company for 525 euro, and give their staff new laptops. For the refurbishing companies it is attractive as well, if they can find buyers for a higher price.

The second hand price of such 3 year old laptops in the C2C market is, however, 30–35% percent, so there is a low margin (105–210 euro per laptop). When a higher price is proposed they lose potential buyers in the market, since the customer surplus value is reduced, see Fig. 2. When they offer built-in warranties, offer a good after sales service, and build a strong brand, they can enhance the market value (WTP in Fig. 2) to 55% to even 70% of the price when new (Based on prices in March 2017 from Leapp, Forza, and iUsed, all specialised in refurbishing of Apple products in the Netherlands), resulting in a margin of 630 Euro for laptops with scratches, up to 945 Euro for the laptops which appear 'new'. Note that higher margins are required here for the service, the guarantees and the image.

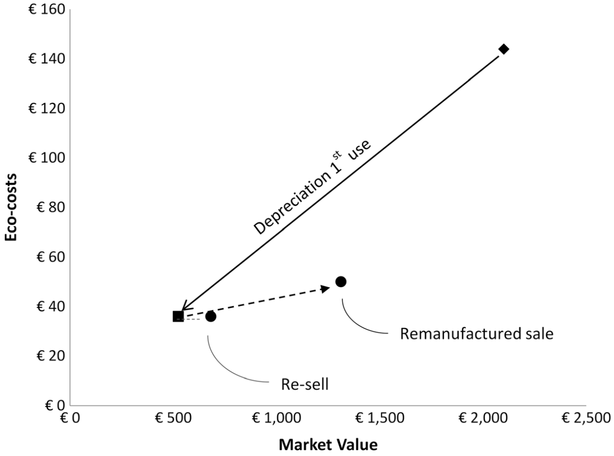

Fig. 5 The EVR chart for successful remanufacturing of the Macbook Pro 15 in

Considering the eco-burden, it is a win-win situation as well. The eco-costs of a Macbook pro 15 in. is 144 Euro, applying all Eco-costs midpoints of Fig. 1, except from the 5 midpoints for the s-Eco-costs. This 144 Euro is calculated with the LCA-method, applying tables of the Idemat database of the Delft University of Technology (see www.ecocostsvalue.com and/or the data of the Idemat Materials Selection Database, available in the App Store and the Google Play store). Applying 'economic allocation', the remaining eco-costs after 3 years is 144/4 = 36 euro. The eco-costs of a new battery is 14 euro (referring the Idemat database), resulting in 36 + 14 = 50 euro for a refurbished laptop which will last for at least another 4 years

To summarise; the new Macbook starts in quadrant 2 of Fig. 4 (price 2100 Euro, Eco-costs 144 Euro); it moves, as 'second hand' to quadrant 3 (price 630–735 Euro, Eco-costs 36 Euro), and after refurbishment to quadrant 4 (price 1155–1470 Euro, Eco-costs 50 Euro). The refurbishing step is characterised by a relative small increase in Eco-costs (the Eco-costs are still low in comparison to new), and a big increase in price (WTP), caused by the business model which is used.

The low intrinsic market value

An important reason that an old product has a considerable lower price than new product is that people like to have the latest available gadgets, and the newest designs (often the reason that people sell their product to buy a new one). In modern consumer markets (contrary to B2B markets) products are thrown away or sold because of obsolescence in terms of 'emotional value', rather than that they no longer function. This is the reason that, for the time being, it can be expected that the price of a remanufactured consumer product cannot be the same as the price of the new product.

This issue is explained, for the case of smartphones, by Fig. 6, which combines the theory of diffusion of innovation [30] with the costs, price, value model of Fig. 2.

Rogers has studied the life cycle of product creations. According to Rogers, there is a small group of people (2–3%) who buy new innovations immediately upon market introduction. This group of people are proud to own the newest and 'hottest' products, and are prepared to pay more. As time goes by, they are followed by the early adaptors (12–13%), who analyse first and buy then. These early adopters have 'respect' in society, and are followed by the early majority (35%), and then by the late majority (35%). At last a group of laggards (15%) will buy the product when it is cheap, which is the moment sales will decline and the product will be taken out of the market.

Smart phones, laptops and other small electronic devices and toys, have a product type lifespan of 4–5 years [44]. Household appliances have a product type lifespan of 7–14 years. Costs are high in the early phase of the lifespan (allocation of R&D costs and high marketing costs), and get gradually lower (economies of scale). It is the nature of remanufacturing that these products come in rather late during the lifespan of the product type.

Looking at Fig. 6 it does not make sense to market the remanufactured product under the original brand name, since the market niche of the remanufactured product (functional buyers who value low costs above an expensive brand name) is totally different from the market niche of the original product (wealthier technology freaks). The branding that is required for these two markets is incompatible, which has two consequences for the OEM:

- It seems to be logical that the remanufacturing is done by third parties, selling their product under a different brand
- It seems unlikely that the OEM suffers from cannibalism of its main brand

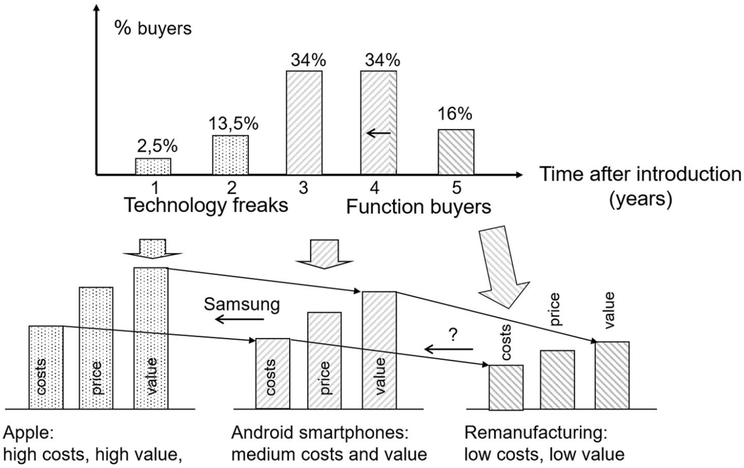

Fig. 6 The theory of diffusion of innovation linked to the costs, the price and the value [41]; example smartphones

The remanufactured smartphones should be branded as “it was perfect yesterday, it will suit you for another 4 years, since you do not need all the newest features of new phones”. The functional buyer will appreciate the lower price. For the remanufacturer the lower price still accommodates a reasonable profit margin, since a high R&D and marketing budget (more than 100% additional to the manufacturing costs of an iPhone) is not needed.

Note that this situation is totally different for the B2B market of Heavy Duty and Off Road (HDOR) equipment (Table 1). In this market, it makes sense that Caterpillar, with its durable, longer life products, remanufactures (i.e. reconditions the heavy parts and replaces the light parts) under his own brand name. In this way Caterpillar underpins the robustness of its equipment, which is a key attribute in the marketing of its new products. Moreover, when Caterpillar can sell these older products at a lower price with a good profit margin, they expand, rather than cannibalise, their own markets.

This suggests that the strategy of marketing remanufactured products depends on a combination of the characteristics of the product type and the product itself. For the product itself, the list of 8 characteristics of Section 1.1 is important. For the product type two characteristics are important: the lifespan, and the quality brand (high, medium, low).

In general, the non-food fast-moving consumer goods (e.g. garments, plastic toys, cheap gadgets in electronics) are not suitable at all for remanufacturing. A product type must last for at least 4–5 years, like smartphones and laptops. The longer the type lifespan, the more suitable the product type is for remanufacturing.

High quality branded products are more suitable for remanufacturing than low cost brands. The simple reason for this is the profit margin of the remanufacturer. High quality brands have high R&D costs and high marketing costs, whereas the remanufacturer has not. Furthermore the remanufacturer benefits from the fact that the OEM applies components with a high technical quality. Last but not least, the buyer regards the OEM product as desirable, so is inclined to buy the remanufactured product, which is affordable. All this leads to a business case with enough profit margin.

For low costs branded products the situation is different: R&D and marketing budgets are low, the quality of components is doubtful, and the level of desire of the buyer of such a remanufactured product is low, which leaves no viable profit margin for the remanufacturer.

The strategic choices of the aforementioned aspects are summarised in Table 4.

For the “no viable remanufacturing business” cases in Table 4, the only viable circular business model is to separate the still working used products and export them to developing economies, in order to give them a second life. Products which are damaged and therefore could be unreliable, must be recycled. This strategy applies to smartphones and laptops which

Table 4 The viability of remanufacturing as a circular business model in consumer markets

Product type life span	Low cost branded products	Medium price and quality	High quality branded products
Fast moving products	No viable business	No viable business	No viable business
3–6 years	No viable business	No viable business	Remanufacturing by 3rd parties
6–12 years	No viable business	Remanufacturing by 3rd parties	Remanufacturing by OEM
More than 12 years	No viable business	Remanufacturing by OEM	Remanufacturing by OEM

can be shredded/melted down to recover a fraction of the metals in it (e.g. the process of Umicore). This approach applies to many other consumer products.

Discussion and conclusions

One of the common views is that companies do not remanufacture their products because it would cannibalise on their sales of new products [7]. In Section 3.3 we argue, however, that this argument is not universally valid. On the contrary, there are companies who enhance the quality image of their products by remanufacturing (Caterpillar and its subsidiaries like Jungheinrich) and use their remanufactured products to compete in low cost markets. The assumption then is that remanufacturing has to be done by the OEM (‘closed loop recycling’), but in reality, successful remanufacturing is often done by third parties (e.g. ink and toner cartridges). Apparently there is an enormous opportunity for the circular economy in consumer markets, but the current practice shows that creating viable businesses is hard to accomplish.

A significant factor contributing to the lack of penetration of remanufactured products, is the relatively high cost of labour compared to mass-produced new products. Given the positive environmental effect of mainstream remanufacturing, a reduction of taxes on labour and increased taxation on “virgin” materials could be extremely effective by supporting the transition to more remanufactured products.

Another driver might come from take-back programmes of OEMs, made obligatory by governmental legislation.

The premise that remanufacturing is always good for the environment, since it reduces the overall use of materials, does not hold true in all cases [12]. When the energy consumption of a product in the use phase is high (e.g. cars, refrigerators), remanufacturing should not only address functional recovery and physical appearance. It should also deal with the fact that modern technology is more eco-efficient than technology of the past.

Although remanufacturing is one of the key opportunities to lower the eco-burden for a sustainable future, the use of sustainability as a sales argument seems to be rather limited. The marketing of remanufactured products should focus on the personal benefit for the buyer, rather than the environmental benefit.

There seem to be five aspects which are key to the development of viable business models:

- the type of buyers differ from the buyers of the ‘new product’
- the quality must be emphazised in all communication
- risk must be taken away from the buyer (either by operational lease or by warranties)
- top level service of repair and maintenance is required to convince the buyer
- a green brand may support the product image

The final conclusion is that remanufacturing can lead to a circular business model which is both environmentally and economically viable. However, careful manoeuvring is required between the costs, all aspects of market value (Customer Perceived Value), and the eco-costs, including the respective communication.

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Publication 5

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Article

Insulation or Smart Temperature Control for Domestic Heating: A Combined Analysis of the Costs, the Eco-Costs, the Customer Perceived Value, and the Rebound Effect of Energy Saving

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Abstract: Calculating the environmental benefits of energy saving systems in dwellings in a life cycle assessment (LCA) has two major issues, namely: how to deal with the customer behaviour and how to deal with rebound effects. Both issues are important for sustainable strategies. From a user-centred design perspective, two fundamentally different strategies are observed, namely: a 'passive' end-user, who invests in insulating the building and maintaining their preferred behaviour routines, versus an 'active' end-user; who must change his or her behaviour in order to save energy. A combined analysis of cost, (market) value, and eco-burden is used to compare and evaluate the two strategies; by applying the methods of eco-costs/value ratio (EVR) and eco-efficient value creation. Simulation software is applied to calculate the results for the active end-user approach (by means of home energy management systems [HEMS]). The energy savings for a passive user approach (applying thermal insulation) are calculated with straightforward heat loss calculations. The rebound effect of energy savings is taken into consideration. From the environmental point of view, the optimal insulation thickness is calculated, by comparing the energy savings with the environmental burden of the insulation materials. This analysis shows that HEMS are effective for poorly insulated houses, but not for well insulated houses. Governmental policies that focus only on insulation, however, lack the urgency of greenhouse gas reduction; the HEMS for existing houses is an indispensable tool for a fast transition to less domestic energy consumption.

Keywords: energy; savings; value; costs; eco-costs; heating; LCA; EVR; eco-efficiency; rebound

1. Introduction

1.1. Insulation or HEMS?

An important step towards a more sustainable society is the reduction of domestic energy use. A major strategy to achieve this reduction is to increase energy efficiency. As is the case with most energy efficiency challenges, residential heating energy savings can be achieved through multiple solutions, such as, in this case, thermal insulation or home energy management systems (HEMS). However, there is often a discrepancy with the potential and actual energy savings achieved through the application of such solutions [1,2], partly because of backslide effects (see Section 1.2.2), and there is a risk of long-term unsustainability through the rebound effects. Besides the physical characteristics of the buildings, the optimal combination of solutions depends to a large extent on user behaviour and the potential rebound effects on the long term. Hence, decision makers in these processes (home-owners, builders, architects, and policy makers) need to balance many different variables from multiple perspectives, as has been it has elaborated upon in the following sections.

To reduce the complexity of the aforementioned issues, the analyses of this paper are focussed on the following: (a) the energy conservation effects of HEMS and the related consumer behaviour in a free standing two story house with three bedrooms, and (b) the effects of enhanced wall insulation of the outer walls.

The corresponding research questions are as follows: (1) Is a HEMS system an efficient and effective solution for energy savings, and if so under which conditions? (2) Is there an optimum insulation thickness of the outer walls, and if so, what is the optimum for each type of insulation material? (3) What are the implications of combining a high level of thermal insulation with a HEMS system?

To get an answer to the research questions, an integral approach is needed of the system costs, eco-costs, and customer perceived value. The existing model of the eco-costs/value ratio (EVR) and the model of the eco-efficient value creation provides such an integral approach, and is therefore used to tackle the research questions. These two models are explained in Section 2.2.

This paper deals with the research questions on a quite high aggregation level, so neither details on the heating or cooling systems, as such, nor the architectural construction details are dealt with. Only the insulation characteristics of certain insulation materials are part of the study, as they determine the rebound effects.

In Section 1.2 of this paper, a literature review is given, showing the existing knowledge and knowledge gaps. Section 2 provides general information on the two methods that have been used, namely: the simulation model for HEMS (HAMBASE) in Section 2.1, and the EVR and eco-efficient value creation in Section 2.2. The results are given in Section 3, with the simulation of HEMS in HAMBASE and its consequences in the EVR model in Section 3.1, optimisations in insulation thickness for different insulation materials in Section 3.2, and a combination of insulation and HEMS in Section 3.3. Discussions, conclusions, and acknowledgements are given in Sections 4 and 5.

1.2. General Literature

1.2.1. Improving Insulation

A well-known passive end-user strategy for domestic energy savings is the improvement of the insulation quality of the house. As a result, significant energy savings (meaning the reduction of energy costs and associated environmental impacts) can be achieved (without the need for an 'active' behaviour change from the end-users).

In the European Union (EU), the EU Directive 2010/31 [3] requires that the member states shall set energy performance requirements with regards to the building envelope, either new or under refurbishment, "with a view on achieving cost-optimal levels". (e.g., in the Netherlands, such a cost-optimal level for new residential buildings is currently determined as Rc = 5). Over the last two decades, there has been an increase in research attention for residential heating energy savings, especially with regards to the insulation of dwellings. Research efforts [4,5] are often aimed at answering the question of whether or not improved insulation is an economically viable strategy, commonly executed using, amongst others, life-cycle costing, net present value, internal rate of return, payback methods, and cost-benefit analyses. Life cycle assessment (LCA) studies are mainly aimed at investigating the additional environmental impacts of the insulation, compared to the environmental benefits of decreasing energy use [6–11].

1.2.2. HEMS in Relation to User Behaviour

On the other end of the dyad, another, more recent strategy is to 'empower' end-users to conserve energy, through mechanisms such as awareness rom the feedback on energy use, environmental impacts and costs [12], advice [13], and social gaming [14]. These product–service systems are generically defined as home energy management systems (HEMS). These usually include 'smart products', sensor networks, and software applications on a (handheld or wall mounted) interface products, and are almost exclusively Information and Communication Technology (ICT)-based. As a result of implementing such a strategy, the end-users should change their behaviour towards lowering and matching their energy-use in order to optimize the utilization of the grid [15]. HEMS are considered as one of the means to change the behaviour of residents.

The most common thermal HEMS are smart thermostats, which require user input to manage the heating system. Usually, the house is equipped with one thermostat controlling the system and therewith the perceived thermal comfort. As consumer perception of thermal comfort is the subject of multiple variables, people tend to have different comfortable temperatures for different areas within the house, at different times [16,17]. This presents a logical further innovation opportunity for thermal HEMS, with regard to energy saving, as it could be programmed and equipped to 'switch off' certain areas within the house when not in use (e.g., bedrooms during the day), or not requiring a high temperature (e.g., the toilet or storage areas). This zoning control HEMS is researched in this paper by including four different scenarios for HEMS control over the heating system.

Research often indicates that if residents are to accept minor losses in thermal comfort, there would be a large potential in energy savings (e.g., [18]). However, important longitudinal research [19] on the consumer use of HEMS products concludes that behavioural changes achieve quite significant energy savings in the first period of use (around 8%), which, on the medium–long term, are not sustained (see Figure 1). In other words, there appears to be a 'behavioural backslide effect': Even the enthusiastic groups that initially achieved energy savings of over 16%, showed a significant decrease in energy savings over a relatively short period of time of 11 months [20].

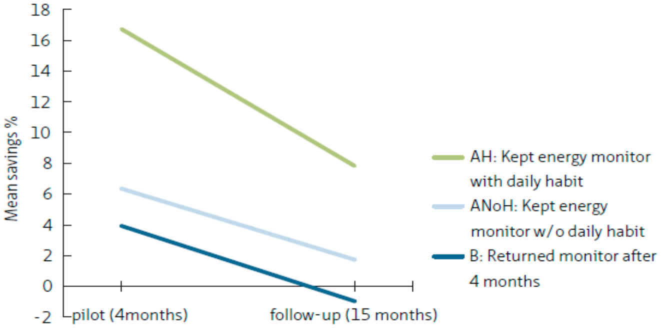

Figure 1. The decrease in achieved energy savings as a result of home energy management systems (HEMS) implementation [20].

Other studies around thermal energy also indicate that initially, quite significant energy savings are likely to be achievable through altering user behaviour, however, over time, only small energy savings are obtainable [17,21,22], due to, for example, a decline in interest.

Within the context of thermal comfort in dwellings, many solutions that are currently available in the market can be defined as product–service systems (PSS). In order to enable the determination of the optimal energy saving solutions, an integrated approach for the design of such PSS and their business models is required, which includes their (long-term) effects on user behaviour and the avoidance of backslide effects, putting the user at the centre of the analysis.

1.2.3. Customer Perceived Value of Thermal Comfort

The general solution developed to cope with the multiple variables influencing perceived thermal comfort is the adaptive heating energy system, which gives users control over the set-point temperature at which they feel comfortable in different states of outdoor temperature, activity, clothing, et cetera.

An interesting study on the relationship between customer perceived value and energy saving measures concerns the consumer willingness to pay (WTP) for passive energy saving measures, such as insulation [23]. Rather than considering the economic and environmental pay-back time (cost-benefit) only, this study shows that consumers also consider other values of insulation, such as high thermal comfort and noise protection. The increased WTP for such measures increases the potential for future market share. Hence, it is concluded that an insulation strategy has the potential for achieving extra customer perceived value.

It is clear that many different variables influence energy saving behaviour [24]. These include costs and environmental impacts, but also customer perceived value. This customer perceived value is defined as all of the factors contributing to the perception of consumers, such as thermal comfort, noise reduction, as well as image and other social values. Most importantly, it is unlikely that consumers are willing to accept a lower customer perceived value. Within the context of domestic energy use, this behaviour is underlined in the studies (such as [25]), where it has been demonstrated that consumers are willing to save energy, wherever it does not compromise convenience. Hence, in order to design systems for domestic thermal energy savings, the customer perceived value has to be taken into account as an important variable. The method of the EVR is well-equipped to do so, as will be set out in Section 2.2.

1.2.4. The Rebound Effect

An important aspect of consumer behaviour within the context of energy use is the rebound effect, first described in relation to the efficiency of coal machinery by Jevons [26]. The rebound effect is described as the expected increase in the consumption of energy, following energy-efficiency improvements. It explains the measured differences between real-life and calculated energy savings. The rebound-effect (also take-back effect) have been widely acknowledged, however, the extent to which they actually take place continues to be the subject of studies and discussions in energy-economics literature [27–30].

In general, three different types of the rebound-effect are distinguished, namely:

a. The direct rebound effect. The direct rebound effect is the spending of saved money from energy efficiency on the increase of energy use in other (or even the same) applications. An example is the tendency that people have to place more lights in their homes and gardens, when the lamps achieve a better efficiency. More on the subject of direct rebound in households can be found in the literature [31–33].
b. The indirect rebound effect. The indirect rebound effect is described as the spending of saved money from energy efficiency on other offerings than energy, with their own respective environmental impacts [34]. As an example, one can think of people spending the saved money on flight tickets.
c. The economy-wide rebound effect. This type of rebound differs from the previous types, by the idea that energy savings on a product level by technical innovation could lead to a sharp increase in the sales of that product, resulting in an increase of energy use by the sum of all of the products. This is the most discussed rebound effect, also referred to as the ‘Jevons Paradox’ [35,36]. Although it is the essence of the case of Jevons (1866), it is hard to prove in reality [30]. However, when, for instance, the driving of cars would become extremely energy efficient (and cheap), it would trigger that more people would buy a car. This could lead to the extra use of energy on a national or global scale.

For insulation improvements, any form of direct rebound (type a) is expected to be low, as consumers are not likely to 'superheat' their homes. Therefore, the main issue in this paper is the indirect rebound (type b). This rebound only starts when there are net savings (i.e., the savings in energy are more than the investment in extra insulation), which will be explained in the next section. The economy-wide rebound (type c) is unlikely to occur, as most residences in the Western world are already equipped with a heating system.

1.2.5. Environmental Impacts over the Full Life-Cycle

Where the insulation of a house reduces the use of heating energy, the insulation, as such, adds to the environmental impacts of the building itself. The added environmental impacts through the increased use of insulation materials (often plastics), requires a significant amount of extra energy savings in order to generate lower environmental impacts over the full life-cycle of the house. The production of HEMS equipment has environmental impacts as well. The obvious advantage of HEMS is that it is relatively easy to install in existing houses, as opposed to insulation.

The environmental data, which have been used in the calculations, are from the Ecoinvent and Idemat LCI databases. The calculations have been made by means of Simapro software. Apart from the CO_2 emissions of the house, all of the data are from so called background processes. More information on the background systems and their boundary limits (from cradle-to-gate, gate-to-gate-and gate-to-grave, and grave-to cradle) can be found at www.ecocostsvalue.com and www.ecoinvent.com (both assessed in August 2018)

1.2.6. The Combined Approach of Costs and Eco-Burden

Figure 2 depicts an analysis of an energy conservation system, where the costs (x-axis) and the eco-burden (y-axis) of a life cycle are combined. The base case is an energy consumption line that ends up in point A, for the case that there is neither extra insulation nor a HEMS system. Then, an investment is made, and the effect on eco-costs and value (price) is shown by lines A–B (this is the 'production phase' in LCA). Note that the slope of the investment line is much lower than the slope of the energy consumption line.

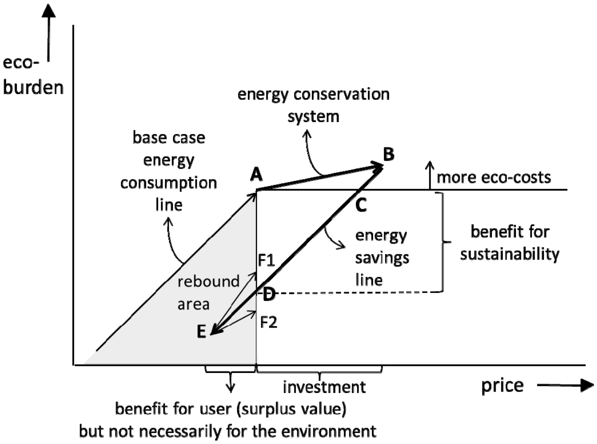

Figure 2. A combined analysis of price and eco-burden of an energy conservation system [37].

The energy savings are depicted by lines B–E (this is the 'use phase' of the LCA), which is in parallel to the 'base case energy consumption line'. This line crosses the 'more eco-costs' lines at point C, which is likely to happen in practice. Point D is the pay-back point of the investment, with a corresponding reduction in the eco-burden from point A to point D. Then, however, the 'energy savings line' enters the 'rebound area'. From point D to E, the owner has a financial benefit (i.e., the owner is saving more money than the investment). That money, however, is likely to be spent on something else [38,39], such as travel, investment in the house, et cetera, which causes a rebound (lines E–F1 for travelling, and lines E–F2 for the renovation or refurbishing a house). The slope of the line for, for example, diesel, is higher than the slope of the energy savings line, causing a severe rebound effect. The slope of the line for renovation and refurbishing is lower than the line of the energy savings, resulting in a small rebound effect. Such a calculation differs for each country, as the (energy) tax level varies from country to country, the climate conditions are different, and the source of the energy may vary as well. The rebound depends also from case to case, but it is safe to assume that the average rebound effect is 100% on eco-costs. That means that lines D–E are a benefit for the user (the user saves money that will be spent on something that the user prefers), but is not a benefit for the environment. In practice, that means that only the first few years (the pay-out period) have a positive impact on the environment; long economic pay-out times eliminate the risk of short-term rebound effects. In practice, consumers will accept long pay-out times as long as they expect extra comfort and convenience.

2. Materials and Methods

To analyse the net efficiency of the two domestic heating energy conservation systems (i.e., HEMS and thermal insulation), two methods are applied, namely:

1. The HAMBASE computer simulation software to analyse the effect of variable room temperatures on energy savings in combination with comfort.
2. The method of the eco-costs/value ratio (EVR) for the combined analysis of costs, customer perceived value, and eco-costs (a monetised single indicator for LCA, based on the marginal prevention costs of eco-burden).

The calculations on the effect on energy savings resulting from extra insulation are based on the reduction of the thermal resistance (the R-value) of the walls, floors, and roofs. For clarity and simplicity, the influences of heat losses via construction elements are kept outside the system boundaries of the calculations.

2.1. HAMBASE

In order to explore the net efficiency of the zoning control strategy, a typical residence, see Figure 3, is simulated in HAMBASE modelling software [40], and is subjected to different heating system control strategies. The main objective is to obtain an idea of the relative magnitudes of energy savings and thermal comfort when applying a zoning control strategy: answering the question to what extent zoning control achieves energy savings combined with comfort.

The HAMBASE modelling software has been selected because it allows for the modelling of buildings, zoning strategies, and climate conditions for calculating energy consumption as well as the predicted mean vote (PMV) and predictive percentage dissatisfied (PPD) from the Fanger Model for thermal comfort. This allows for a comparison between energy consumption in MJ and the modelled average customer perceived value in terms of the average score for thermal comfort (PMV) as well as the percentage of residents experiencing thermal discomfort (PPD).

The following four different scenarios have been simulated:

(1) Single thermostat, continuous temperature setting of 21 °C (representing the worst-case scenario).
(2) Single thermostat, day temperature setting of 21 °C, night set-back temperature of 15.5 °C.
(3) One thermostat per floor (2), day temperature setting of 21 °C, zoning (only heating when floor is occupied), day and night set-back temperature of 15.5 °C.

(4) One thermostat per room, day temperature setting of 21 °C, zoning (only heating when room is occupied), day and night set-back temperature of 15.5 °C (representing the hypothetically optimal scenario).

The zoning strategy is based on the following division of different types of rooms in a typical residential building: Zone 1—living room and Kitchen; Zone 2—office/study; Zone 3—bedrooms; Zone 4—bathroom; Zone 5—entrance and hallways; and Zone 6—storage and toilets.

In each scenario, the energy demand for the radiators and the floor-heating systems are calculated. Further details regarding the HAMBASE simulation can be found in Appendix A (the simulation of scenarios for building energy use). Also, in the Appendix A, the modelling scenario for the simulation of a typical Dutch apartment can be found.

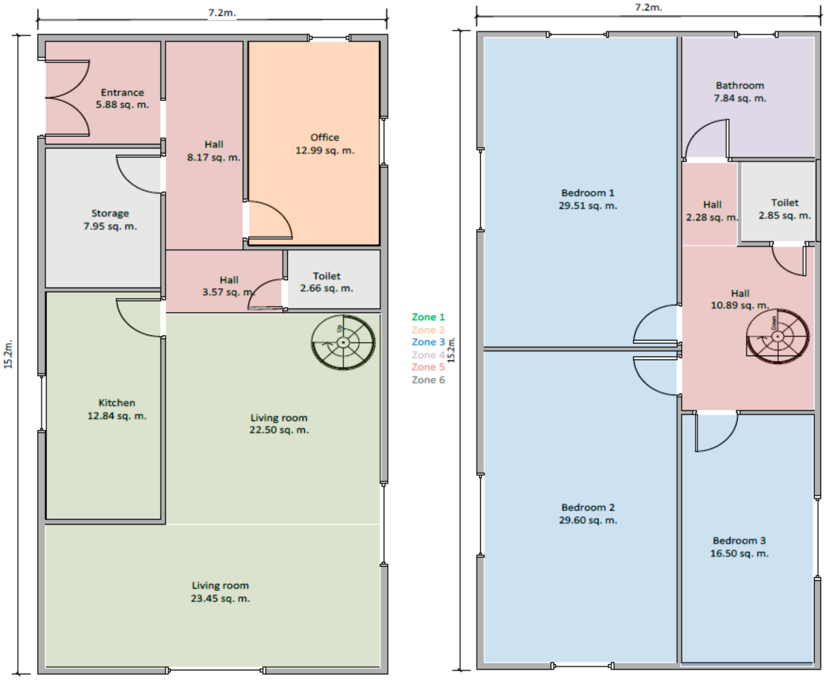

Figure 3. Blueprint of the free standing two story house, modelled in the simulation model for home energy management systems (HEMS) (HAMBASE).

2.2. *The EVR and Eco-Efficient Value Creation*

The method of the eco-costs/value ratio (EVR) is a combined analysis of the costs, the (market) value, and the eco-costs of a product or product service system. It is LCA based, and is developed for eco-efficient value creation in (product-, service-, and product–service-system) design and innovation. It resolves a basic shortcoming of the LCA benchmarking of two (or more) product or services; LCA benchmarking requires that the products or services in the comparative study have the same functionality and quality (tangible as well as intangible). In innovation, this is never the case, as innovations add either functionality or quality to the benchmark, otherwise the innovation does not make sense. Keeping costs, market value, and eco-costs strictly separate in the analysis has the advantage that the aspects of the production costs and market value are not ignored in the decision-making process for achieving better environmental sustainability. The system can also be applied to analyse and develop business solutions in the circular economy (e.g., cradle-to-cradle systems) [37,41].

Eco-costs are a so-called 'single indicator' in LCA. It is a measure to express the amount of environmental burden of a product on the basis of the prevention of that burden; the costs which should be made to reduce the environmental pollution and materials depletion in our world to a level that is in line with the carrying capacity of our earth (the 'no effect level'). The eco-costs should be regarded as hidden obligations, also called 'external costs' in environmental economics.

The eco-costs have been introduced in the Journal of Cleaner Production [42] and in the International Journal of LCA [43], and have been updated in 2007, 2012, and 2017 (see, for a short description, http://en.wikipedia.org/wiki/Eco-costs, accessed August 2018).

The market value equals the price in this EVR analysis for existing products. When a product or service is not yet available on the market, the value equals the willingness to pay (WTP). The costs are defined in the model as the production costs (or life cycle costs), and must not be confused with the price (which is the costs for the consumer). In this paper, the price is used to conduct the analysis, as the focus is on the costs of the consumer. With regard to the value, we have to zoom in to the level of the consumer, revealing a more complex issue, the perception of the individual buyer, see Figure 4. For definitions, see Table 1.

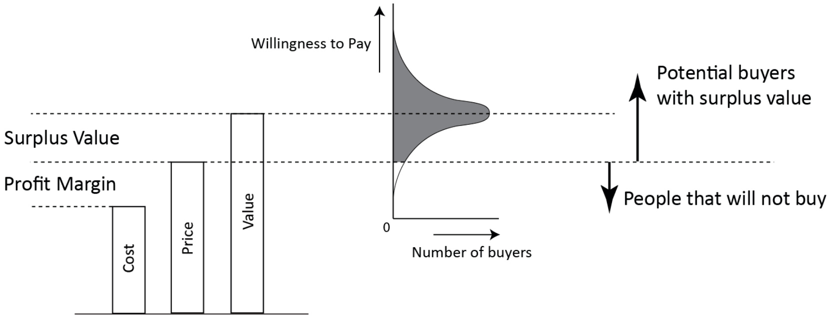

Figure 4. The relation between the costs of production, the price at point of sale, and the customer perceived value of a successful offering. Only buyers that perceive surplus value will consider buying the offering [37].

Table 1. A summary of important concepts used in this paper.

EVR	The eco-costs/value ratio
Eco-costs	A prevention based single indicator for environmental impacts (€)
Value	The sum of the perceived product- and service-quality, and the image (€)
Price	The price at which these offerings are sold in the current market (€)
WTP	Willingness to pay (€)
Customer Perceived Value	The expected use and fun of a product and/or service after the purchase (€)
Surplus Value	The difference between the price and the customer perceived value (€)
Eco-efficient Value Creation	The overall aim of application of the EVR Model (the double objective)
Double Objective	Lowering of the eco-burden of a product and/or service and at the same time enhancing the value

In Figure 4, the difference between the costs and the price is the profit margin for the seller, and the difference between the price and the (customer perceived) value constitutes the 'surplus value'. The higher the surplus value, the more desirable the offering is.

The eco-costs/value ratio (EVR) is basically an indicator of the sustainable buying behaviour of consumers. It is also related to the rebound effect, as depicted in Figure 2.

As most people are inclined to almost spend in their life all of what they earn, the ratio of eco-burden per euro spent is an important indicator for sustainability. It matters what people buy, for example, do they spend their money on diesel or on their health. The EVR of products in the EU are provided in the literature [44] (in the eco-costs tables; accessed in 2017). The current average EVR is 0.4 in the EU, so we should aim at a considerable reduction of the EVR, say less than 0.04.

An important issue is that manufacturers cannot improve the EVR of their products just by increasing the price. Figure 4 shows that when the price is more than the value, there is no surplus value, and the product will not be bought.

On a product level, this leads to a 'double objective' of the 'eco-efficient value creation' in innovation, namely:

- create lower eco-costs, and at the same time
- create higher value

The higher value enables a higher price, which creates the opportunity to pay the extra costs that are required to lower the eco-costs.

Recent papers [45–47] show how such a double objective can be achieved in product design. The consequences for business models in the circular economy are provided in the literature [37,41,48]. Case studies with the consequences for governmental policies are given in the literature [48,49].

3. Results

3.1. The HEMS Strategy in HAMBASE

Table 2 shows the findings of the application of the HAMBASE model for the two-story house as well as the four scenarios, as described in Section 2.1. Insulation is assumed with an R value of two for the outside walls and an R value of five for the roof.

Table 2. Modelled annual heating energy and savings for four different scenarios [50] for a free standing two story house with R = 2 (m^2 K/W) for the outside walls.

	Baseline Case	**Single Zone Thermostat Control, Day Distinction and Night Setback**		**Two Floor Zones Thermostat Control, Day Distinction and Night Setback**		**Six Room Zones Thermostat Control, Day Distinction and Night Setback**	
	Energy Use (GJ)	**Energy Use (GJ)**	**Change Respective to Baseline**	**Energy Use (GJ)**	**Change Respective to Baseline**	**Energy Use (GJ)**	**Change Respective to Baseline**
Radiators	36.15	30.90	−14.5%	28.80	−20.3%	27.61	−23.6%
Floor heating	37.31	31.81	−14.7%	28.77	−22.9%	22.34	−40%

Note: the R value, the heat resistance, (m^2 K/W) is the reciprocal of the U value, the thermal transmittance coefficient (W/m^2 K).

It is clear that, as expected, the energy use is lower for the scenarios where certain zones are not heated during certain periods of time. The best savings are achieved in the third scenario (six room zones), with up to 40% savings of heating energy.

However, in order to fulfil the double objective of the eco-efficient value creation, this should not go hand-in-hand with a lower perceived value, in this case, mainly thermal comfort. As shown in Table 3, the HAMBASE modelling indicates that the double objective is not achieved; the predicted percentage dissatisfied of the users is significantly higher for the individual zones scenario compared to the baseline scenario. The lack of comfort is probably the main reason for the reported evading success of HEMS [21,22,51]. Modern people seem to want maximum comfort when they can afford it.

The data are summarized in the EVR chart of Figure 5. It shows the degree of eco-efficient value creation for the zoning control strategy.

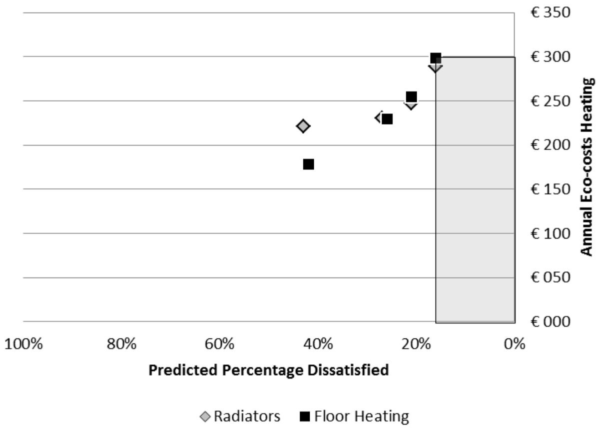

Figure 5. The eco-costs/value ratio (EVR) chart expressed in eco-costs for energy use and the predicted percentage dissatisfied (the grey area represents the target area for eco-efficient value creation).

Table 3. The predicted percentage dissatisfied (PPD) for the four scenarios (two-story free-standing house with radiators) [50].

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Average
Baseline scenario	20%	20%	20%	18%	10%	9%	16%
Single-zone scenario	26%	26%	28%	22%	15%	11%	21%
Two floor-zones scenario	27%	27%	44%	37%	16%	13%	27%
Six zones scenario	29%	34%	45%	45%	55%	52%	43%

The main finding is that quite significant energy savings can be achieved (up to 40%), however, a lower perceived thermal comfort (increased PPD) is unavoidable. This means that the zoning control strategy has little chance of contributing to a transition towards a more sustainable society, because only a very small percentage of consumers are expected to accept lower thermal comfort in their house for the sake of the environment; zoning control is not able to achieve the double-objective of eco-efficient value creation.

Even if the more intelligent thermostats are considered, which are designed to diminish the hassle of programming and adjusting the settings by 'sensing/learning' the user's behaviour, the physical heating system will require a 'heat-up time', resulting in thermal discomfort if the occupants deviate from their usual behaviour. This will eventually lead to users overriding the automatic programming, and decreasing the energy savings.

After a while, only a mild form of temperature setback is applied by users at night and when they are away (e.g., two to max three degrees C lower temperature at periods when people are always at sleep and normally at work). Although many smart thermostats are accompanied by high claims for energy savings, a seemingly more reliable figure is measured by a producer of a popular smart thermostat, who stated that the average savings of 175,000 devices are approximately 5% (https://www.duurzaambedrijfsleven.nl/energie/10903/175000-toon-thermostaten-besparen-5-procent-energie). The potential of 14.5% savings, in Table 1, will not last, because of the fact that the corresponding extra 5% loss of comfort (21–16% of Table 3) is not accepted; the user reverts to a higher setback temperature and a smaller setback time. Independent studies on the heating energy savings of smart thermostats report achieved savings in the range of 3–5% [52,53]. This paper assumes slightly higher achievable energy savings of 6.5%, accounting for future innovations as well as user behaviour.

Thermal HEMS systems can be bought in a price range of approximately €600–800 for systems that can control the six zones, and approximately €160–240 for single zone systems, without installation (both types can be programmed to handle time dependent settings, e.g., night setback). We did not include the fact that many HEMS nowadays also require a monthly subscription fee.

The estimated eco-cost of single zone HEMS is €49 [51] from cradle-to-grave. The eco-costs of a six-zone system is estimated to be €170. The assumption is made that the life span of a central-heating boiler is 15 years, and that the thermostat is replaced then as well (the life span of the automatic valves of the six-zone system is estimated at 30 years). This scenario is depicted in Figure 6.

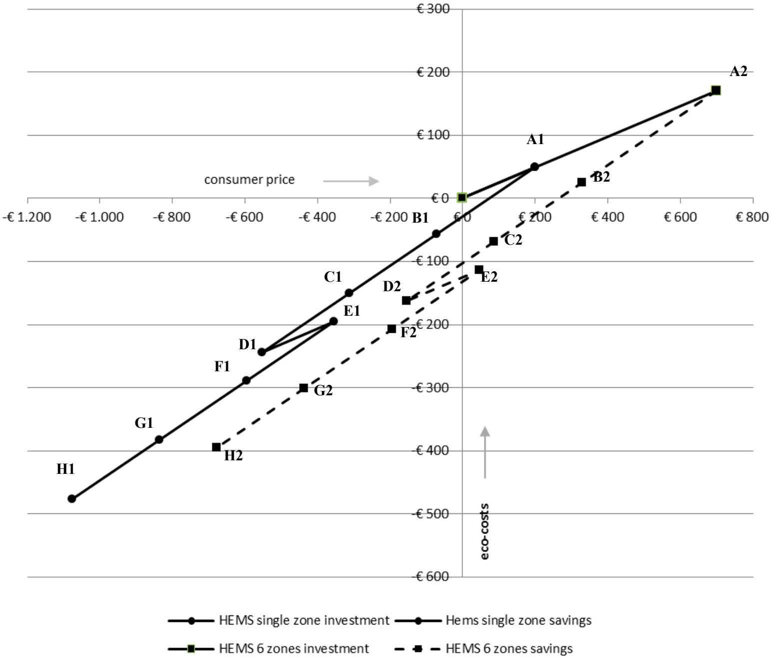

Figure 6. The relation between eco-costs and market price of the HEMS single zone strategy over a period of 30 years, for the two-story house of Figure 3, R = 2 (m^2 K/W) of the outer walls (the lines starting from the origin up to points A1 and A2 represent the eco-costs and consumer prices of single zone and multiple zone HEMS; points A1 and A2 are the start of the use phase; B1 and B2 after 5 years; C1 and C2 after 10 years; D1 and D2 after 15 years; E1 and E2 after replacement of thermostat; F1 and F2 after 20 years; G1 and G2 after 25 years; H1 and H2 after 30 years).

It can be concluded from Figure 6 that the HEMS single zone system scores better than the HEMS six zone system in terms of net price savings, however, the single zone system depends heavily on the rebound effect, as depicted in Figure 4.

The underlying assumption in Figure 6 is the savings line of Figure 7. After the introduction of a single zone HEMS, a percentage of 14.5% can be expected (Table 2, single zone), which is estimated to deteriorate to 6.5%, as described above. In the first weeks there is a steep learning curve, but from the third month on the decay will start. Figure 7 presumes an exponential curve for the learning stage as well as for the decay. The parameters for the decay stage have been chosen so that the curve approaches the measurements [20] previously discussed in Figure 1, namely:

S = a + b × EXP [−(t − 3)/5], for t > 3, where S is the percentage savings, and t = time in month.

For the single zone Hambase simulation a = 6.5% and b is 8%, which is depicted in the savings line of Figure 7.

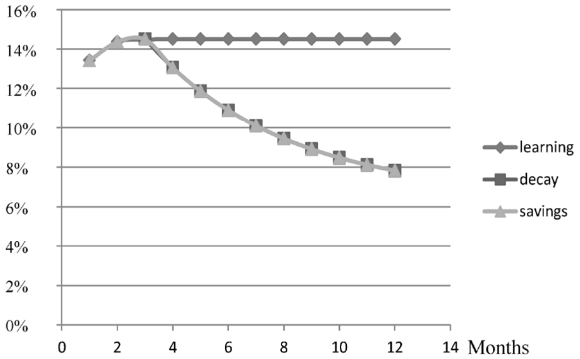

Figure 7. The percentage of energy savings as a function of time, applied to the calculations of the HEMS single zone strategy.

3.2. The Insulation Strategy

Insulation is an energy conservation strategy that does not compromise thermal comfort, therefore, it has the potential of fulfilling the double objective of eco-efficient value creation, as mentioned in Section 2.2. On top of that, insulation has the potential for surplus value, as discussed in Section 1.2.3.

To find the maximum potential cost savings, as well as savings in the eco-costs, calculations have been made on the reduced heat flux per year through a 1 m^2 wall, as a function of the heat resistance of the insulation slab ($m^2 \cdot K/W$), the so-called R value. The calculations are based on 3000 heating degree days per annum (which applies to domestic heating in, e.g., the Netherlands, Belgium, the United Kingdom, Denmark, Germany, and the cities of New York and Vancouver).

The base case is R = 2, which refers to a reasonably well insulated house (insulation slab thickness of 7 cm for stone wool, approximately 8 cm for expanded polystyrene [EPS], and 4.4 cm for polyisocyanurate [PIR]). The consequences of thicker insulation slabs have been determined up to R = 8 (approximately 28 cm for stone wool, approximately 31 cm for EPS, and 18 cm for PIR).

Consumer prices in 2015 were taken from www.rockwool.nl for stone wool, from www.isobouw.nl for EPS, and from www.dakconcept.com for PIR (all accessed August 2015).

Figure 8 depicts the eco-costs versus the consumer price of stone wool for four cases of increased heat resistance. This graph has the same structure as Figure 2. The investment is depicted by the line, which starts in the origin, and goes up to eco-costs of approximately €2.73/m^2, corresponding with a price of €23.72/m^2 for R = 8 (when the added R value is added, the price and the eco-costs increase). The savings are the lines that go down. The savings in price and eco-costs are related to the reduction of natural gas for heating for a total period of 30 years (six steps over five years).

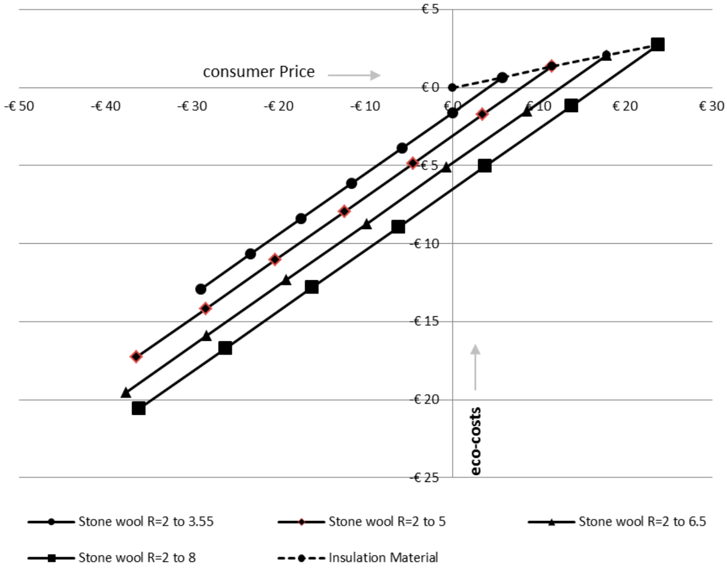

Figure 8. The eco-costs and the consumer price for the additional insulation of stone wool (increase of R from 2 to 3.55, 5, 6.5, and 8, respectively) for a wall of 1 m^2 over a period of 30 years.

A remarkable conclusion is that, over a period of 30 years, the differences in net price savings of R = 2 to R = 5, R = 2 to R = 6.5, and R = 2 to R = 8 are rather low, however, higher R values relate to lower eco-costs.

Note that two segments of the savings line have to be distinguished, the lines at the right of the y-axis (consumer price $\geq$0), and the lines at the left of the y-axis (consumer price $\leq$0). The savings at the left of the y-axis will have a rebound (as explained in Section 2.2). At the point of the pay-back time (consumer price = 0 at 5–12 years), there are already remarkable reductions in eco-costs (at the right of the y-axis), especially for high insulation values.

These LCA calculations (for the insulation slabs cradle-to-gate) have been done for other single indicators as well, namely, the carbon footprint (kg CO_2 equivalent) and ReCiPe H/A Europe (mPt). Although the indicators are different, the graphs for the stone wool show the same pattern. Table 4 shows the main results on the extra eco-burden of the production, and the reduction of eco-burden in the use phase. Table 4 also shows the results for expanded polystyrene (EPS) and polyisocyanurate (PIR), which are quite similar to the results for stone wool. Table 4 shows that stone wool is the best solution in terms of eco-costs (environmental savings), and that PIR scores better in terms of price (cost savings). This result is also depicted in Figure 9.

The results for the PIR insulation are quite remarkable; as the eco-costs/price slope of PIR is similar to the eco-costs/price slope of natural gas, there is, at the pay-out time point, no savings in eco-costs, see Figure 9. That means that PIR insulation does not have an inherent environmental benefit (see point C and D in Figure 2, Section 1.2). Therefore, the environmental benefits of PIR solely depend on the customer behaviour with regard to the rebound effect (i.e., when the savings are spent on products with a low EVR, like diesel for driving, the overall environmental benefit of this type of insulation is negative).

Table 4. The costs, eco-costs, carbon footprint, and ReCiPe data for insulation improvements for stone wool, EPS, and PIR (R = 2 to R = 5).

Insulation from R = 2 to R = 5 for 1 m^2 Outer Wall	Price and Eco-Burden of Investment (a)	Pay-Back Time (Year) (b)	Net Savings over 30 Years (c)	Gain Eco-Burden Divided by Price Investment (d)
Stone wool		7		
price (per m^2)	€11.50		−€36.41	
eco-costs (per m^2)	€1.36		−€17.28	−1.50 (euro/euro)
carbon footprint (per m^2)	4.83 kg CO_2e		−129.48 kg CO_2e	−11.26 (kg CO_2/euro)
ReCipe points (H/A Europe)	0.47 mPt		−5.92 mPt	−0.51 (mPt/euro)
EPS (expanded polystyrene)		9		
price (per m^2)	€14.21		−€33.47	
eco-costs (per m^2)	€2.40		−€16.16	−1.08 (euro/euro)
carbon footprint (per m^2)	5.75 kg CO_2e		−126.22 kg CO_2e	−8.46 (kg CO_2/euro)
ReCipe points (H/A Europe) per m^2	0.63 mPt		−5.60 mPt	−0.38 (mPt/euro)
PIR (Polyisocyanurate)		6		
price (per m^2)	€9.89		−€39.25	
eco-costs (per m^2)	€3.61		−€15.51	−1.57 (euro/euro)
carbon footprint (per m^2)	8.77 kg CO_2e		−127.25 kg CO_2e	−12.87 (kg CO_2/euro)
ReCipe points (H/A Europe) per m^2	0.89 mPt		−5.53 mPt	−0.56 (mPt/euro)

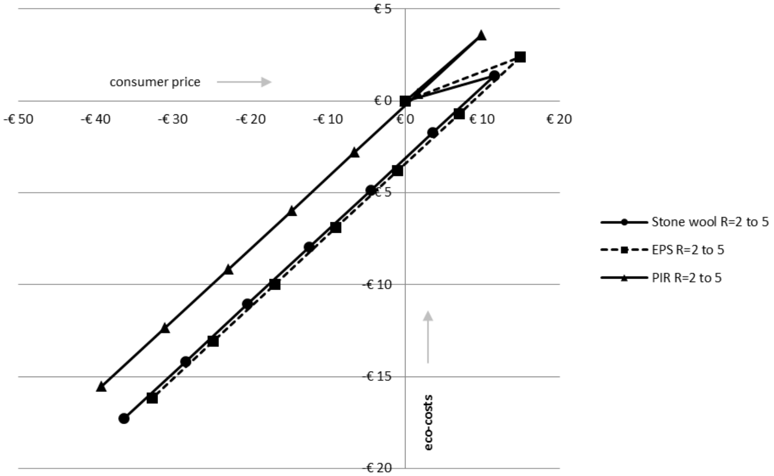

Figure 9. The eco-costs/price ratio for R = 2 to 5 insulation upgrade for stone wool, expanded polystyrene (EPS), and polyisocyanurate (PIR) for 1 m^2 of outer wall, over a period of 30 years.

3.3. Combination of Insulation and HEMS

In the Netherlands, new buildings require a minimum of R = 5 insulation, as of 1 January 2015. Potential energy-aware buyers might want to choose between further upgrading their insulation or accept the minimum required insulation combined with the use of a thermal HEMS. The modelled building in HAMBASE (which was modelled as a typical modern Dutch mid-terrace house, see Section 2.1) and its energy use are calculated for the two conservation strategies for a 113 m^2 surface area of the exterior walls. The scenario for insulation is based on a 30 year lifespan, where the thermal HEMS is assumed to have a lifespan of 15 years (the life span of a central-heating boiler). The remote operated valves in the six zone systems are assumed to have a life span of 30 years. The results are depicted in Figure 10.

Figure 10 shows rather long pay-out times for the additional investments, almost 20 years for the HEMS single zone system, and approximately 22 years for the additional insulation. The positive aspect of these long pay-back times is that there is hardly a rebound effect. The HEMS six zone system, however, does not even reach the pay-back point within 30 years, and there are hardly eco-costs savings (the eco-pay-back time is 27 years).

The issue in Figure 10 is whether or not to invest either in HEMS, or in extra insulation (in addition to the insulation of R = 5). Figure 11 depicts the situation when, in addition to the insulation of R = 5, an extra investment is done in an extra insulation plus a HEMS system.

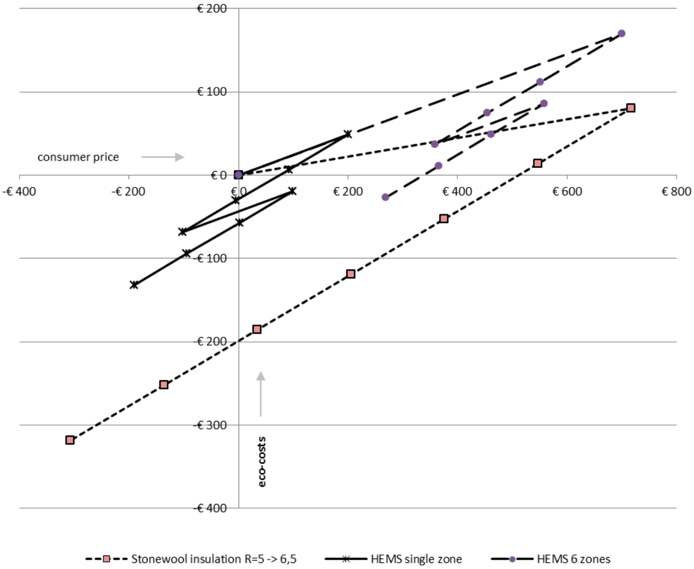

Figure 10. Case-study for the Dutch context, comparing stone wool insulation improvements from R = 5 to R = 6.5 for 113 m^2 of outer wall, against implementing HEMS over a period of 30 years (additional to insulation of R = 5).

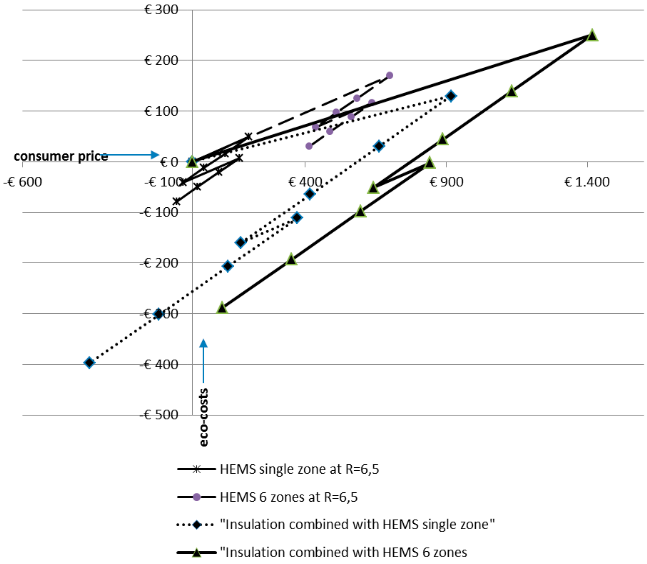

Figure 11. The integrated results for combining extra insulation (from R = 5 to R = 6.5) with either HEMS single or HEMS six-zone systems.

4. Discussion

In this multivariate analysis, the cooling of houses has not been analysed, as the forced cooling of houses is not common in the Netherlands. However, the same principle applies to HEMS and insulation, as, in summer, less cooling energy is needed because of improved insulation, whereas with HEMS, the automated setback savings are estimated to be marginal (4%) if the residents do not accept a higher comfort temperature [54].

Man-hour installation costs have not been taken into account, as it is assumed that the extra insulation does not require significant extra installation hours for new buildings. For HEMS, these extra installation hours are out-of-scope as well. Additional insulation in existing dwellings, however, usually requires many man-hours. Often, these installation hours are done by the owner (DIY), and, in that case, these hours are not to be counted. When these installation hours are done by a contractor, the installation costs are likely to be substantial. A rule of thumb is that, in that case, €20 per m^2 must be added to the investments, which are used in this study. The inclusion of such costs could significantly influence the economic pay-back time, and is likely to cancel out the rebound effect for insulation.

The price increases of natural gas have not been taken into account in the current analysis. Overall, the expectation is that the prices for fossil energy will continue to rise. Especially for insulation strategies, the economic pay-back time could be significantly reduced when prices of energy increase more than inflation.

Another issue is that the surplus value of insulation has not been taken into account in this analysis. In this case, the surplus value can be found in the increased value of the house on re-sale, mainly due to the lowered expected energy bills but also less quantifiable values such as, increased comfort and better noise insulation.

In current policies of many European countries, better insulation of dwellings, and HEMS are regarded as good strategies to reduce greenhouse emissions. This study, however, reveals that, in practice, such strategies may have less effect than the expected environmental impact reductions related to the total potential energy savings, because of the following three main issues:

(a) The environmental impacts related to the production of insulation materials and HEMS
(b) The reversion of changed user behaviour
(c) The rebound effect after the pay-back period

An interesting aspect is that the systems with a long pay-back period have less rebound, resulting in less environmental pollution.

Note that the relative importance of point (a) is higher for single indicators, which takes resource depletion into account (i.e., eco-costs and ReCiPe points), than for, for example, the carbon footprint indicator.

Our case study is about new dwellings where the outside measures are already fixed; it is about the decisions of individual future owners in a later stage of the architectural design, where only the internals can be individualised. Such a case is not much different from existing dwellings. Consequently, the living area (the functional unit in LCA) is a bit smaller. This will result in higher costs (as well as the eco-costs) per m^2. In the example of Section 3.2, this increase is 0.8% of the floor area for R = 5 to R = 6.5 for stone wool and EPS. The price per m^2 living area was approximately €2300 for the house of Figure 5 (200 m^2) in 2015. So, the loss of m^2 results in an economic loss of a value of 2300 × 200 × 0.8% = €3679, which is much more than the €718 of the marginal costs required to insulate the house from R = 5 to R = 6.5.

When the inner living area is kept constant, the outside size of the building must be enlarged to accommodate the thicker insulation material. This has the consequence that the building costs of the house will increase (approximately with a similar amount, as calculated above, as the house will be 0.8% larger). The footprint of the house will be more in that case. In the urban areas of big cities, where the price of land is high, the extra costs of land will be even higher than the costs of the insulation material. The price of land in the Netherlands varies from 200–2000 €/m^2, resulting in increased costs of the house of Figure 5: €175–€1750 (109.5 m^2, 0.8%).

Please note that the reader is free and encouraged to adapt the assumptions in this approach to their own specific scenario and context. This could include variations to the model applied to simulate energy savings and thermal comfort. Although we feel that the main conclusions regarding energy use and thermal comfort will stand, the magnitude of both metrics might differ slightly. Additionally, other models and simulation software packages might include more or other variables for modelling energy use and thermal comfort that are suitable to other specific situations.

5. Conclusions

The combined analyses of costs, eco-costs, and value (i.e., the EVR approach) explains the potential magnitude of the rebound effect, as it clearly demonstrates the point of economic and environmental payback and the likelihood for potential rebound effects. The rebound effect plays an important role, because of two issues, namely:

The net environmental benefit of the energy savings is often overestimated because of the rebound effect.

A long financial pay-back time seems to be beneficial for the environmental benefit, as it reduces the rebound effect.

Hence, it is concluded that the eco-efficient value creation approach and the eco-costs/value ratio are valuable design and evaluation tools for balancing ecological and economic considerations.

With regard to the three research questions of Section 1.1, three conclusions are provided in the following paragraphs: Research Question 1: "Is a HEMS system an efficient and effective solution for energy savings, and if so under which conditions?". Because of the high absolute price for the insulation of a house compared to HEMS, it is more likely that consumers will invest in HEMS rather than in insulation in their existing houses. This is especially true if the installation costs of insulation are to be included as well. This paper shows that HEMS are a reasonable solution for existing houses with poor insulation (R = 2 or less), see Figure 6. The strength of HEMS is that the high heat loss due to poor insulation makes it worthwhile to shut off the heating system or reduce the mean temperature settings by 1 or more degrees.

Research Question 2: "Is there an optimum insulation thickness of the outer walls, and if so, what is the optimum for which type of insulation material?".

The optimal insulation for stone wool, EPS, and PIR seems to be U = 6.5 (±1.5), see Figures 8 and 9. From an environmental impact perspective, stone wool insulation material has lower impacts than EPS and PIR. The difference in environmental impacts over the full life-cycle between stone wool, EPS, and PIR, however, can be considered to be marginal. The differences in the economic terms over the total life cycle (LCC) are also small, see Table 4. Research Question 3: "What are the implications of combining a high level of thermal insulation with a HEMS system?".

For well insulated houses, HEMS is less effective, see Figures 10 and 11. However, governmental strategies that only focus on the insulation of newly built houses (R = 5 or more), will result in a transition that is far too slow. This is because of the long life-span of houses (longer than 50 years); it will take a long time before a significant share of houses are well-insulated.

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Appendix A. Simulation of Scenarios for Building Energy Use

The HAMBASE tool used to model and simulate the building energy use was selected based on the following four selection criteria:

- good user-interface
- accessible coding
- multitude of available reference data (outdoor climate, building construction characteristics, heating systems, etc.)
- the capability to simulate: multiple zones within the building, radiator as well as floor heating systems, multiple time-periods, and temperature set-points.

HAMBASE is capable of simulating the indoor temperature, indoor humidity, and the energy usage for heating and cooling in a multiple-zone in Matlab/Simulink [55]. HAMBASE has been used in research projects and its results were within limits of the ASHRAE-test [56]. Within the context of the Nieuwveense Landen project, no data about the exact construction details were available at the time of simulation, therefore two buildings were modelled according to the following input parameters for the HAMBASE simulation.

Appendix A.1. Input Parameters

The following generic dimensions were used to model a free-standing house and apartment, as shown in Tables A1 and A2.

Table A1. Size of the modelled houses for the simulation.

Building Type	Dimensions (m)	Area (m^2)	Volume (m^3)	Window Area (m^2)
Two floor Detached House	7.2 × 15.2 × 5	200	500	47.7
One-Story Detached House	15.5 × 10.0 × 2.6	139	361.4	27.7

Table A2. Sizes of the zones modelled for the simulation.

Building 1: Two-Floor Detached House		
Zone	**Rooms**	**Volume (m^3)**
Zone 1	Living room, kitchen	145.0
Zone 2	Office	32.5
Zone 3	Bedrooms (3)	190.0
Zone 4	Bathroom	20.0
Zone 5	Entrance, halls	77.5
Zone 6	Toilets (2), storage/technical area	35.0
Building 2: One-Story Detached House		
Zone	**Rooms**	**Volume (m^3)**
Zone 1	Living room, kitchen	140.4
Zone 2	Office	26.0
Zone 3	Bedrooms (2)	83.2
Zone 4	Bathroom	20.8
Zone 5	Entrance, halls	65.0
Zone 6	Toilet, storage/technical area	26.0

Appendix A.1.1. Modelling the Exterior Walls and Roof

The exterior walls of the building prototypes are modelled as four material layers with different thicknesses, a 214 mm layer of limestone, followed by an insulation layer (glass wool) of 120 mm, a well-ventilated cavity of 50 mm, and 100 mm of brick. It was also assumed that there are no thermal bridges observed at the ceiling of the building. For the two prototype buildings, the construction characteristics of the exterior walls are the same.

A flat roof design is modelled for both buildings as soft board, with expanded polystyrene as an insulation layer and a thin polyvinyl chloride (PVC) roofing membrane.

Appendix A.1.2. Modelling the Windows for the HAMBASE Simulation

It is assumed that the windows have HR++ glazing with an interior sunblind. The surface area of glazing in the modern houses is estimated at 20% of the total surface area of the building, that is, 40 m^2 for the two-story houses and 27.7 m^2 for the apartment buildings. It was assumed that there were no external obstacles that create shadows over the windows' effective area.

Appendix A.1.3. Constant Temperature Boundaries

The floor construction is modelled as a 250 mm concrete slab with a 80 mm layer of insulation (expanded polystyrene [EPS]) in the middle, as follows:

Adiabatic external walls,
The building is modelled without adiabatic walls, and
Internal walls.

It was assumed that the inner walls are made of a plaster layer (13 mm), an insulation layer (74 mm of glass wool), and a second plaster layer (13 mm). Additionally, the walls separating the toilets and the bathroom with another room are made of tiles (10 mm) and limestone (70 mm).

Appendix A.1.4. Climate, Time, and Internal Gains

The simulations were executed from 1 January 2006 until 31 December 2006 using the outdoor climate conditions of De Bilt, The Netherlands. The simulation time was 365 days in order to evaluate the annual performance of the system. Three different seasons were modelled with different inputs for clothing, activity levels, and window operation.

For each zone in the modelled houses, a different profile is assigned based on the inputs described in Table A3.

Appendix A.1.5. Time Periods

Table A3. Time setting virtual thermostat used for the simulation.

Two-Floor House (Working Days)										
			Floor Zones		**Individual Zones**					
Time Schedule	**Base**	**Single Zone**	**Zone 1**	**Zone 2**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**	**Zone 6**
00:00–06:00	21.0	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	-
06:00–09:00	21.0	21.0	21.0	21.0	21.0	15.5	21.0	21.0	18.0	-
09:00–17:00	21.0	21.0	21.0	15.5	21.0	15.5	15.5	15.5	18.0	-
17:00–18:00	21.0	21.0	21.0	15.5	21.0	21.0	21.0	21.0	18.0	-
18:00–22:00	21.0	21.0	21.0	15.5	21.0	21.0	15.5	15.5	18.0	-
22:00–23:59	21.0	15.5	15.5	21.0	15.5	15.5	21.0	15.5	15.5	-

Table A3. *Cont.*

Two-Floor House (Weekend)										
			Floor Zones		Individual Zones					
Time Schedule	**Base**	**Single Zone**	**Zone 1**	**Zone 2**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**	**Zone 6**
00:00–08:00	21.0	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	-
08:00–10:00	21.0	21.0	21.0	21.0	21.0	15.5	21.0	21.0	18.0	-
10:00–17:00	21.0	21.0	21.0	15.5	21.0	21.0	15.5	15.5	18.0	-
17:00–18:00	21.0	21.0	21.0	15.5	21.0	21.0	15.5	15.5	18.0	-
18:00–23:00	21.0	21.0	21.0	15.5	21.0	21.0	15.5	21.0	18.0	-
23:00–23:59	21.0	15.5	15.5	21.0	15.5	15.5	21.0	15.5	15.5	-

One-Story House (Working Days)								
			Individual Zones					
Time Schedule	**Base**	**Single Zone**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**	**Zone 6**
00:00–06:00	21.0	15.5	15.5	15.5	15.5	15.5	15.5	-
06:00–09:00	21.0	21.0	21.0	15.5	21.0	21.0	18.0	-
09:00–17:00	21.0	21.0	21.0	15.5	15.5	15.5	18.0	-
17:00–18:00	21.0	21.0	21.0	21.0	21.0	21.0	18.0	-
18:00–22:00	21.0	21.0	21.0	21.0	15.5	15.5	18.0	-
22:00–23:59	21.0	15.5	15.5	15.5	21.0	15.5	15.5	-

One-Story House (Weekend)								
			Individual Zones					
Time Schedule	**Base**	**Single Zone**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**	**Zone 6**
00:00–08:00	21.0	15.5	15.5	15.5	15.5	15.5	15.5	-
08:00–10:00	21.0	21.0	21.0	15.5	21.0	21.0	18.0	-
10:00–17:00	21.0	21.0	21.0	21.0	15.5	15.5	18.0	-
17:00–18:00	21.0	21.0	21.0	21.0	15.5	15.5	18.0	-
18:00–23:00	21.0	21.0	21.0	21.0	15.5	21.0	18.0	-
23:00–23:59	21.0	15.5	15.5	15.5	21.0	15.5	15.5	-

Appendix A.1.6. Heating and Cooling Systems

The convection factor of the heating system is 0.8 when the radiators are installed and 0.6 when a floor heating system is installed.

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Publication 6

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Article

Eco-Efficient Value Creation of Residential Street Lighting Systems by Simultaneously Analysing the Value, the Costs and the Eco-Costs during the Design and Engineering Phase

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Abstract: In search of sustainable business models, product innovation must fulfil a double objective: the new product must have a higher (market) value, and at the same time a lower eco-burden. To achieve this objective, it is an imperative that the value, the total costs of ownership, and the eco-burden of a product are analysed at the beginning of the design process (idea generation and concept development). The design approach that supports such a design objective, is called Eco-efficient Value Creation (EVC). This approach is characterised by a two-dimensional representation: the eco-burden at the y-axis and the costs or the value at the x-axis. The value is either the Willingness to Pay or the market price. The eco-burden is expressed in eco-costs, a monetised single indicator in LCA (Life Cycle Assessment): an app for IOS and Android, and excel look-up tables at the internet, enable quick assessment of eco-costs. A practical example is given: the design of a new concept of domestic street lighting system for the city of Rotterdam. This new concept results in a considerable reduction of carbon footprint and eco-costs, and shows the benefits for the municipality and for the residents, resulting in a viable business case.

Keywords: street lighting system; TCO; EVR; EVC; eco-efficient value creation; eco-costs

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1. Introduction

1.1. The Issue: Progress in Sustainable Product Innovation, and Circular Business Models

There is a general concern about the increasing concentration of greenhouse gases in our atmosphere, materials scarcity, degradation of biodiversity, the plastic soup in the oceans, and many other pollutants like fine dust and NOx. As politicians set stricter targets (Kyoto protocol, Paris Agreement), and citizens become more and more aware of the severe consequences, business people realise that they should innovate their products and services. New business proposals must have a double objective: the new product must have a higher customer value, and at the same time a lower eco-burden. The higher customer value is needed to make the introduction of the product at the market a success, without the need for state subsidies.

The fact is that sustainable product innovation and introduction of circular business models is not easy. Although circular business models became a hype in Western Europe after the introduction of the Cradle-to-Cradle philosophy [1], and the business aspects of it [2,3], real successful implementations are rather limited [4–7] for many commercial business reasons. In addition, the environmental gains of circular business models are often much lower than it is suggested, especially with regard to the shift to services [8]. White et al. [9] (p. 1) writes about services: "*It is clear that the simplest and most optimistic view—a service economy is inherently clean economy—is insufficient and incorrect. Instead, the service economy is better characterized as a value-added layer resting upon a material-intensive, industrial economy*". Tukker [10] has drawn a similar conclusion on Product Service Systems (PSS) after the comprehensive SusProNet study: PSS did not bring the enormous change that was hoped for. PSS might *support* new business models, but are not the solution as such. White et al. conclude that, even though growth in services might be less environmentally damaging than growth in manufacturing: "*If services are to produce a greener economy, it will be because they change the ways in which products are made, used and disposed of—or because services, in some cases, supplant products altogether*" [8] (p. 1). Therefore, one of the crucial aspects of the innovative design of sustainable products or services is that people will buy it and use it (instead of unsustainable alternatives). That is why we focus in this paper on value creation in the fuzzy front end of the design process, since that is the moment where the real sustainable innovation can take place. It is the moment for designers to contemplate radically different product or service systems, e.g., identifying 'functional result' alternatives [9]. In user-centred design, value creation for the customer is the main aim [11]. In Ecodesign, sustainability is the main aim [12]. However, in sustainable product innovation we need a combination of both [13], where value creation and sustainability go hand in hand, and where the classical contradiction between ecology and economy is being reconciled in a clever way. Only LCA (Life Cycle Assessment) can reveal to what extent a new design of a product chain is better in terms of sustainability. A practical issue in design is that the classical LCA method is too laborious and complex to be doable in the early design stages. The result is that, especially in the early design stages, the aspect of sustainability is only dealt with on a qualitative 'gut feeling' basis, often leading to wrong conclusions. The LCA is then done (if at all) when the detailed design is ready. At that stage, however, it is too late for drastic changes, resulting in a product design that is far from the optimum. In eco-efficient value creation, this issue has been solved in a practical way by tools for 'Fast Track LCA', enabling the assessment of the environmental impacts of multiple design concepts in a quick way.

1.2. The Challenge: A Sustainable Street Lighting System for the City of Rotterdam

This paper presents the results of a practical case of eco-efficient value creation. It is the design of a street lighting system for a typical city in Western Europe: the city of Rotterdam.

Public street lighting has a major influence on safety [14,15], the perception of safety, and in general the atmosphere in the street. The municipality of Rotterdam has the desire to create a pleasant atmosphere in the city during both day and night by street lighting systems. An additional aspect of well-being in cities is the local presence of nature, i.e., trees [16,17]. So lighting and trees are both important aspects of the value for the citizens. However, in the conventional design of street lighting systems, there is a conflict below the ground: the roots of the trees interfere with the power cables, see Figure 1. This conflict causes difficulties during installation, maintenance and operation as well as end-of-life, which all lead to higher costs for the application of street lighting systems.

The underground conflict between tree roots and power cables can be solved in two different ways: (1) find other ways to create residential green, e.g., with plant boxes; or (2) redesign public street lighting. Within the first direction many solutions can be found, however, that is not the scope of this paper. To find acceptable solutions for the second direction is not easy. Since 1800, the lamppost has looked the same: a light source on a pole. Other forms such as hanging street lighting with hanging power cables above the ground are generally not regarded as desirable.

From the point of view of sustainability, the system requirement is obvious: the design must combine LED lighting with local PV cells as the source for the required electricity. Replacing the classic lamps by LED lamps is easy. Where to place the PV cells is less easy: (1) PV cells above the street will require expensive construction; (2) PV cells on the roof are a logical choice, but why would the owner of the building allow the municipality to attach the PV cells?

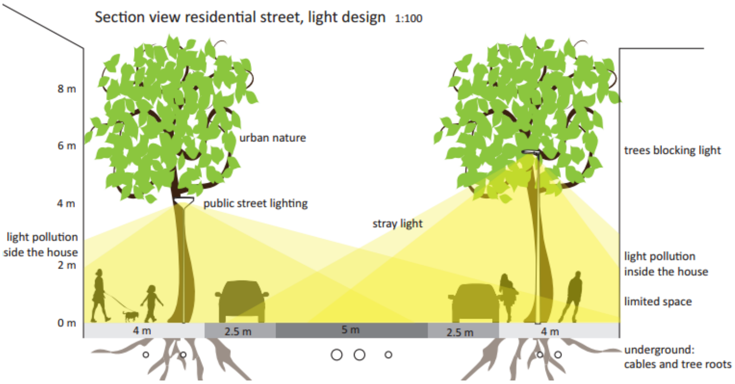

Figure 1. Conflict between residential street lighting systems and trees: the power cables are entangled in the roots.

The design of a new street lighting system has to fulfil three value aspects for the 3 stakeholders: (1) the requirement of streetlights in combination with trees, which is the value for the citizens; (2) it must be affordable (not too expensive) for the municipality; (3) it must resolve the issue "what is in it for me?" for the house owner with regard to the PV cells. At the same time, the new system must have a (much) lower eco-burden score in LCA compared to the classical system of Figure 1.

2. The Methods

2.1. The Eco-Costs, a Monetized Single Indicator in LCA

The assessment of the eco-burden of a system is done by LCA. An important issue here is the choice of the indicator that is used for benchmarking. Such a benchmarking indicator can be a so called midpoint indicator (e.g., greenhouse gas, acidification, eutrification, fine dust, human toxicity, ecotoxicity), but the issue here is that every indicator leads to its own optimum choice in product design. A well-known example is the engineering of the Volkswagen diesel: by focusing on CO_2 emissions only, and ignoring the consequences for NOx emissions, the strategic decisions of the company lead to losses of several billion euros.

The solution is to apply a so called endpoint indicator, which combines all midpoint indicators in one single score (i.e., damage based indicators like ReCiPe [18] and Ecological Footprint [19], both in 'points', or monetized scores like EPS [20] and eco-costs [21]). There is no single truth in single endpoint indicator systems, since such a system reflects a set of values and assumptions, but it is generally acknowledged that single score systems are needed in LCA benchmarking. A well-documented scientific single indicator system is always better than a set of many midpoint scores of which one or two are selected on the basis of a personal, subjective point of view [22,23].

It is useful to select a monetised single indicator in LCA, since it is related to the concept of 'external costs' (i.e., environmental costs to our society that are not included in the current product costs) and thus enables the comparison with the costs and the market value of the design. In the scientific literature there are two operational monetized systems that are widely applied in LCA: EPS 2015 (a damage-based indicator) [20] and Eco-costs 2017 (a prevention-based indicator) [21]. The advantage of monetized systems is that they do not suffer from the inaccuracies of the normalisation and weighting steps.

For the street lighting system study in Rotterdam, the eco-costs was selected as a monetised single indicator, since it is the most comprehensive system in terms of midpoints, see Figure 2, and it is the most applied system in science as well as design engineering.

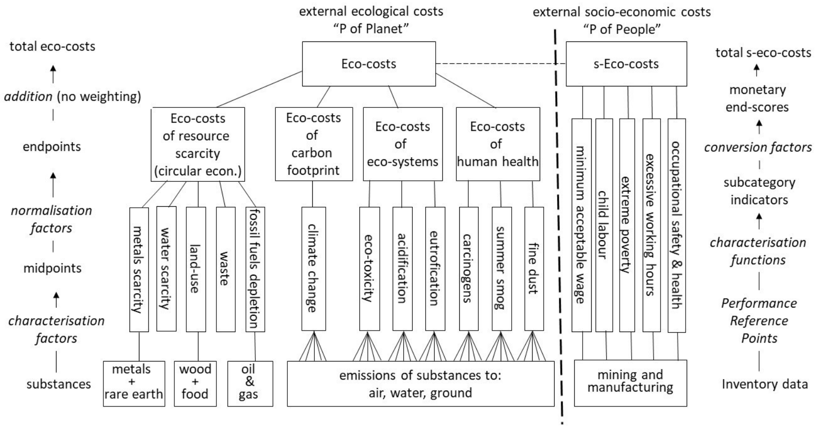

Figure 2. The total eco-cost system in life-cycle assessment.

The eco-costs system has been developed in the period 1999–2002 [24–26] and updated in 2007, 2012 and 2017 [27]. The system is in compliance with ISO 14008 [28]. A further description of the monetisation factors can be found in [29].

The way the total eco-costs of a system like street lighting are calculated, is explained by Figure 3. The first step in LCA is to determine the so called Life Cycle Inventory (LCI) list of all polluting emissions (CO_2, SO_2, NOx, fine dust, etcetera) and all required resources (metals, energy carriers, water, land). The system delivers a product or service as output (in this case light), and comprises a lot of subsystems and processes (in this case the lampposts, the cables, the light bulbs, the installation processes, and the end-of-life processes). All these subsystems and processes need material, transport and energy (electricity and heat) as input.

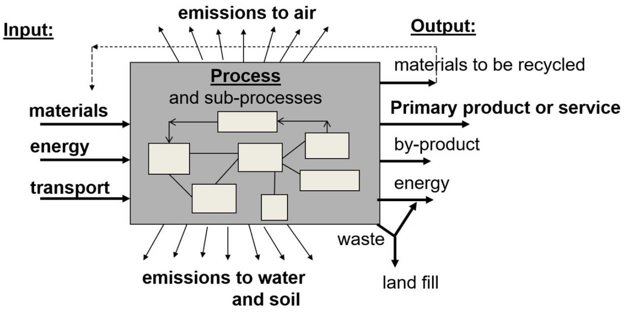

Figure 3. The system components of Life Cycle Assessment.

The second step in LCA is called the Life Cycle Impact Assessment (LCIA). The goal of this step is to provide a practical interpretation of the long list of emissions and required resources of Figure 3. According to ISO 14044 [30], this is done via the calculation structure of Figure 2. The substances of the list are classified in terms of their effect, multiplied by characterisation factors, and added up within their own 'midpoint' groups (i.e., climate change, eco-toxicity, acidification, fine dust, carcinogens, etcetera). Then the midpoint groups are combined to 'endpoints' (so called Areas of Protection) after either a monetisation step (e.g., eco-costs), or by 'normalisation' (e.g., 'points' in the ReCiPe system).

In the case of monetisation, the 'endpoints' can be added up to a total end-score, in our case eco-costs. (Non-monetised systems need an extra step to weight the relative importance of the points of the Areas of Protection).

LCA calculations can be made either with special software (e.g., Simapro, Gabi, Open LCA), or by means of look-up tables in excel. These tables are available for eco-costs of pure emissions, but also for the aggregated eco-costs at the level of materials (metals, plastics, wood etc.), manufacturing processes (deep drawing, turning, welding, extrusion, coating etc.), components (lamp bulbs, printed circuit boards, PV panels), transport, energy, and end-of-life processes [31]. These look-up tables have been calculated with the use of formal LCI databases, and enable a simplification of the final LCA calculation (without losing accuracy) in a way that is quite similar to cost accounting in projects (multiplying quantities with its eco-costs scores of supplies and processes, and adding it up to the total eco-costs). An example of such an LCA is given in Table 1. The table provides output data (in eco-costs and in CO_2 equivalent) for one classical lamppost (type 'Kegeltop' on a 4 m pole). Note that the calculations in Section 3 (Results) show data per year, under the assumption that the lifespan of a lamppost is 40 years, and per street, under the assumption that a street has 100 lampposts.

Table 1. An example of an excel LCA table, based on the BOM (bulk of materials) of the base case of a classical lamppost in a street (type 'Kegeltop' on a 4 m pole, per lamppost).

Unit	Amount for 1 FU	LCI Database Line	Eco-Costs Per Unit	CO2e Per Unit	Eco-Costs Per FU	CO2e Per FU
kg	3.52	Aluminium trade mix (45% prim 55% sec)	2.12	6.26	7.5	22.0
kg	34.93	Steel (21% sec = market mix average)	0.60	1.61	20.8	56.2
kg	2.10	Polyester (unsaturated) 70%	2.04	7.46	4.3	15.7
kg	0.90	Glass fibre 30%	0.10	0.48	0.1	0.4
kg	1.78	PC pellets	2.05	7.78	3.7	13.9
kg	0.07	Copper trade mix (56% prim 44% sec)	2.70	1.82	0.2	0.1
kg	0.31	PP pellets	1.05	1.97	0.3	0.6
kg	0.04	ABS pellets 50%	1.32	3.40	0.1	0.1
kg	0.04	PC pellets 50%	2.05	7.78	0.1	0.3
kg	1.50	Glass, uncoated	0.22	0.98	0.3	1.5
kg	0.08	PWB desktop, including components and Ics	60.71	160.41	4.9	12.8
m	16.60	Electric cord, 1000 W, 3 × 0.5 mm^2, domestic	0.07	0.14	1.2	2.3
kg	0.06	Crude iron	0.42	1.51	0.0	0.1
kg	0.002	Silicon	2.21	10.59	0.0	0.0
kg	0.07	67SiCr5, spring-steel	0.77	1.85	0.1	0.1
kg	0.55	X5CrNi18 (Stainless steel 304)	2.66	3.85	1.5	2.1
kg	0.41	PVC	0.702	2.006	0.3	0.8
		Material supplies			**45**	**129**
		Production processes				
kg	34.00	Drawing of pipe, steel	0.170	0.360	5.8	12.2
m2	10.25	Electroplating Zinc, outside use, per 10 years	5.479	2.974	56.2	30.5
m2	2.56	Powder coating, steel/RER S	1.105	4.570	2.8	11.7
kg	5.43	Injection molding plastics	0.264	1.333	1.4	7.2
kg	2.02	Casting, aluminium	0.018	0.157	0.0	0.3
kg	1.50	Cold transforming Al	0.019	0.104	0.0	0.2
kg	0.99	Deep drawing steel	0.065	0.316	0.1	0.3
		Manufacturing processes			**66**	**62**
		Material supplies + manufacturing processes excluding transport and installation			**112**	**192**

2.2. *The Model of the Eco-Costs/Value Ratio*

The basic idea of the model of the Eco-costs / Value Ratio (EVR) is to link the value chain of Porter [32], to the ecological product chain. In the value chain, the added value (in terms of money) and the added costs (from Life Cycle Costing, LCC) are determined for each step of the product chain, cradle-to-grave. Similarly, the ecological impact of each step in the product chain is expressed in terms of money, the eco-costs. See Figure 4.

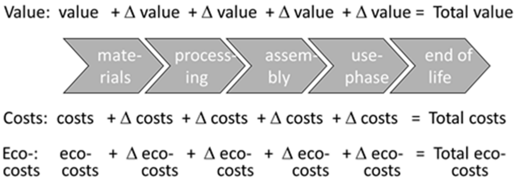

Figure 4. The basic idea of the Eco-costs/Value Ratio (EVR): combining the value chain with the ecological chain [33].

The theory of Porter, and so Figure 4, deals with the manufacturing of (physical) products for end-users (consumers). In a slightly more complex form, this theory can also describe the 'profit pool' [34] of a circular business model, or a service, since industrial services are bundles of products that deliver a function to the end-user. Street lighting is an example of such a service: its main function is light at night to provide safety, delivered by a bundle of products and services (lampposts, electricity, and maintenance). It is important here to realise that the value (of a product or service) for an individual buyer is not equal to the market price. The value is the Customer Perceived Value (CPV) [35–37], also called Willingness to Pay. The relationship between the costs, the price and the CPV is depicted in Figure 5.

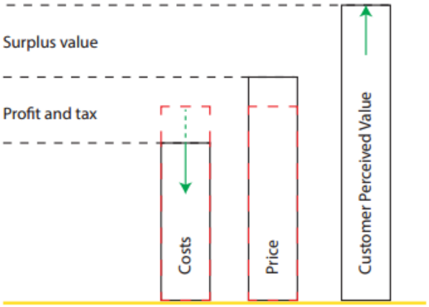

Figure 5. The costs, the price, and the Customer Perceived Value (CPV) of a product.

In our free market economy, the costs should be lower than the price, to support the profit of the company without subsidies. On the other hand, a product can only be marketed successfully when the CPV is higher than the market price, since people tend to buy things only when the perceived value for them is higher than the price they have to pay. The CPV can be defined as the benefit (utility plus joy) that is expected after the purchase. We call the difference between the price and the CPV the Surplus Value for the individual buyer. In the free market economy, the (market) price is set at a level that attracts sufficient buyers in order to reach an economy of scale that keeps the costs low enough.

For a municipality, costs and price are the same (red dotted lines in Figure 5), because they do not have the goal of making profit. However, the surplus value (for its citizens) must be positive, otherwise a project will not be accepted by the public.

In fact, the EVR model entails multiple dimensions. However, to show the build-up of the product in the chain, it is better in most cases to display only two dimensions at a time (see the figures in Sections 3.1 and 3.2 as an example for the base case of streetlighting) to avoid complex 3-D charts: the eco-costs at the y-axis, and one of the financial dimensions at the x-axis.

Under the assumption that most of the households spend in their life what they earn in their life (the bank savings ratio is <5% in most countries), the total EVR of the spending of households is the key towards sustainability. Only when this total EVR of the spending is consistently lowered, the eco-costs related to the total spending will be reduced (even at a higher level of spending). This issue is explained by a short macro-economic analysis on what happens in the European Union. Figure 6 shows the EVR (= eco-costs/price) on the Y-axis as a function of the cumulative expenditures of all products and services of all citizens in the EU25 on the X-axis. The data is derived from the EIPRO study of the European Commission (EIPRO = environmental impact of products) [38].

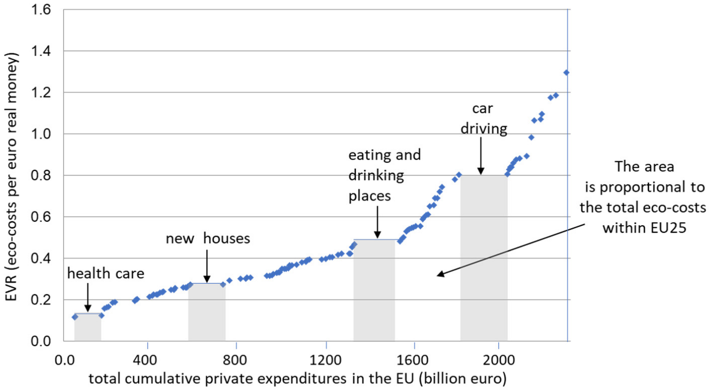

Figure 6. The EVR and the total expenditures of all consumers in the EU25 (from the environmental impact of products (EIPRO) study [38]).

The area underneath the curve is proportional to the total eco-costs of the EU25. Basically, there are two strategies to reduce the area under the curve:

- force industry to reduce the eco-costs of their products (this will shift the curve downward);
- try to reduce expenditures of consumers in the high end of the curve, by attractive offerings at the low end of the curve (this will shift the middle part of the curve to the right).

The question is now how designers and engineers can contribute to this required shift towards sustainability. Key is product innovation that fulfils the double objective of a higher CPV, and at the same time a lower eco-burden. To achieve this objective, it is an imperative that the designer must look at the CPV as well as the eco-costs at the beginning of the design process (i.e., idea generation and concept development). Eco-efficient Value Creation is a structured design method to achieve this.

2.3. Eco-Efficient Value Creation

In search of sustainable business models, product innovation must fulfil the double objective of eco-efficiency [39–41]. To achieve this objective, it is an imperative that the value, the total costs of ownership, and the eco-burden of a product are analysed at the beginning of the design process (idea generation and concept development).

The successful design options for Eco-efficient Value Creation are:

- to increase value where value is high (more quality, service, life span, and image);
- to decrease the eco-costs where the eco-costs are high (a shift to bio-based materials, recycling and renewable energy).

End-of-life solutions are important as well. Landfill reduces the value of the total system, and leads to higher eco-costs. Recycling (as well as re-use and remanufacturing) results in an added value combined with lower eco-costs ('end-of-life credits' in LCA).

A comprehensive checklist on the reduction of eco-costs is provided by the LiDS Wheel of Eco-Design [12], but the real issue of eco-efficient value creation is how to enhance the Customer Perceived Value of a green product at the same time. Mestre [13] studied the eco-efficient value creation with cork as bio-based material, and described the basic principles for the fuzzy front end of the design, see Figure 7, where, according to Mestre, "it is the talent of the designer that creates the value of the product" (page 13). In fact, sometimes a bit more eco-costs must be allowed to enhance the value considerably, leading to a better EVR score of the design.

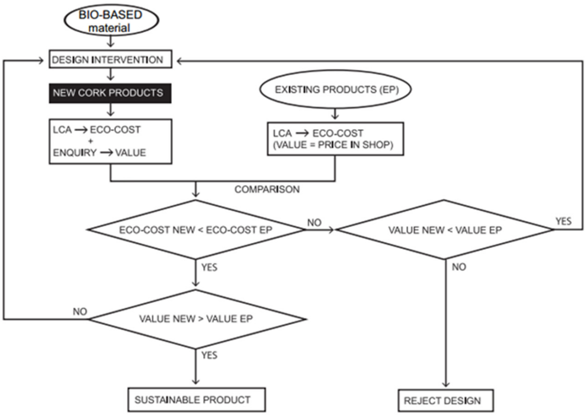

Figure 7. The basics of eco-efficient value creation in the fuzzy front end of the design [13].

Figure 7 clearly shows that the transformation towards a circular economy fulfils the double obligation of eco-efficient value creation. However, it also shows that designing a sustainable circular system needs to address more than circularity only: other aspects such as clean production, minimum transport and optimal marketing play an important role as well. To assess the environmental aspects (eco-costs), LCA is an indispensable tool throughout all stages of product development, see Figure 8. However, the classical LCA approach is only doable at the final detailed design stage, because it is too laborious [42]. To enable LCA-based materials selection in the fuzzy front end of idea generation, excel look-up tables [31] and an app for IOS and Android have been developed [43]. A special version of this app can make Fast Track LCAs, to optimize the design in the concept development phase (e.g., to analyse the trade-off of choices on materials, transport distances, and required energies).

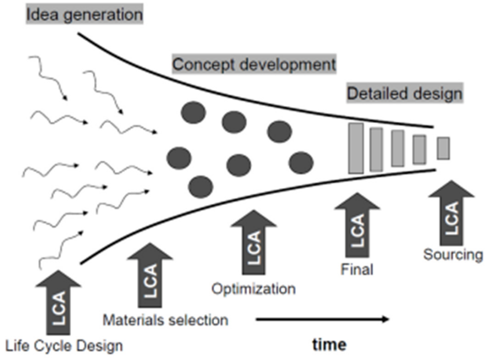

Figure 8. The use of LCA during all product development stages [44].

The approach of eco-efficient value creation can be characterised by 6 sequential steps:

Stpe 1 Life Cycle Thinking: At the start of the design process, the basic questions on circular design are whether or not the product must be suitable for easy repair, takeback + remanufacturing, or takeback + recycling of the materials. Note that circular designs are not always realistic in practice (because of long life times, high costs of return transport to the factory, low quantities, high remanufacturing costs, governmental regulations etc.). So Life Cycle Thinking must comprise many aspects that are on a higher level than the product chain itself [45].

Step 2 Functional requirements, and possible add-ons to enhance the CPV: Establish the 'musts' and the 'wants' in terms of functionalities, and in terms of enhancing the CPV [46].

Step 3 Idea generation and materials selection: The designer might be inspired by biomimicry, nature-inspired design, bio-inspired design, C2C, and other philosophies and design tools [47]. Since the choice of materials plays a governing role in this design stage [48], the LCA-based Idemat app for materials selection (specially developed to support eco-efficient value design) might be applied [43].

Step 4 Concept development and design optimisation: This is a highly iterative process as depicted in Figure 7.

Step 5 Detailed design with a final product LCA and with sourcing of components (materials): This is the stage of the classical LCA, to find the environmental the hotspots of the final design.

Step 6 Selection of suppliers: At the stage of sourcing of the components and materials, LCA should be applied to select the preferred suppliers.

3. Results: Example of the Design of a Street Lighting System

3.1. Base Case: the EVR of a Traditional Design in the City of Rotterdam

The base case for the design is the currently dominant existing system. The chosen lamppost for this base case is the "Kegeltop", on a 4 m aluminium pole. This luminaire is one of the most used ones in residential streets in the Netherlands and is a well-known design.

The Functional Unit (FU) of the analysis is: (1) one street, 1200 × 20 m (2) one year with a light level according to regulations (minimum of 3 lux at street level and a uniformity rate of at least 25%). The life span of a lamp post system is set to 40 years. The life span of PV cells is assumed to be 20 years.

The Total Costs of Ownership (TCO) of the base case comprises:

- Manufacturing and installation costs. These costs include the purchasing costs of the pole and luminaire and the working hours and administration costs of the installation process. Creating a grid connection, digging for cables and the pole are expensive: about 55% of the installing costs. Purchasing the pole and luminaire is the other 45%.

- Technical management. This is mainly related to maintenance work, such as: replace light bulbs, repair electronics and cable failures (after accidents), clean luminaires.
- Administrative management. These costs are related to desk work. Examples are: office expenses and taxes, inspections of luminaries and processing of the inspection reports.
- Energy consumption. This is based on the most used light source for residential streets: 36 W PL fluorescent lamps. The yearly operating time of a single light bulb is 4200 h. In addition, some taxes are included in the energy consumption costs.
- End of life. These are the costs for the removal tax of a pole and luminaire, and the removal costs of the current grid connection.

The TCO of the base case is depicted in Figure 9.

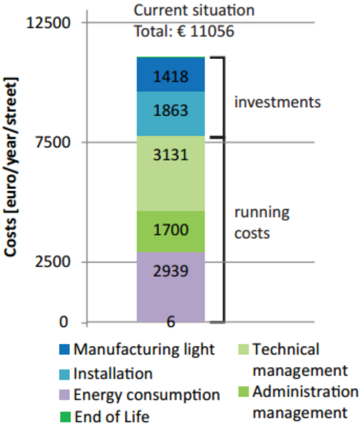

Figure 9. Costs (Total Costs of Ownership, TCO) for lighting: one street for one year of the base case.

The eco-costs of lighting system is depicted in Figure 10. Not all issues of the TCO have relevant eco-costs: administration and technical management consist out of labour, which is usually not part of an LCA. Maintenance does require some car kilometres to be driven, but that can be neglected in the LCA. The eco-costs of the energy consumption are highest together with the eco-costs of manufacturing. The eco-costs of the End of Life phase are negative since the material of the pole (aluminium) is reused in the circular business model of the contractor.

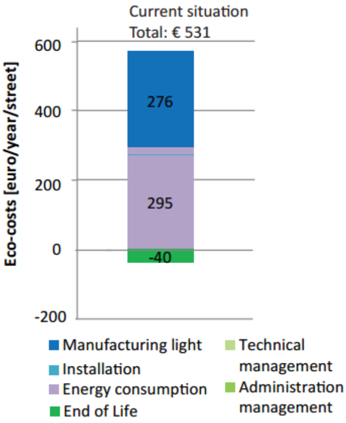

Figure 10. Eco-costs costs for lighting: one street for one year of the base case.

The costs, which represent the value, and eco-costs are plotted against each other in Figure 11. This graph shows which life cycle steps are most harmful for the environment and which steps are most expensive. The EVR ratio is highest after the manufacturing phase followed by the energy consumption, installation phase and technical and administration management.

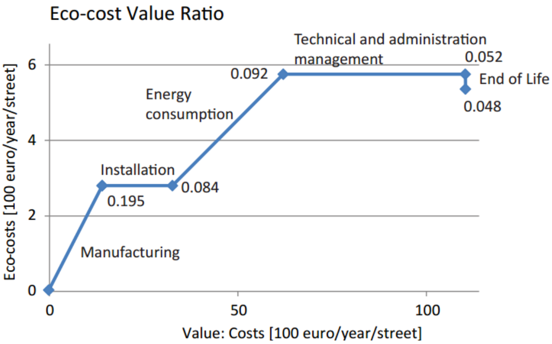

Figure 11. The 2-dimensional representation of costs and eco-costs of the base case (one street, one year). The absolute EVR is provided at each point of the curve.

From this graph it can be concluded where improvements should be made. The 'manufacturing' and 'energy consumption' phase cause the biggest rise in eco-costs, so it makes sense to focus on these issues to reduce eco-costs in the design process. Costs can be saved mainly in 'installation', 'energy consumption', and 'technical and administration management'.

3.2. The Design of the New System

At the idea generation phase of the design, several ways were investigated to fulfil the functional requirements. This is the phase where designers look at all kinds of materials (look and feel [48], recycled or bio-based, shapes (Nature-Inspired Design) [47], and systems (C2C, Life Cycle Thinking). Designers focus on maximum value for the stakeholders. User groups are asked for their preferences.

The eco-burden of concepts at the idea generation phase are normally dealt with by gut feeling, however, this gut feeling is often not fully in line with the reality of LCA. Since the eco-costs of materials weigh heavy in the total eco-costs of the manufacturing of physical products, the LCA-based materials selection app [43] has been developed to give guidance to the designer. When transport and/or energy in the use phase is important, the LightLCA version of the app is required. With the aid of such an app, the environmental aspects of the design are readily available "at your finger tip", so that the designer can focus on the most important aspect of the design at this stage: the creation of value.

In the case of the street lighting system in Rotterdam, the Customer Perceived Value relative to the base case was tested in a small user group for five design concepts: (1) surrounding light attached to the walls of the houses; (2) bamboo posts; (3) Arc light hanging above the street; (4) lamps attached to trees; (5) rooftop-mounted lamps. The rooftop-mounted lamps, see Figure 12, scored the best. A comparison with the base case is shown in Figure 13.

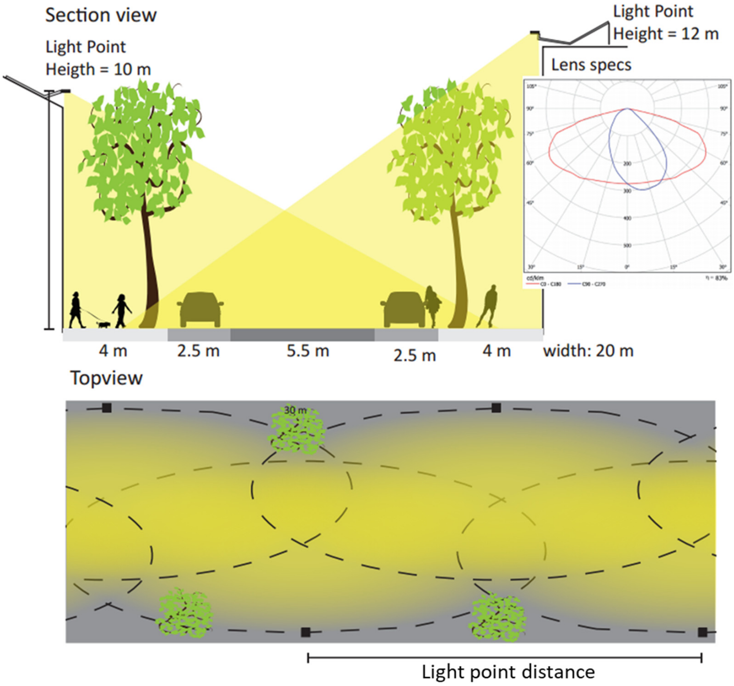

Figure 12. Light design proposal with small and asymmetric beam to avoid light shining into houses.

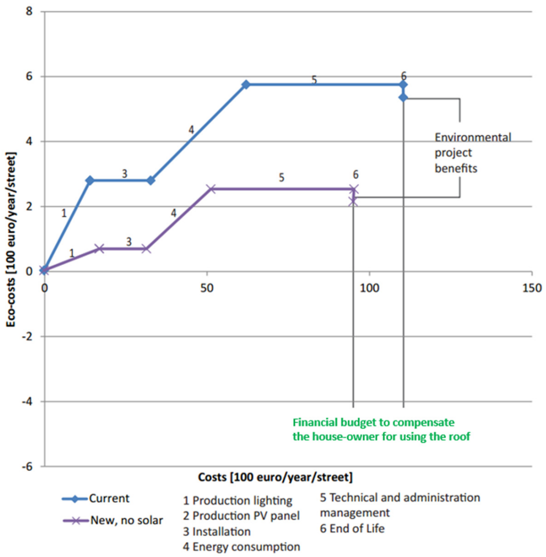

Figure 13. The rooftop lighting system (without PV cell) compared to the base case (one street one year).

An important design issue of Figure 12 is the equal distribution of light, which is a major aspect of the perceived value of street lighting. Shades of shadow cause feelings of unsafety. The combination with trees in the street requires special attention in the system design.

Interesting observations in Figure 13 are: (1) the production costs of the rooftop system are not lower that the production costs of the lamp post system, however, the installation costs are lower; (2) the eco-costs of the rooftop system are considerably lower; (3) the replacement of the PL fluorescent lamps by LED results in less electricity (less costs as well as eco-costs); note that these savings could have been realised with a new lamp post system as well; (4) the benefit of the new system compared to the old system might be used to compensate the house-owner (in this case a housing association) for using the roof.

At a later moment in this project, in the concept development stage, the rooftop-mounted lamps were combined with one PV cell on the roof, a logical system extension in regard to sustainability. The comparison of such a system with the bases case is shown in Figure 14.

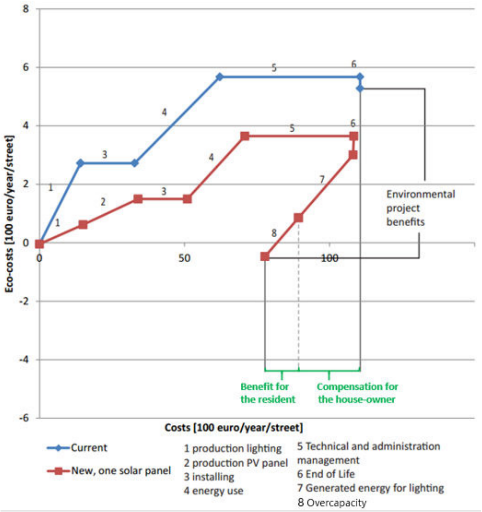

Figure 14. The rooftop lighting system, with one PV cell, compared to the base case.

In the EVR approach, the cost savings of the PV cell (the delivered electricity) is depicted in an extra line at the end of the curve: line 7 + 8. This line has the same slope as line 4, since they are both electricity. At the end of line 7, the amount of electricity that is used by the lamp, is delivered by the PV cell. Line 8 depicts the overproduction of the PV cell. An interesting issue of Figure 15 is how to divide the benefit of a lower Total Costs of Ownership of the new system (compared to the base case) between the house-owner and the resident of the building (to compensate for the extra burden caused by the municipality). Such a division is arbitrary, and will result from negotiations, but the point between line 7 and line 8 might be a logical choice: the benefit for the resident is the overproduction of the PV cell.

Figure 15. A prototype of set 2 PV cells plus lamp.

It is obvious that the owner of the building, in this case a housing association, might take the opportunity of installing extra PV cells. That is kept outside this analysis, but is shown in Figure 15: the first prototype of a set of 2 PV cells plus lamp. This prototype has been redesigned for a test pilot in the Marconistraat 43 in Rotterdam (an industrial area). The test pilot is still operational.

4. Discussion and Conclusions

This project of street lighting systems reveals two important issues:

- The sustainable innovation is not necessarily found in the application of radically new technologies, products or services. Sustainable innovation is the way in which existing technologies, products and services constitute a new sustainable product-service system with a viable business model that adds value to all the three stakeholders: (1) the municipality, by more value for the same costs; (2) the citizens in the street, by adding safety at night in combination with the trees in the street; (3) the owner and/or residents of the building, by reducing the costs of electricity.
- the chosen solution actually has potentially a spin-off effect that might become even more important than the system itself: the design concept *inspires* end-users to place additional, privately owned, solar panels on their roofs, alongside the solar panel of the municipality. Note that this is a very cost-effective way, since the installation of extra panels hardly adds to the installation costs.

Fossil Energy-saving systems (e.g., insulation, heat pumps, windmills, PV cells), have the characteristic that the TCO is less than the investment costs. In the EVR charts, this is characterised by a line with a negative slope, since there are savings in eco-costs as well as costs (see Figure 14). These savings are developing over time. After the pay-back period of the system, the extra cost savings will have a rebound effect [49], since these savings will result in other expenditures (e.g., on cars or holidays). When the EVR of such an expenditure is more than the EVR of the savings, the net result is negative for the environment. When the EVR of the expenditure is less than the EVR of the savings, the net result for the environment is positive [49]. The net result of energy savings has, therefore, a behaviour aspect.

Products for consumer markets must have a surplus value at the moment of purchase, whereas in cases of non-profit organisations, the non-profit organisation has an intermediate position between the stakeholders that pay for the project, and the stakeholders that benefit from the project. As a consequence, eco-efficient value creation for non-profit organisations like a municipality, has two distinct project phases: (1) the choice of the system concept, and the trade-offs between the value (in this case the CPV of the citizens), the eco-burden, and the costs (TCO), are done prior to the start of the implementation project, leading to a budgetary TCO limit. (2) after the project approval, this TCO limit will restrict the further design freedom, however, the approach of eco-efficient value creation still continues for designing further details: creating maximum value at minimum eco-costs. The same situation exists for big infrastructural projects and building design.

The design of a new concept of domestic street lighting system for the city of Rotterdam is a practical example of the approach of Eco-efficient Value Creation. The new concept results in a considerable reduction of carbon footprint and eco-costs, shows the benefits for the municipality and for the residents, and results in a viable business case. The end-result might seem logical and obvious, as it is the case for many good innovations. For all parties that were involved in the design, however, it was clear that such an achievement was the result of the well-structured design process in combination with the establishment of the CPV and eco-costs for several design alternatives in the early design stages (see Supplementary Materials). The design project won the Future Ideas Thesis Competition.

Supplementary Materials: https://www.ecocostsvalue.com/EVR/img/references%20ecocosts/Nine%20Klaassen%20Report.pdf and https://www.ecocostsvalue.com/EVR/img/references%20ecocosts/Nine%20Klaassen%20Appendices.pdf.

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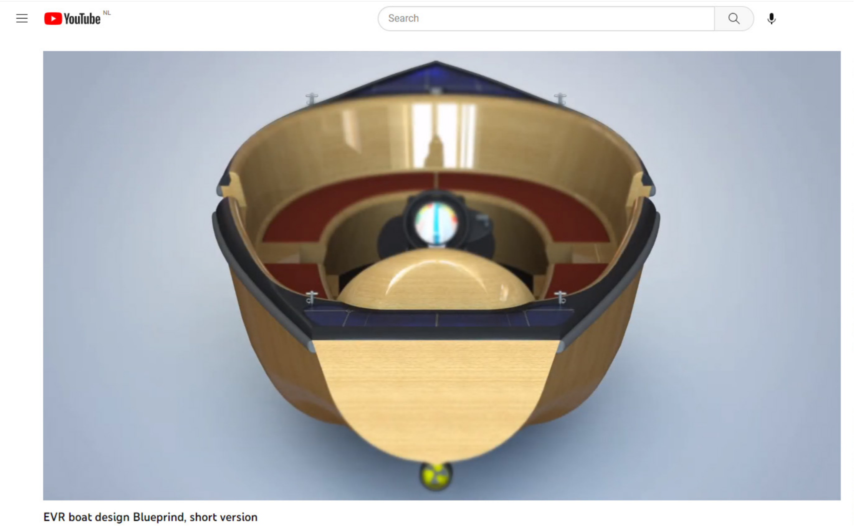
Part III: Appendix

As described in the Part 1 of this thesis, RQ6 investigates the applicability of the EVC approach by students. Aside from publication 6, the students in another project were introduced to the EVC approach and were challenged to apply the approach in their project. This appendix contains the results of a project for BSc students at the Delft University of Technology, the Explore Lab IO3834 course, in 2013-2014. Based on the project results and the students' self-evaluations, the outcomes suggest that students are capable of understanding and applying the approach succesfully. The results of the project, including an overview of the approach and important design decisions, is captured in the presentation video the student group has developed within the design project, of which a still is shown in figure 5.



EVR boat design Blueprind, short version

Figure 5: still taken from design project video available through:

https://www.youtube.com/watch?v=bBJIMUHaWzs

As can be seen in the video, the students describe their EVC project approach using the EVR model, which design choices have been made during application of the EVC approach and they showcase the product system design compared to the selected benchmark product.

The results of the design project indicate that the students were capable of using the EVR model in the EVC approach to create a design that had a lower EVR compared to their benchmark, making the case that their design would be able to obtain higher market prices due to a higher customer perceived value combined with a lower eco-cost compared to their benchmark product already available in the market.

They used the EVC approach throughout the design process, applying the EVR model to support design decision-making to the problem definition, ideation, conceptualization and evaluation phases of the design project.

For example, they applied the EVR chart for sustainable business strategies to guide their problem definition phase, as shown in figure 6.

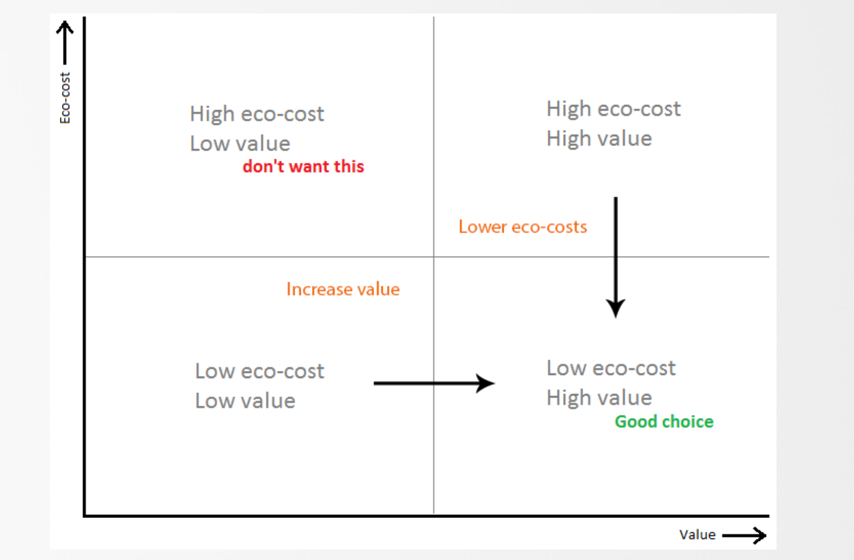


Figure 6: Use of the EVR Chart by the students in their design project report (taken from the design project report)

Another example of uptake of the EVC approach by the students is where the students also focused on sustainable materials selection using the EVR approach, as shown in figure 7.

Since we need to design the boat to have a high value, we did a survey for the different wood types to determine which wood has the highest value. 20 people were randomly selected to rank the different wood species from lowest to highest value. These were the differen wood types:

Figure 6.9. Wood types of survey

On a scale from 1 to 10, the survey resulted in this (full results in Appendix E):

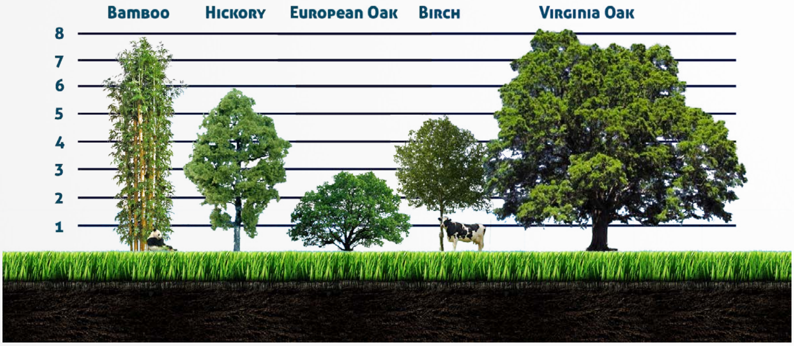
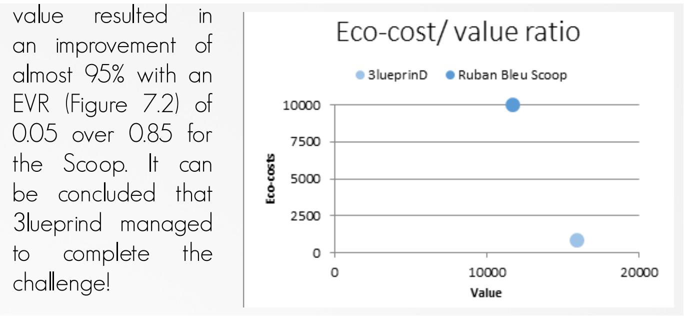


Figure 7: Use of the EVR approach for materials selection in the design process by investigating the perceived value of different low-impact materials (taken from the design project report)

The students concluded their design project with an evaluation of the achieved EVR of their product system design, including the proposed business model, cost estimations and expected customer perceived value, as shown in figure 8:



value resulted in an improvement of almost 95% with an EVR (Figure 7.2) of 0.05 over 0.85 for the Scoop. It can be concluded that 3lueprind managed to complete the challenge!

Figure 8: The amount of estimated Eco-efficient Value Creation achieved by the student design project (taken from the design project report)

The resulting product design supporting the amount of eco-efficient value creation is shown in figure 9.

Figure 9: The product design resulting from application of the EVC approach (taken from the design project report)

The students were also requested to reflect on the use of the EVR model and the EVC approach. The below self-evaluations of the students show that they were able to grasp the concept of eco-efficient value creation and appreciated the approach.

One student reflected:
"My knowledge on the sustainability side of a design increased dramatically. I found the Eco-cost/Value method inspiring and knowing your impact very useful. That's why in the project I chose to take part in our EVR research. Value being something you strafe for in Architecture as well. Now I learned to take a look at the environmental impacts, and costs and see the connection between them as well."

Another student reflected:
"I am glad that I was in the group which used the EVR method. It think that it is a good way to analyze a product using eco-costs. It can help you to find the hotspots of the product. I also liked the way to achieve a luxurious product which can be also more sustainable. I also learned, because of the EVR model, you do not always have to go for 100% eco-friendly materials, as long as the value increases you will have a low EVR. However, the eco-costs should remain low. "

The full report described in this Appendix is available upon request.

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This research project explores the application of the design approach of Eco-efficient Value Creation and the model of the Eco-cost/Value Ratio to practical cases, in order to advance the potential contribution of designers to accelerating the transition towards an environmentally sustainable society.

The Eco-efficient Value Creation approach is aimed at enabling designers to effectively create design solutions which combine a low environmental impact with a high customer perceived value, in order to achieve an increase in sustainable design solutions capturing market share over unsustainable design solutions currently on the market.

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DfS