Strategic design for remanufacturing

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DOI
10.4233/uuid:b8315d98-97b7-4509-b33c-bd3ac8627179

Publication date
2022

Document Version
Final published version

Citation (APA)
Boorsma, N. E. (2022). *Strategic design for remanufacturing*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:b8315d98-97b7-4509-b33c-bd3ac8627179

Remanufacturing is one of the product recovery approaches in a circular economy. In the remanufacturing production process, used products are returned to their original product specifications. When compared to original manufacturing, remanufacturing results in lower raw material consumption and reduces carbon emissions. Despite having been operative for decades, across multiple industries, remanufacturing remains a niche company activity.

The engineering knowledge on how to design products to improve the fit with the remanufacturing process is widely reported in academic literature. This thesis explores the role of strategic design in the context of remanufacturing and aims to promote a wider implementation of remanufacturing in industry. Strategic design determines the extent to which a product meets market needs, what its functionality should be, and whether it supports the company's long-term objectives.

This thesis contains three conference papers and three journal papers. The research is based on literature review, company workshops, interviews, an in-depth case study and methodology development. The outcomes include an overview of the design management role in remanufacturing, learning materials for companies, and the 'Circular Product Readiness' method.

Nina Boorsma
2022

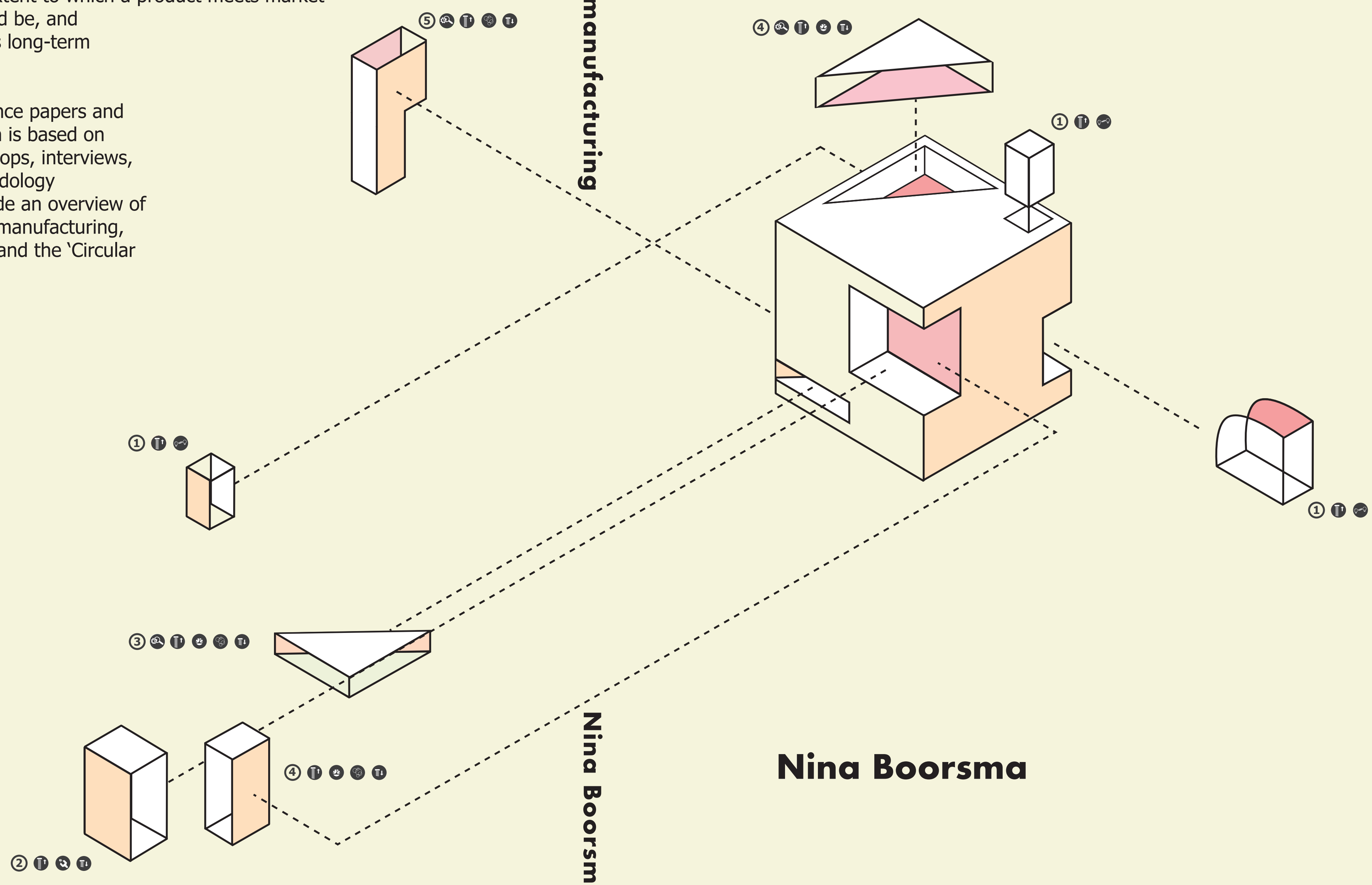
TU Delft | Industrial Design Engineering

Remanufacturing process steps

- Diagnostics
- Disassembly
- Testing
- Replacing
- Maintenance
- Cleaning
- Reassembly

Lifetime expectancy

number of use-cycles



Strategic design for remanufacturing

Nina Boorsma

Strategic design for remanufacturing

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STRATEGIC DESIGN FOR REMANUFACTURING

Nina Boorsma

Strategic design for remanufacturing

Dissertation
for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, prof.dr.ir. T.H.J.J. van der Hagen,
chair of the Board for Doctorates
to be defended publicly on
Wednesday 23 November 2022 at 15:00 o'clock

by

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This research was conducted as part of the 'Resource-efficient Circular Product Service Systems' (ReCiPSS) project, a project funded by the European Commission under the Horizon 2020, Grant Agreement 776577-2, in which the goal was to establish large-scale demonstrators of circular manufacturing systems.

TU Delft

European Commission | Horizon 2020 European Union funding for Research & Innovation

Keywords:
Remanufacturing, Circular Economy, Strategic Design, Design Management, Circular Product Design, Implementation, Design Method, Case study.

Front & Back cover design:	Nina Boorsma, Emma Haagen
Published by:	TU Delft
Lay-out by:	Ilse Modder, www.ilsemodder.nl
Printed by:	Gildeprint, www.gildeprint.nl

ISBN 978-94-6384-388-1

An electronic version of this dissertation is available at: http://repository.tudelft.nl.

To my parents, my brother and my sister.

SUMMARY

The aim of the circular economy is to keep materials in loops through a number of recovery approaches, and this way reduce our raw material uptake and all environmental impacts. One of the product recovery approaches in a circular economy is remanufacturing.

Remanufacturing is a production process which returns used products to original product specifications, and through that, allows products to re-enter the market and be functional for multiple use-cycles. The academic literature shows a misalignment between current product design, the remanufacturing process, and future market needs. The engineering knowledge on how to design products to fit the remanufacturing process is widely reported in the literature, yet this is not common practice in industry. For this reason, this dissertation looks into using strategic design to improve the implementation of Design for Remanufacturing in practice.

Strategic design helps position a product on the market in relation to other company offers. It determines the extent to which a product meets market needs, what its functionality should be, and whether it supports the company's long-term objectives. By doing so, it also dictates a product's potential to re-enter a market after being remanufactured and informs the way design engineers can meet remanufacturing requirements.

To explore the role of strategic design in the context of remanufacturing, I formulated the following main research question:

> *How can strategic design contribute to the wider implementation of remanufacturing?*

To answer this, I investigated the following six sub-research questions:

- What capabilities are needed to help remanufacturers overcome barriers to start up or scale up their remanufacturing activities? (Chapter 2)
- For remanufacturing, what is the role of soft barriers at the product development stage? (Chapter 3)
- What are the opportunities and barriers to implementing Design for Remanufacturing in early stage product development? (Chapter 4)
- How can design management support the strategic integration of design for remanufacturing in industry? (Chapter 5)
- How can remanufacturing barriers found in literature and field studies

be translated into lifelong learning materials for remanufacturers? (Chapter 6)

- What design indicators from literature are useful for monitoring circular design implementation in industry? (Chapter 7)

Throughout this dissertation, I used design management theory to simultaneously investigate the strategic value of design and the value of detailed design engineering. Design management is a field of research at the intersection of the management and design fields. It helps align design and strategy, it prioritizes and organizes design activities, it coordinates resources, and manages stakeholder needs. An important design management framework used in this dissertation is the balanced scorecard for design management. A balanced scorecard is known to incorporate the intangible value of business activities. It steers away from a predominant financial-oriented focus, and introduces the customer value perspective, process or performance value perspective, and learning perspective in parallel. I adjusted this framework to fit the context of remanufacturing.

Most studies rely on a combination of literature review and company involvement through workshops, interviews, or case studies. To investigate which capabilities are needed to overcome remanufacturing barriers, we reviewed the literature to create an overview of commonly reported barriers, presented in **Chapter 2**. To further explore these barriers and the required capabilities, company interviews were conducted with remanufacturers from different industries (e.g., IT, building parts, and car parts). Results show that the literature predominantly focusses on technical capabilities and developing integrating and coordinating capabilities. Soft capabilities like sensing and learning are less developed than the technical capabilities and need to be further advanced to help remanufacturers mature their business. These capabilities should be able to deal with barriers like the difficulty of determining the right price for remanufactured goods and the non-technical barriers to implementing Design for Remanufacturing into the product development process.

After acquiring this initial understanding and identifying a gap regarding soft, strategic barriers, we report the results of a case study in **Chapter 3**. We evaluated a set of predictors for new product performance for a company initiating recovery operations in the building parts industry. The main focus of the case company, a manufacturer of building products, has been to develop a value proposition for remanufactured products that offers high-quality and is attractive to the customer. This value proposition is based on technical knowledge of the product, including the use of high-grade materials and its ease of dis- and reassembly, and data from their existing markets. The company misses information on market acceptance and procedures for product retrieval from End-of-Life buildings. No dedicated market research has been performed to gain insights into market needs and requirements. Thus far, the procedure for product retrieval has remained undefined.

In **Chapter 4** we reviewed the literature to determine which design management roles can be derived from existing literature to support remanufacturing. Building on these roles, we conducted interviews with experienced remanufacturers and companies to investigate opportunities to start up recovery operations. The most common barriers found through the interviews with respect to the implementation of remanufacturing in strategic design are related to determining future market needs and predicting future technological developments. We identified opportunities related to making the value of Design for Remanufacturing explicit to the company at large and embedding Design for Remanufacturing into existing processes by means of Key Performance Indicators (KPIs) and roadmaps. Design management roles, like 'connecting different disciplines within the company to develop relevant, high-quality offers through recovery', 'making recovery roadmaps at an early design stage', and 'identifying the intangible value of remanufacturing to a company', were found to be key in the process.

As a next step, **Chapter 5** reports the results of an in-depth case study, which was conducted to understand how design management is used in a company wanting to implement remanufacturing in strategic design. The case company selected for this study is a globally operating OEM of professional imaging equipment, with a long history of remanufacturing. The Strategy Map resulting from the case analysis presents 12 main strategic elements through which the case company can advance the integration of remanufacturing in strategic design. This can be accomplished, amongst others, by steering towards appropriate, non-negotiable remanufacturing design guidelines, and by identifying critical parts (categories) to remanufacturing (e.g., high-value parts, software-related parts, spare parts, etc.). Another point is to consider the inclusion of remanufacturing in customer research and to develop a dedicated brand identity and marketing strategy. The company could also adopt a business strategy which integrates both newly manufactured and remanufacturing products. Design management was found to help reveal the value remanufacturing can have to a company at large and ensure aligned action from different company disciplines for increased commitment. The proposed strategic elements contribute to embedding Design for Remanufacturing into the design process.

Chapter 6 presents results of a literature review and the company workshops used to translate knowledge from the literature into lifelong learning materials for industry. Building on the literature review, remanufacturing barriers were translated into learning materials for professionals which were used in company workshops. To address these barriers, workshop exercises were designed to steer towards in-depth explorations of important strategic circular topics. The exercises addressed topics like defining the steps of the recovery process, describing the circular offer, selecting a business model, and assessing product suitability. The learning materials address most barriers and can be further developed to address any remaining barriers like those related to 'product-related data' and 'metrics'.

Finally, a combination of literature, knowledge coproduction sessions with experts, and company evaluation was used to develop a monitoring method for the implementation of circular design in practice, described in **Chapter 7**. Existing indicator methods were found to either (1) lack depth with regards to circular design (2) be incomplete, and/ or (3) lack a designer's perspective. The

Circular Product Readiness method developed in our study provides a means to give guidance to and monitor the status of circular design implementation. We identified 20 indicators which cover all product life-cycle stages through six themes, from strategy and planning to recoverability. The monitoring method helps companies assess their readiness level to design the different aspects of circular product service systems. The method report shows a company's overall score, and the score for all themes, indicators, and questions separately, as well as opportunities for improvement. In terms of design management, the method helps coordinate Design for Remanufacturing in relation to the other circular design strategies a company pursues.

The research in this dissertation directly tackles common remanufacturing barriers by taking a strategic perspective instead of the commonly used technical perspective. The outcomes can also help remanufacturing transform from an End-of-Life strategy into an integrated recovery approach, by adopting a product portfolio focus. Making this shift also allows this sustainable innovation strategy to more accurately address social needs from product performance over long-time horizons, to ensure long-term relevance to the market, and with that, ensure the inclusion of multiple use cycles in a circular economy.

SAMENVATTING

Het doel van een circulaire economie is om materialen in kringlopen te houden door middel van een aantal productterugwinningsbenaderingen, om op die manier ons grondstoffenverbruik te verminderen en alle milieueffecten te verminderen. Een van de productterugwinningsbenaderingen in de circulaire economie is remanufacturing.

Remanufacturing is een productieproces waarbij gebruikte producten worden teruggebracht tot de oorspronkelijke productspecificatie, zodat ze opnieuw op de markt kunnen worden gebracht en gedurende meerdere gebruikscycli functioneel kunnen zijn. Uit de academische literatuur blijkt dat er een wanverhouding bestaat tussen de huidige productontwerpen, het remanufacturingproces en de behoeften van toekomstige markten. De technische kennis over hoe producten te ontwerpen om ze geschikt te maken voor het remanufacturingproces wordt uitgebreid beschreven in de literatuur, maar dit is geen gangbare praktijk in de industrie. Daarom wordt in dit proefschrift gekeken naar manieren om de implementatie van Design for Remanufacturing in de praktijk te verbeteren door gebruik te maken van strategisch ontwerp.

Strategisch ontwerp helpt bij het positioneren van een product op de markt in relatie tot ander aanbod van het bedrijf. Het bepaalt in hoeverre een product voldoet aan de behoeften van de markt, wat de functionaliteit ervan moet zijn, en of het de langetermijndoelstellingen van een bedrijf ondersteunt. Op die manier bepaalt het ook het potentieel van een product om opnieuw op de markt te komen nadat het is remanufactured, evenals de manier waarop ontwerpingenieurs kunnen voldoen aan de ontwerpeisen van remanufacturing.

Om de rol van strategisch ontwerp in de context van remanufacturing te verkennen, werd de volgende hoofdonderzoeksvraag geformuleerd:

> *Hoe kan strategisch ontwerp bijdragen aan de bredere implementatie van remanufacturing?*

Dit is onderzocht aan de hand van de volgende zes onderzoeksvragen:

- Welke capaciteiten zijn nodig om remanufacturers te helpen barrières te overwinnen om hun remanufacturing activiteiten op te initiëren of op te schalen? (Hoofdstuk 2)
- Wat is voor remanufacturing de rol van zachte barrières in de productontwikkelingsfase? (Hoofdstuk 3)

- Wat zijn de kansen en belemmeringen voor het implementeren van Design for Remanufacturing in een vroeg stadium van productontwikkeling? (Hoofdstuk 4)
- Hoe kan designmanagement de strategische integratie van Design for Remanufacturing in de industrie ondersteunen? (Hoofdstuk 5)
- Hoe kunnen de belemmeringen voor remanufacturing die gevonden zijn in de literatuur en in veldstudies vertaald worden in duurzaam leermateriaal voor remanufacturers? (Hoofdstuk 6)
- Welke ontwerpindicatoren uit de literatuur zijn bruikbaar voor het monitoren van circulaire ontwerpimplementatie in de industrie? (Hoofdstuk 7)

In dit proefschrift is de designmanagementtheorie gebruikt om tegelijkertijd de strategische waarde van design en de waarde van gedetailleerde design engineering te onderzoeken. Designmanagement is een onderzoeksgebied dat zich bevindt op het kruispunt van de management- en ontwerpgebieden. Het helpt ontwerp en strategie op elkaar af te stemmen, het prioriteert en organiseert ontwerpactiviteiten, het coördineert middelen, en het beheert de behoeften van belanghebbenden. Een belangrijk raamwerk voor designmanagement dat in deze dissertatie wordt gebruikt is de balanced scorecard voor designmanagement. Een balanced scorecard staat erom bekend de immateriële waarde van bedrijfsactiviteiten te incorporeren. Het laat een overwegend financieel georiënteerde focus los, en introduceert parallel het klantwaardeperspectief, het proces- of prestatiewaardeperspectief, en het leerperspectief. De balanced scorecard werd aangepast aan de context van remanufacturing.

De meeste studies zijn gebaseerd op een combinatie van literatuuronderzoek en betrokkenheid van bedrijven door middel van workshops, interviews, of casestudies. Literatuuronderzoek heeft geholpen om een overzicht te maken van vaak gerapporteerde barrières in **Hoofdstuk 2**, om zo het antwoord te kunnen op de eerste onderzoeksvraag. Om deze barrières en de vereiste capaciteiten verder te onderzoeken, werden bedrijfsinterviews gehouden met remanufacturers uit verschillende soorten industrieën, zoals IT, bouwonderdelen, en auto-onderdelen. Resultaten tonen aan dat de focus in de literatuur tot nu toe overwegend lag op de technische capabilities, door het ontwikkelen van integrerende en coördinerende capabilities. Soft capabilities, zoals sensing en learning, blijven minder ontwikkeld dan de technische capabilities, en moeten verder worden ontwikkeld om remanufacturers te helpen hun bedrijf volwassen te maken. Dergelijke capabilities moeten in staat zijn barrières aan te pakken, zoals de moeilijkheid om de juiste prijs voor remanufactured goederen te bepalen en niet-technische barrières om Design for Remanufacturing in het productontwikkelingsproces te implementeren.

Na het verwerven van het eerste inzicht en het identificeren van een leemte met betrekking tot zachte, strategische barrières, werd casestudyonderzoek uitgevoerd in **Hoofdstuk 3**. Deze casestudy evalueert een set van voorspellers voor nieuwe productprestaties voor een bedrijf dat hersteloperaties beoogt te starten in de bouwonderdelenindustrie.

De belangrijkste focus van het casestudybedrijf, een fabrikant van bouwproducten, was het ontwikkelen van een waardepropositie voor remanufactured producten die hoge kwaliteit biedt en aantrekkelijk is voor de klant. Deze waardepropositie heeft het bedrijf gebaseerd op technische kennis van het product, zoals het gebruik van hoogwaardige materialen en het gemak waarmee het kan worden gedemonteerd en geherassembleerd, en op gegevens over hun bestaande markten. Het bedrijf miste informatie over marktacceptatie en procedures voor het terughalen van producten uit gebouwen aan het einde van hun levensduur. Er wordt geen specifiek marktonderzoek verricht om inzicht te krijgen in de behoeften en eisen vanuit de markt. De procedure voor het terughalen van producten was nog niet gedefinieerd. De studie in **Hoofdstuk 4** maakt gebruik van literatuuronderzoek om te bepalen welke ontwerpmanagementrollen uit de bestaande literatuur kunnen worden afgeleid om remanufacturing te ondersteunen. Voortbouwend op deze rollen zijn interviews gehouden met vertegenwoordigers van ervaren remanufacturers en bedrijven die de mogelijkheden onderzoeken voor het opstarten van hersteloperaties. De meest voorkomende barrières met betrekking tot de implementatie van remanufacturing in strategisch ontwerp die uit de bedrijfsinterviews naar voren kwamen, hebben te maken met het bepalen van toekomstige marktbehoeften en met het voorspellen van toekomstige technologische ontwikkelingen. Kansen die werden geïdentificeerd hebben betrekking op het expliciet maken van de waarde van Design for Remanufacturing voor het bedrijf als geheel en het inbedden van Design for Remanufacturing in bestaande processen door middel van Key Performance Indicators (KPI's) en roadmaps. Designmanagementrollen zoals 'het verbinden van verschillende disciplines binnen het bedrijf om relevante, hoogwaardige aanbiedingen te ontwikkelen door middel van remanufacturing', 'het maken van remanufacturing roadmaps in een vroeg ontwerpstadium' en 'het identificeren van de immateriële waarde van remanufacturing voor een bedrijf' bleken een sleutelrol te spelen in het proces.

Als volgende stap werd een diepgaand casestudy onderzoek uitgevoerd om te begrijpen hoe designmanagement in een bedrijfssetting wordt gebruikt om remanufacturing te implementeren in strategisch ontwerp in **Hoofdstuk 5**. Het casestudybedrijf dat voor deze studie werd geselecteerd is een wereldwijd opererende fabrikant van originele apparatuur voor professionele productieprinters, met een lange geschiedenis op het gebied van remanufacturing. De Strategy Map, die het resultaat is van de analyse van de casus, bevat twaalf belangrijke strategische elementen waarmee het casustudybedrijf de integratie van remanufacturing in de strategische ontwerpfase kan bevorderen. Dit kan bijvoorbeeld worden bereikt door te sturen op passende, niet-onderhandelbare richtlijnen voor remanufacturingontwerp, door middel van de identificatie van kritieke onderdelen voor remanufacturing (bijvoorbeeld onderdelen met een hoge waarde, softwaregerelateerde onderdelen, reserveonderdelen, etc.). Een ander punt is het opnemen van remanufacturing in klantonderzoek en het ontwikkelen van een specifieke merkidentiteit en marketingstrategie. Maar het bedrijf kan ook een bedrijfsstrategie volgen die zowel nieuw vervaardigde als remanufactured producten integreert. Designmanagement bleek te helpen om de waarde die revisie kan hebben voor een bedrijf als geheel zichtbaar te maken en om te zorgen voor op elkaar afgestemde actie van verschillende bedrijfsdisciplines voor een grotere betrokkenheid. De voorgestelde strategische elementen dragen bij aan de inbedding van Design for Remanufacturing in het ontwerpproces.

Literatuuronderzoek en bedrijfsworkshops werden gebruikt voor het ontwikkelen van duurzaam leermateriaal voor de industrie in **Hoofdstuk 6**. Remanufacturing barrières werden vertaald in lesmateriaal voor professionals dat gebruikt werd in bedrijfsworkshops. Om deze barrières aan te pakken, werden workshopoefeningen ontworpen die aansturen op diepgaande verkenningen van belangrijke strategische circulaire onderwerpen. De oefeningen gingen in op onderwerpen zoals het definiëren van de stappen van het remanufacturingproces, het beschrijven van het circulaire aanbod, het selecteren van een businessmodel en het beoordelen van productgeschiktheid. Leermaterialen over de volgende drie onderwerpen kregen van de deelnemers de hoogste waardering: 'beoordelen van productgeschiktheid', 'selecteren van een businessmodel', en 'plannen van de retourlogistiek'. Het leermateriaal pakt de meeste barrières aan en kan verder worden ontwikkeld om ook de resterende barrières aan te pakken, zoals die in verband met 'productgerelateerde gegevens' en 'metriek'.

Tenslotte is een combinatie van literatuur, kenniscoproductiesessies met experts, en bedrijfsevaluatie gebruikt om een monitoring methode te ontwikkelen voor de implementatie van circulair ontwerpen in de praktijk in **Hoofdstuk 7**. Bestaande indicatormethoden bleken ofwel (1) te weinig diepgang te hebben met betrekking tot circulair ontwerpen, ofwel (2) onvolledig te zijn, en/of (3) het perspectief van een ontwerper te missen. De in deze studie ontwikkelde Circular Product Readiness-methode biedt een middel om sturing te geven aan en toezicht te houden op de status van circulaire ontwerpimplementatie. Er zijn twintig indicatoren vastgesteld die alle fasen van de levenscyclus van het product bestrijken in zes thema's, van strategie en planning tot terugwinbaarheid. De monitoringmethode helpt bedrijven bij het beoordelen van hun gereedheidsniveau om de verschillende aspecten van circulaire productservicesystemen te ontwerpen. Het rapport met de resultaten van de methode toont de totaalscore van een bedrijf en de score voor alle thema's, indicatoren en vragen afzonderlijk, en daarmee de mogelijkheden voor verbetering. In termen van ontwerpmanagement helpt de methode Design for Remanufacturing te coördineren in relatie tot de andere circulaire ontwerpstrategieën die een bedrijf nastreeft.

Het onderzoek in dit proefschrift draagt bij aan het aanpakken van veel voorkomende barrières bij remanufacturing door een strategisch perspectief te kiezen in plaats van het gebruikelijke technische perspectief. De uitkomsten van dit proefschrift kunnen ook helpen remanufacturing te transformeren van een End-of-Life strategie naar een geïntegreerde herstelaanpak, door over te stappen op een geïntegreerde productportfoliofocus. Door deze verschuiving kan revisie een meer impactvolle, duurzame innovatiestrategie worden, door nauwkeuriger in te spelen op de maatschappelijke behoeften van productprestaties over lange tijdsbestekken. Zo kan de relevantie voor de markt op lange termijn worden gegarandeerd en kunnen producten worden ontwikkeld die meerdere gebruikscycli meegaan in een circulaire economie.

ACKNOWLEDGEMENTS

I would like to thank my supervisory team, Conny, Ruud, and Dave, for the opportunity of doing a PhD. Your interest in exploring this topic with me, your guidance, vision, and dedication have helped me develop a lot. I am very grateful that I got to go through this journey with the three of you. I have learnt so much.

Thanks to my colleagues. You made my days fun, interesting, and worthwhile. I enjoyed the interesting discussions we had on numerous topics (un)related to circular economy. Your perspectives, knowledge and experiences have really enriched my time as a PhD researcher. To the PhDs who started before me and paved the way: Flora, Phil, Deborah, Mariet, Emilia, Vivian, Jan, Beatriz, Brian and Prang. To my buddy, Jelle, whom I started doing a PhD with around the same time: thank you for your spirit, enthusiasm, help and reflections. To the PhDs who joined the team later on, with whom I have had great fun and a feeling of belonging: Renske, Karl, Mahshid, Sagar, Puck, Linda, Julieta, Theresa, Alma and Riel. And, of course, the other inspiring PhDs whom I shared the PhD room with: Valeria, Jiwon, and other DOS PhDs. I'd also like to mention the colleagues from the Design for Sustainability research group, and specifically those who I have collaborated and connected with along the way: Esra, Gyoung, Abby, Sonja, Ingrid and Yumi.

Thanks to the co-authors I got to write papers with: Susan, Tanya T., and Tanya B.. I'd also like to thank the European Commission for the opportunity to conduct my PhD research in the ReCiPSS project.; to the incredible ReCiPSS team: Saman, Malvina, Asif, Amir, Niloufar, Alena, Radek, Aleš, Simon, Markus, Dominik, Birgit, Dana, and many more; and to the companies I got to learn from and with during my research.

Thanks to my precious friends for the fun and adventure we had which helped me balance work life. Thanks to the ones who helped me get through difficult times, you truly have golden hearts. You mean the world to me.

Thanks to my Dutch, Norwegian and Finnish family who never cease to inspire me. Who encourages me to be exactly as I am, love me as I am and always welcome me with open arms.

Thanks to my brother and sister who give the best possible example to look up to. I enjoy your authenticity, courage, and determination. I'm grateful to have you close.
Thanks to my parents who always offer loving support and share their wisest words. Who are always full of excitement to hear about the things I learn and experience in (PhD) life. Who make space for me to be who I am and at the same time challenge me

to get the most out of myself. Who always catch me no matter what.

My deepest appreciation to everyone who have helped me complete my PhD.

LIST OF PUBLICATIONS

THIS THESIS

Journal papers:

Boorsma, N., Balkenende, R., Bakker, C., Tsui, T., & Peck, D. (2021). Incorporating design for remanufacturing in the early design stage: a design management perspective. *Journal of Remanufacturing*, *11*(1), 25-48. (Chapter 4)

Boorsma, N., Peck, D., Bakker, T., Bakker, C., & Balkenende, R. (2022). The strategic value of design for remanufacturing: a case study of professional imaging equipment. *Journal of Remanufacturing*, *12*, 187–212. (Chapter 5)

Boorsma, N., Polat, E., Bakker, C., Peck, D. & Balkenende, R. (2022). Development of the Circular Product Readiness method in circular design. *Sustainability*, *14* (15), 9288. (Chapter 7)

Conference papers:

Boorsma, N., Peck, D., Fischer, S., Bakker, C., & Balkenende, R. (2018). Capabilities required to tackle barriers to remanufacturing. In Proceedings of Going Green-CARE INNOVATION Conference. (Chapter 2)

Boorsma, N., Peck, D., Fischer, S., Bakker, C., & Balkenende, R. (2018). Remanufacturing workshops with professionals to overcome barriers-outcomes of two EU projects. *Proceedings of Conference Going Green—Care Innovation*. (Chapter 6)

Boorsma, N., Tsui, T., & Peck, D. (2019). Circular building products, a case study of soft barriers in design for remanufacturing. In *Proceedings of the International conference of Remanufacturing*. (Chapter 3)

ADDITIONAL PUBLICATIONS

EU reports:

Boorsma, N., & Bakker, C. (2019). D3. 1 - Defining the current baseline and the target circular design methodologies.

Boorsma, N., Bakker, C., van Dam, S. & Polat, E. (2021). D3.3 - Long-term design strategies.

Boorsma, N., Bakker, C., van Dam, S. & Polat, E. (2022). D3.4 - Circular design methodologies.

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LIST OF ABBREVIATIONS AND ACRONYMS

Business development, sales and marketing department	Bus.
Business-to-Consumer	B2C
Business-to-Business	B2B
CAtalyse REmanufacturing through Design bootcamp	CARED
Circular Economy Indicator Prototype	CEIP
Circular Economy Transition in Product Chains	CE-TPC
Circular Economy	CE
Circular Product Readiness	CPR
Compliance & quality department	Compl.
Contracted Remanufacturer	CR
Design for Remanufacturing	DfRem
Design Science Research	DSR
European Institute of Innovation and Technology	EIT
Equipment Manufacturer	OEM
European Commission	EC
European Remanufacturing Network	ERN
European Union	EU
Independent Remanufacturer	IR
Intellectual Property	IP
Key Performance Indicator	KPI
Knowledge and Innovation Communities	KIC
New Product Development	NPD
Product development department	Prod.
Product Recovery Management	PRM
Quality Function Deployment	QFD
Recourse Efficient Circular Product Service Systems	ReCiPSS
Remanufacturing	Reman.
Remanufacturing Pathways	RemanPath
Bridging the raw materials knowledge gap for reuse and remanufacturing professionals	ReUK
Key success factors for Re-Use Networks	RUN
Sustainable Development Goals	SDGs
United Nations	UN
Waste Electronics and Electrical Equipment	WEEE
Willingness To Pay	WTP

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 THE LANDSCAPE OF REMANUFACTURING

The way we design products determines how well they are suited to future recovery scenarios (Singal et al. 2020). Climate change and resource constraints demand that these use scenarios are highly sustainable. In its 2020 Circular Economy Action Plan, the European Commission (EC) reports on the importance of product design and its effects on the transition towards climate neutrality and resource-efficiency (EC 2020). Instead of continuing on the linear economy route, in which a single use of products and generating significant quantities of waste a year is the norm, the aim is to pursue circular thinking to keep materials in a loop (EMF 2013). One of the circular economy model's approaches is remanufacturing, a production process that returns used products to original product specifications, allowing products to re-enter the market and be functional for multiple use-cycles (IRP 2018).

Remanufacturing came to Europe in the 1940s via the UK and was applied in the engine manufacturing industry long before the concept of circular economy was born (de Ruijter 2020). The benefits at the time were to have access to 'as-new' products in times of scarcity: it saved costs and resources. From there it slowly started to spread to the manufacturing countries of Germany, Italy, France, and Poland (de Ruijter 2020). The same pioneering company that initiated remanufacturing in Europe, now claims a reduction in CO2 emissions from 111kg for engine manufacturing to 4 kg for engine remanufacturing, emphasizing the additional benefit of environmental gain (LDS 2021; Sundin & Lee 2012). Since then, many industries have taken up remanufacturing, including printing equipment, car parts, heavy-duty and off-road equipment, medical devices, locomotives, and many more (Neto & Dutordoir 2020; UNSITC 2012).

Remanufacturing can be applied by three types of parties: The Original Equipment Manufacturer (OEM), the Contracted Remanufacturer (CR) and the Independent Remanufacturer (IR) (Östlin 2008). The studies in this dissertation are predominantly focused on remanufacturing practices that fall under the same organization as the original product developer, which is typically the case for OEMs. The following definition of remanufacturing by the International Resource Panel (IRP 2018) was used throughout this study, "[Remanufacturing] refers to a standardized industrial process that takes place within industrial or factory settings, in which cores are restored to original as-new condition and performance, or better. The remanufacturing process is in line with specific technical specifications, including engineering, quality, and testing standards, and typically yields fully warranted products. Firms that provide remanufacturing services to restore used goods to original working condition are considered producers of remanufactured goods."

This definition of the process of remanufacturing consists of a number of process steps with a clearly defined output (Gray & Charter 2007; Ijomah 2010). It starts off with identifying the product type and diagnosing the quality of a core (i.e., a product returning from the market), which means inspecting a product on several pre-determined points critical to the product's potential to function for another use-cycle. The selected products continue to the cleaning station where any contamination and dirt (i.e., oil, dust) are removed. It then proceeds to the disassembly station where it is disassembled to the level of individual components. These components are then sorted, tested, cleaned, and, where needed, replaced. The sub-assemblies are then reassembled and tested. As a final step, all sub-assemblies are reassembled, and the resulting product is tested again to ensure it meets the original quality specification and is ready for market-release.

There are many reasons for companies to engage in remanufacturing. The most prominent of these is that remanufacturing yields higher profit margins, as it exploits the remaining value of an existing product, thereby avoiding the need for a full development and manufacturing cycle (Parker et al. 2015; Ijomah 2010; Guidat et al. 2015). Another closely linked reason is the notion of continued market demand for a product, which cannot be met (with similar effort) by offering newly manufactured products (Guidat et al. 2015). In addition to these two drivers, there are numerous other advantages of remanufacturing. For example, remanufacturing increases market share (Parker et al. 2015; Guidat et al. 2015) as it offers high-quality products against lower product prices (Östlin 2008) which may appeal to another audience than the market for newly manufactured products. Furthermore, it gives society the choice of purchasing lower impact products. Strategic advantages, like asset and brand protection are commonly mentioned benefits (Parker et al. 2015; Guidat et al. 2015; Östlin 2008). From an operational point of view, remanufacturing helps to reduce resource security risks, as it brings back a flow of products to the OEM and avoids a share of new raw material input (Östlin 2008). It can also help reduce lead times and, with that, reduce time-to-market, which can be a serious competitive advantage in today's highly competitive markets (Parker et al. 2015). Another expected upcoming driver is securing spare part supply through remanufacturing. This is due to an increase in supply chain disruptions and newly introduced regulations about the required availability of spare parts (Parker et al. 2015; Guidat et al. 2015).

In the light of sustainable development and research in circular economy, sustainability has also become an essential driver. Although the exact effects differ case-by-case (Neto & Dutordoir 2020), reduced environmental impact is an often-mentioned benefit (Parker et al. 2015; Ijomah 2010; Guidat et al. 2015; Östlin 2008). This reduction is not only visible in the reduced uptake of raw materials or reduced carbon emissions, also less water and energy is needed compared to newly manufactured products (Gunasekara et al. 2018). Sustainability, however, is seldom a single driver for a company to remanufacture (Guidat et al. 2015).

When taking a look at reasons for companies not to engage in remanufacturing, the difficulty of balancing supply and demand is the most prominent issue (Guidat et al. 2015; Ijomah 2009; Östlin et al. 2009). Predicting the size of the return flow of products from the market carries risks and uncertainties. Adding to this is the difficulty of aligning this with the timing of demand for remanufactured products. This is in line with the argument that remanufacturing is complex as it includes reverse logistics and remarketing of products (Guidat et al. 2015; Gunasekara et al. 2018). Fluctuations in the quality of cores is another frequently mentioned, and costly, aspect that makes companies reluctant to remanufacture (Parker et al. 2015; Guide 2000). Another frequently voiced drawback is the customers' attitudes towards remanufactured products (Abbey et al. 2015). Either customers are unfamiliar with the quality of products the process can produce as they live under the assumption that 'new is better', or the customer segments are scarce and companies may even lack sales channels to reach them (Abbey et al. 2015; Guidat et al. 2015). The fear of cannibalizing markets for new products is often raised as an important market-related argument (Atasu et al. 2010) as are entries of low-cost competitors (Parker et al. 2015). From an operational point of view, costs associated with labor and reverse logistics are typical drawbacks (Parker et al. 2015; Guidat et al. 2015). Product-related drawbacks include a lack of product knowledge, in terms of use-history and remanufacturing potential (Parker et al. 2015), and a mismatch with the original technology, either due to its rapid evolution or because it has become outdated (Parker et al. 2015). A final argument, central to this dissertation, is the misalignment of product characteristics to the remanufacturing process and future markets (Parker et al. 2015; Guidat et al. 2015).

1.2 DESIGN FOR REMANUFACTURING

In the next sections, I dive into more details regarding Design for Remanufacturing, which investigates the suitability of a product to be remanufactured. The academic literature discusses various ways to determine remanufacturability and the term itself is multifaceted. Remanufacturability essentially refers to the ability to remanufacture a product from a technical point of view (Liu et al 2019; Wu 2012), as well as its viability in terms of market competitiveness once it has been remanufactured (costs and market potential) (Omwando et al. 2018; Xing and Gao 2013). Environmental gains are frequently incorporated in suitability assessments, yet seldom listed as a core element to determine remanufacturability (Du et al. 2012; Omwando et al. 2018; Zwolinski et al. 2008).

The body of literature on Design for Remanufacturing predominantly focuses on the technical aspects of remanufacturability. Based on an analysis of 75 unique remanufactured products, Lund (1998) developed seven criteria for product remanufacture: (1) the product is a durable good; (2) the product fails functionally; (3) the product is standardized and the parts are interchangeable; (4) the remaining value-added is high; (5) the cost to obtain the failed product is low compared to the remaining value-add; (6) the product technology is stable; and (7) the consumer is aware that remanufactured products are available." From a design perspective, dis- and reassembly are often mentioned as the first to consider, as these form the doorway to the successive process steps (Hammond et al.1998; Du et al. 2012; Fang et al. 2016; Omwando et al. 2018). Gray and Charter (2007) add that by designing products for dis- and reassembly, the time and effort needed to perform other process steps decreases. Research also emphasizes the importance of safeguarding product quality by avoiding damage to parts in the process (Shu & Flowers 1999; Sundin and Lindahl 2008). Design guidelines include reducing the number of parts, quantity and tools required (Ijomah 2007); indicating access points (Ijomah 2007); optimizing the product architecture for cleaning (Ijomah 2007); and using modularity to isolate possible obsolescence into smaller sub-sections of products (Sundin & Lindahl 2008). With an eye on keeping products future proof, the interchangeability of components and upgradability are also recommended (Ijomah 2007; Gray and Charter 2007). More recent literature on Design for Remanufacturing focuses on the requirements of organizing the design process in such a way that design knowledge can easily be transferred from the remanufacturing department to the designers (Lindkvist Haziri & Sundin 2020).

In addition to these technical aspects, the strategic, economic, and sustainability aspects of remanufacturing have also been studied. Strategic aspects, like determining the destination market and mapping the active competitors on those markets, influence whether products can be remarketed (Zwolinski et al. 2008). In terms of economic aspects, the need to minimize process costs is frequently mentioned, as well as product acquisition, overhead, and original manufacturing costs (Bulmuş et al. 2014; Du et al. 2012; Ghazalli and Murata 2011; Liu et al. 2019; Omwando et al. 2018). An analysis of environmental characteristics shows that waste reduction is often an important factor, together with the reduction in energy use (Du et al. 2012; Ghazalli and Murata 2011). In addition, to manage levels of resource consumption, the component salvage rate is often referred to together with new material consumption (Liu et al 2019; Omwando et al. 2018; Zwolinski et al. 2008). The majority of factors concern operationability or engineering issues. Strategic considerations, in relation to design, are far less adopted when determining remanufacturability (Yang et al. 2015). Our analysis shows that there is a gap in the research literature regarding the strategic aspects of remanufacturability

1.3 STRATEGIC DESIGN FOR REMANUFACTURING

To further detail this gap in knowledge, we will look deeper at the early stages of product design, also referred to as strategic design. Strategic design has a significant influence on the implementation of remanufacturing in the design process (Ong et al. 2016; Hatcher et al 2011; Zwolinski et al. 2008). In particular, early-stage strategic design plays a significant role in product performance over multiple use-cycles and a product's potential to be remanufactured (Fadeyi et al 2017; Favi et al 2017). Strategic factors help position a product on the market in relation to other company offers, it determines the extent to which a product meets market needs, and whether it supports the company's long-term objectives. It basically indicates a product's potential to re-enter a market (Du et al. 2021). Product market segmentation approaches and differentiation strategies are elements that determine a product's strategic performance (Atasu et al. 2008; Bulmuş et al. 2014; Wu 2012).

In generic terms, the strategic design phase in the new product development process is referred to as "the period between when an opportunity is first considered and when an idea is judged ready for development" (Kim & Wilemon 2002) (Table 1.1). After the strategic design phase, the design process continues with the new product development phase, which consists of concept development, the product definition, and embodiment design.

TABLE 1.1 The phases of strategic design, adapted from Khurana & Rosenthal (1997).

Strategic design					**New product development**		
Strategic vision	Product portfolio management	Product platform strategy	Product-line strategy	Design brief	Concept development	Product definition	Embodiment design

A strategic vision describes a company's unique position on the market, based on what it is capable of offering and what it wants the market to expect (Buijs 2003; McGrath & Gilmore 1995). Having such a vision is fundamental to building a successful product strategy (Khurana & Rosenthal 1997). This strategic vision is then materialized in product portfolio management, where a company tries to find coherence between its (planned) product offers and the target segments, based on parameters like price levels (Khurana & Rosenthal 1997). When developing the product platform strategy, foundational decisions are made regarding a range of products including the type of operating system, the interface, and the processor architecture (Khurana & Rosenthal 1997). The product line strategy describes how the design evolution of a certain product develops over time, looking at how the market develops, and whether new opportunities for improvement arise (Khurana & Rosenthal 1997). This phase develops product concepts in line with the strategic design decisions made in previous phases concerning the foundation elements (Khurana & Rosenthal 1997; Ullman 2010). It is characterized by finding solutions to earlier found gaps and opportunities and is based on technology-visioning and market-visioning (O'Connor & Veryzer 2001; Reid & De Brentani 2004). The product design brief covers the product concept statement and its evaluation and denotes the end of the strategic design phase (Smith and Reinertsen, 1992). The design process has now become plannable and manageable and can move into new product development. (Kim & Wilemon 2002; Smith and Reinertsen, 1992).

1.4 DESIGN MANAGEMENT THEORY

Throughout this dissertation, design management theory was used to simultaneously study the strategic value of design and the value of detailed design engineering. Design management is a field of research at the intersection of the management and design fields. It aligns design and strategy, it prioritizes and organizes design activities, it coordinates resources, and manages stakeholder needs (Erichsen & Christensen 2013). Design management takes a bird-eye view on the value of design throughout the entire product development process and manages both (the value of) strategic design and detailed embodiment design (Cooper et al. 2013; Johansson & Woodilla 2008). An important design management framework used in this dissertation is the balanced scorecard for design management by Borja de Mozota (2006). A balanced scorecard is known to incorporate intangible value of business activities (Kaplan & Norton 2004). It steers away from having a predominantly financial-oriented focus, and introduces the customer value perspective, the performance value perspective, and the learning perspective in parallel. This framework was adjusted to fit the context of remanufacturing (Boorsma et al. 2022).

1.5 DISSERTATION AIM

Despite having been operative for decades in multiple industries, remanufacturing has remained a niche activity within companies (Matsumoto et al. 2016). This means that apart from the benefits it brings economically and environmentally, there are still many unresolved barriers before remanufacturing becomes an integrative part of business operations. This is clear from the observation that generally only a marginal share of a company's products is remanufactured, leaving potential (strategic) value unused (Boorsma et al. 2022). In addition, decision-making to remanufacture a product typically takes place when products reach their End-of-Life, which implies that remanufacturing is separate from a companies' core business or strategy. Hence remanufacturing is often used as a reactive instead of a proactive approach (D'adamo & Rosa 2016). Researchers in the field of remanufacturing frequently refer to the importance of strategic design; however, this has not been researched in detail (Fadeyi et al. 2017; Favi et al. 2017). In addition, Ansari et al. (2019) found that remanufacturing has significant potential to contribute strategic value. To explore the value strategic design can have to remanufacturing, as well as to the implementation of Design for Remanufacturing, the following main research question was formulated:

> *How can strategic design contribute to the wider implementation of remanufacturing?*

This research was conducted in the context of several H2020 programs: RUN ('Key success factors for re-use Networks'); ReUK ('Bridging the raw materials knowledge gap for reuse and remanufacturing professionals'); and ReCiPSS ('Recourse Efficient Circular Product Service Systems') under grant agreement number 776577-2, all funded by the European Commission. These projects opened up the possibility to have in-depth discussions with, and input from, the affiliated industry partners over a longer period of time. It also implies that the focus had to be on the European Union and on technologically complex product groups for business-to-business markets like printers and machinery, which meet criteria as typified by Lund (1998).

Research into a company's ability to overcome barriers to remanufacturing is heavily focused on technical, hard factors. The soft factors, on the other hand, have significantly lower representation in literature (D'adamo & Rosa 2016). The following research question was formulated to explore the research balance between hard and soft capabilities, and to define what soft capabilities entail in the context of remanufacturing. This gap leads to the **sub-research question 1**:

1. *What capabilities are needed to help remanufacturers overcome barriers to start up or scale up their remanufacturing activities?*

Having established that soft, strategic factors form a gap in the remanufacturing literature, a next step was to investigate how these factors influence decision-making for design in practice, by answering **sub-research question 2**. Remanufacturing has been practiced for decades, and the study of Design for Remanufacturing has been growing ever since (Hatcher et al. 2011). Yet, the uptake of this design knowledge in practice has been marginal (Lindkvist Haziri & Sundin 2020). As the suitability of products to the remanufacturing process was found to be an important barrier to setting up or scaling up remanufacturing, the following research question focuses on the role of soft barriers in the product development stage.

2. *For remanufacturing, what is the role of soft barriers at the product development stage?*

Although strategic design has been noted as being important when implementing Design for Remanufacturing, the academic literature has not yet reviewed its link to remanufacturing (Hatcher et al. 2013; Lange 2017). Strategic design deals with preparing products to fit a selected company strategy, by means of, for example, customer research, product portfolio management, and innovation management, over longer periods of time (Khurana & Rosenthal 1997). Design management theory was applied to gain insights in the strategic design activities, and to bridge the gap between the strategic value of design and the value of detailed design engineering. This led to **sub-research question 3**, that investigates the opportunities and barriers to implementing Design for Remanufacturing in strategic design.

3. *What are the opportunities and barriers to implementing Design for Remanufacturing in early stage product development?*

Once the role of strategic design for remanufacturing was defined based on design management theory, the next step was to investigate this role in practice through an in-depth case study. Case studies in the strategic domain are scarce (Karvonen et al. 2017) and extending the investigation to practice permitted corroborating the findings from literature, as well as gaining a richer understanding of the dynamics at play. This was accomplished through answering **sub-research question 4**.

4. *How can design management support the strategic integration of design for remanufacturing in industry?*

The knowledge cross-over from theory to industry plays a crucial role in advancing the implementation of (design for) remanufacturing in practice. A common way of facilitating knowledge transfer to designers is by developing design methods and tools. This was a central aim when assigning the RUN and ReUK EU projects. The gap identified by the European Commission was the need for lifelong learning materials for (potential) remanufacturing professionals; this led to **sub-research question 5**.

5. *How can remanufacturing barriers found in literature and field studies be translated into lifelong learning materials for remanufacturers?*

Similarly, the European Commission has indicated a need for tailored design methods for large-scale circular manufacturing systems as part of the EU project ReCiPSS. Research into circular product design often focuses on individual strategies like design for durability, repair, or remanufacturing. In reality, these design strategies influence each other, may have a certain overlap, and to function effectively, they should be considered in parallel. The final research question, **sub-research question 6**, was formulated to help monitor the progress of implementation, for which to date, an all-encompassing, design-specific, monitoring method is missing.

6. *What design indicators from literature are useful for monitoring circular design implementation in industry?*

1.6 DISSERTATION OUTLINE

This dissertation consists of six chapters that together answer the main research question (Table 1.2). Each chapter is based on a publication and follows the structure of introduction, background, research method, results, discussion, and conclusion.

The first two chapters, 2 and 3, explore the barriers to (design for) remanufacturing. These chapters help define the problem space that stands in the way of scaling up remanufacturing operations and its implementation in the design process.

Chapters 4 and 5 dive deeper into the dynamics of the design process and the role of strategic design. They define the opportunities and barriers for implementing Design for Remanufacturing and how design management theory can help in progressing this implementation.

The final two chapters, 6 and 7, build on the findings from the previous chapters and focus on the development of tools and methods that can assist in the implementation process. Chapter 6 aims at facilitating innovative thinking in the early stage development of initiating remanufacturing. Chapter 7 describes the use of an assessment method to manage implementing a portfolio of design strategies in parallel.

TABLE 1.2 Sub-research questions and methods.

Chapters	Research questions	Methods
Chapter 2	What capabilities are needed to help remanufacturers overcome barriers to start up or scale up their remanufacturing activities?	Literature review and interviews
Chapter 3	For remanufacturing, what is the role of soft barriers at the product development stage?	Literature review and company workshops
Chapter 4	What are the opportunities and barriers to implementing Design for Remanufacturing in early stage product development?	Literature review and interviews
Chapter 5	How can design management support the strategic integration of design for remanufacturing in industry?	Literature review and case study research
Chapter 6	How can remanufacturing barriers found in literature and field studies be translated into lifelong learning materials for remanufacturers?	Literature review and company workshops
Chapter 7	What design indicators from literature are useful for monitoring circular design implementation in industry?	Literature review, knowledge coproduction sessions and company evaluation

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CHAPTER 2

CAPABILITIES REQUIRED TO TACKLE BARRIERS TO REMANUFACTURING

This chapter has been published as:
Boorsma, N., Peck, D., Fischer, S., Bakker, C., & Balkenende, R. (2018, November). Capabilities required to tackle barriers to remanufacturing. In Proceedings of Going Green- CARE INNOVATION Conference.

ABSTRACT

The transition towards a circular economy proposes to deliver sustainable, lower carbon opportunities to society, governments and companies. This paper focuses on finding barriers encountered during remanufacturing activities and interpreting the barriers by using a framework for dynamic capabilities. Dynamic capabilities enable companies to adjust to changes in their business activities. In the literature, remanufacturing is described as a process to restore used products to a 'as good as new' condition, through a series of steps. This paper discusses the analysis of in-depth interviews with a selection of five remanufacturing companies. The companies are from the following sectors: automotive, IT, photocopiers, industrial robots and building components. Results show they have a tendency to put technical capabilities at the core of their research, leaving 'softer' capabilities, such as sensing and learning, less developed.

2.1 INTRODUCING REMANUFACTURING CAPABILITIES

A range of different drivers steer companies to invest in strategies to prolong product lifetime. Remanufacturing is a promising example of such recovery strategies. Drivers to pursue this strategy vary from intrinsic to regulatory drivers and from environmental to financial, with an emphasis on the financial. Products which would otherwise be discarded at the end of use are reintroduced to the market for, at least, a second time, allowing businesses to generate revenue, with a lower energy and material investment, when compared to newly produced goods.

Remanufacturing has already been established in sectors with capital-intensive, (semi) professional products, often operating in Business-to-Business (B2B) markets. There are, however, further opportunities regarding value recovery. The underlying reasons for product remanufacturing not currently operating to its full capacity are disparate [16]. This paper focuses on the dynamic capabilities needed to help remanufacturers overcome barriers in order to start up or scale up their remanufacturing activities. Dynamic capabilities are the capabilities needed to adjust to new situations and therefore can help interpret barriers [33]. Technical capabilities are well represented in literature, while significantly less attention is paid to the 'soft' capabilities. Soft capabilities are crucial for strategic positioning of a company, as well as for learning how to re-shape existing capabilities into new ones to grow a circular, sustainable business.

A literature review is conducted to identify barriers, followed by in-depth interviews in selected companies for validation and to establish a deeper understanding of the barriers. Finally, the results were interpreted by means of a framework for dynamic capabilities.

2.2 REMANUFACTURING ENTREPRENEURSHIP

Remanufacturing is defined as bringing back the functionality and appearance of a used product, through a series of standardized process steps, to a like-new condition and with a customer warranty to match [6][25][43]. Even though remanufacturing activity has grown in recent years, the remanufacturing approach has been applied since the 19th century. In recent decades the industrial fields where remanufacturing has been more prevalent are mobility and energy generation. Product examples include: steam engines, railway infrastructure, power & machine tools and aerospace [28]. Consequently other sectors moved into remanufacturing including products such as medical devices, photocopiers and professional coffee machines [17][22][37][39][45]. The motives for developing product recovery strategies, like remanufacturing, are likely to mitigate environmental concerns, even though that may not be the driver [11]. Typically the main driver is the financial potential of the strategy, due to the comparatively competitive sales price for a remanufactured product, compared to other product recovery strategies [26][27[37][40]. However, since remanufacturing operations are typically more labour- intensive than the operations of other recovery strategies, it is often restricted to higher-value product markets [14][15].

Another important driver is cost reduction and the potential energy and material savings range from 30- 90%, leading to significant cost reductions [1]. This can be achieved because the energy used during manufacturing, to produce a part's functionality, also known as embodied energy, is maintained [3][32].

It is not unusual for third party remanufacturers to be the first to anticipate business opportunities, with the Original Equipment Manufacturer (OEM) being the second mover, in order to protect brand quality, or to realize market expansion. Moreover, product recovery strategies allow companies to maintain control over the materials in the product, potentially including critical raw materials. Threats from material supply shortage becomes increasingly apparent over the years [35].

Imperative to the success of remanufacturing activity, is the overlap of remanufactured product demand and the availability of used products which are retrieved, called cores [13]. To secure the return of these used products and to obtain information about quality and quantity, a number of companies have adopted different forms of customer service models, allowing customers to pay for a product's function, or performance results, instead of ownership [4][28][43]. In regards to the design of a product in the remanufacturing context, the most essential requirements are: sufficient potential useful life after use and the ability to restore a product to its original, or higher, state. The first critical contributor to this ability is whether disassembly and reassembly is possible [32]. Also important is a stable product technology profile and the tendency to reach end-of- use due to functional failure [15][27][28]. Designs which can further facilitate remanufacturing are those with the ability to be upgraded, allowing remanufactured products go beyond their original product design specification [5][34].

As societies approach and exceed planetary boundaries for a healthy living environment, it has become increasingly urgent to facilitate businesses to adopt strategies which emit less carbon [36]. For this reason, it is of interest for the Government, businesses and society to equip companies with a set of capabilities to help remanufacturing activity to grow. This paper therefore focuses on presenting a detailed overview of some barriers encountered by remanufacturers in relation to dynamic capabilities. The following section explains the set-up of the qualitative data collection and analysis, including the literature review and a framework for dynamic capabilities, developed to interpret the barriers found during the data collection.

2.3 METHODOLOGY

The set of collected data is derived by conducting qualitative research, through a literature review and by conducting interviews. The data analysis is achieved by mapping the barriers onto a framework for dynamic capabilities, which aims to find patterns and support the drawing of conclusions.

2.3.1 LITERATURE REVIEW

A selection of peer-reviewed literature, published in journals, forms the initial data input for this paper. This literature is collected on Scopus and Web of Science. The titles, abstracts and keywords are searched for the combination of:
((remanufactur* OR "repair W/2 overhaul" OR "extensive refurbishment") AND barrier*).
Using this approach, the search yielded 86 abstracts. The primary selection criterion is that the papers have the potential to reveal barriers or drivers in relation to remanufacturing activities. Also important is that the targeted company uses technical materials'. In this preliminary research, papers with a restriction to the European context were selected to be studied in more detail. An initial scan through the non-European literature did not immediately reveal many additional unique barriers. Following this first filter phase the literature set was reduced to 37 papers of which 16 were included in the overview. This selection is done on basis of their broad and generic view on remanufacturing and their impact.

2.3.2 INTERVIEWS

Since a gap was found regarding soft barriers during the literature review, five in-depth expert interviews were conducted to further explore this topic. Representatives from existing remanufacturers in the following sectors were selected: automotive, IT, photocopiers, industrial robots and building components (Table 2.1). This selection was made to get a mix different of products and therefore different material streams, recovery processes and target markets. But also, the maturity of recovery activities of the companies varied, which helped to assess barriers at different stages. In a semi-structured setting, all facets of the business model were discussed as well as the barrier gap found during literature study.

TABLE 2.1 Remanufacturing experts.

Referral code	Industry	Remanufacturing activity
Interviewee 1	Automotive parts	A third-party and independent remanufacturer of motors and gear boxes
Interviewee 2	IT	A non-for-profit IT company that remanufactures phones and other IT hardware
Interviewee 3	Industrial robots	A third-party and independent remanufacturer of industrial robots
Interviewee 4	Building components	A third-party and independent remanufacturer of building parts like windows
Interviewee 5	Photocopiers	A third-party and independent remanufacturer of IT products like printers

2.3.3 FRAMEWORK FOR DYNAMIC CAPABILITIES

A framework for dynamic capabilities is used to interpret data and draw conclusions. Most of the barriers companies experience result from inadequate or missing capabilities in order to resolve a particular problem. Barriers which cannot be resolved internally are then external barriers, concerning, for example, legislation or sectoral technological readiness. In order to obtain insight in the type of capabilities needed to overcome the identified barriers, the framework of Pavlou & El Sawy for dynamic capabilities in the context of New Product Development (NPD) was used [33]. In the context of remanufacturing 'New Product' does not refer to the pristine nature of a product, but to the value potential of the product, which is 'as good as new'. The work of Pavlou & El Sawy is used to explain the framework in the following text.

In literature two different types of capabilities have been distinguished: operational and dynamic capabilities. Herein a capability is defined as (a collection of) high-level routines. Operational capabilities are sets of routines needed to execute a plan in detail, whereas dynamic capabilities cover routines which contribute to the innovative nature of processes and products, routines where adoption to changes takes in a central position. Dynamic capabilities can be used to adjust misaligned operational capabilities to regain their effectivity. Dynamic capabilities can be divided into the following four (reciprocal) categories:

- Sensing Capability – The ability to recognize, and anticipate on, market opportunities, taking into account internal strength and external opportunities
- Learning Capability – The ability to apply new knowledge to conceptualize and realize ideas resulting from market opportunities
- Integrating Capability – The ability to let newly obtained knowledge become part of the routines of the entire unit
- Coordinating Capability – The ability to find and effectively allocate resources to tasks

2.4 RESULTS

In this section an overview is provided of barriers to remanufacturing based on literature and interviews and their matching dynamic capabilities. First, the results of linking the focal points of the papers with dynamic capabilities are presented, according to the framework of Pavlou and El Sawy, subdivided over the four dynamic capabilities [33]. Thereafter, the four categories of barriers are discussed in more depth.

2.4.1 DYNAMIC CAPABILITIES FOR REMANUFACTURING

The aim of this overview is to describe the focus of the literature which discusses potential areas of improvement for the remanufacturing industry. Even though the focal points of the papers are diverse, they demonstrate a clear pattern of attention paid to each capability. To make this pattern visible an overview is presented, for which the objectives of the papers were linked with the targeted dynamic capability, and this is shown in Table 2.2. A quote has been included from each of the papers, which conveys the link with the capability.

The overview points out that the main focus has been to develop integrating and coordinating capabilities, the more technical capabilities, in order to optimize the ongoing processes. Few papers exist with a core focus on the sensing and learning dynamic capabilities, the softer capabilities.

2.4.2 BARRIERS LINKED WITH CAPABILITIES

2.4.2.1 Sensing capability

The sensing capability, earlier described as a SWOT- like capability, where opportunities provided by the market can be realized by finding the internal strength to anticipate them. It is essential to retrieve the right information from the market and transforming this information into viable business concepts. The barriers relating to the dynamic capability are described next.

Typically, the sales of remanufactured products will take place in different markets from the virgin product sales, mainly due to consumer perception of non- virgin products (Interviewee 1; Interviewee 5). The reduced sales price of remanufactured products merely strengthens this perception. Since the product quality is brought back to as-new, or even better than new, the sales prices could potentially be equally high or even higher. However, offering remanufactured products at 60-90% of the initial sales prices, made possible by more cost-effective operations, can foster a competitive advantage [2]. In the IT-industry the lack of customer acceptance can be turned into a unique selling point when combined with, for example, smart phone user training for elderly people (Interviewee 2). In an example from the building parts industry, remanufacturing has more than doubled the life-time of a window, with a significant lower increase in amortization time, invalidating the suspicion towards remanufactured products (Interviewee 4).

The original product design determines the potential of a product to be remanufactured and this can be accounted for in different ways. On the one hand, changes in product design can be approached in incremental steps, by optimizing a product design for the remanufacturing process. This is further discussed in section 4.2.3. On the other hand, it can also be addressed in a more radical way, by integrating remanufacturability in the conceptual design of a product. The second option, for example, allows design for product upgrades, increasing the economic viability of a product for multiple use cycles. Product design changes have the biggest potential when taken into account during new product development process of the original product (Interviewee 2; Interviewee 3).

Characteristics of the sensing capability of this section are:

- The ability to develop new value propositions for a previously owned product, which the market is willing to accept
- The ability to understand the consumer needs of the new target group and anticipate on this by offering for example extra services.
- The ability to set a price for a previously owned product, which the market is willing to accept
- The ability integrate design for remanufacturing on a conceptual level into the new product development process

TABLE 2.2 Research objectives linked with targeted capabilities.

Article details		Dynamic capabilities			
Author	**Year**	**Sensing capability**	**Learning capability**	**Integrating capability**	**Coordinating capability**
Thierry, M., Salomon, M., Nunen, J . Van, Wassenhove, L. van	1995	"Analyzing these [Product Recovery Management] PRM opportunities and threats should be the first step for any company that is (forced to get) involved in PRM."			
Ferrer, G.	2001	„This paper analyzes a generic widget, to understand what makes a strong or weak candidate for a remanufacturing operation."			„This paper analyzes a generic widget, to understand what makes a strong or weak candidate for a remanufacturing operation."
Ijomah, W.L., Childe, S., McMahon, C.	2004				„This paper presents a robust remanufacturing definition and a comprehensive generic remanufacturing business process model that can be used to improve remanufacturing expertise."
Toffel, M.W.	2004	„This article has described several factors that motivate manufacturers to engage in voluntary product recovery: reducing production costs, enhancing brand image, meeting customer demands, protecting aftermarkets, and preempting regulations."			
Sundin, E., Bras, B.	2005	„[T]he objective of this study was to investigate and evaluate in what manner products can be designed in order to facilitate remanufacturing and functional sales"			

TABLE 2.2 Continued.

Article details		Dynamic capabilities			
Author	**Year**	**Sensing capability**	**Learning capability**	**Integrating capability**	**Coordinating capability**
Guide, V.D.R., Jr, Li, J.	2010		„In this research, we use a novel research strategy by auctioning products donated by Robert Bosch Tools, NA and Cisco Systems, Inc. to determine the difference between consumers' willingness to pay (WTP) for new and remanufactured products and to help assess the extent of cannibalization of new product sales by remanufactured products"		
Sundin, E., Lee, H.M.	2012				„The aim of this paper is to explore the environmental performance of remanufacturing in comparison to material recycling and manufacturing of new products. The different kinds of studies in quantifying the environmental impacts of remanufacturing were reviewed. Investigations made were relating to the kinds of products, the system boundaries and the measurements taken."
Goepp, V., Zwolinski, P., Caillau, E.	2014				„The objective of this paper is therefore to develop such models (i.e. eco-design process and data models) for sustainable design of remanufactured products by instantiating and completing the reference model of the eco-design process in general, proposed in."

TABLE 2.2 Continued.

Article details		**Dynamic capabilities**			
Author	**Year**	**Sensing capability**	**Learning capability**	**Integrating capability**	**Coordinating capability**
Kurilova-Palisaitiene, J., Sundin, E.	2014				„The need to improve vital indicators remanufacturing business is of the revealed. The major remanufacturing challenges are identified and classified into three categories: product quality, lead time and inventory level challenges."
Matsumoto, M., Yang, S., Martinsen, K., Kainuma, Y.	2016			„Research on forecasting, product scheduling, capacity planning, production planning, inventory management, and others for remanufacturing is necessary, and further integrated methodologies are expected to be developed"	„various conditions such as OEM and/ or remanufacturer costs/benefits, demand side acceptance, legislation, and other relevant factors, have to be coordinated. This article highlighted four topics on R&D for remanufacturing."
D'adamo, I, Rosa, P.	2016				„This paper aims to improve the understanding of management practices concerning remanufacturing activities."
Hartwell, I. & Marco, J.	2016			„This paper addresses two of the barriers, often cited, that inhibit organizations from adopting a remanufacturing strategy—ambiguity regarding the meaning of remanufacturing and uncertainty in how to manage intellectual property (IP)."	

TABLE 2.2 Continued.

Article details		Dynamic capabilities			
Author	**Year**	**Sensing capability**	**Learning capability**	**Integrating capability**	**Coordinating capability**
Esmaeilian, B., Behdad, S., Wang, B.	2016			„Recent research in remanufacturing is explored under the following categories: • Business models [..] • Production, scheduling and inventory planning. • Determination of recovery options. • Environmental and cost analyses of remanufacturing operations. • [...] product design. • Industrial case studies."	
Lieder, M., Rashid, A.	2016				„[...] major part of these attempts has been lacking a systematic approach [...]"
Karvonen, I., Jansson, K., Behm, K., Vatanen, K., Parker, D.	2017			"[...] to identify and sort out central barriers that currently prevent large scale capitalisation of remanufacturing potential."	"[...] to identify and sort out central barriers that currently prevent large scale capitalisation of remanufacturing potential."
Zlamparet, G.I., Ijomah, W., Miao, Y., Kumar Awasthi, A., Zeng, X., Li, J.	2017			„This paper will articulate the remanufacturing typologies from different aspects, as implementation strategies, and a strategic solution for sustainable global WEEE management [...]"	
Total		4	1	5	9

2.4.2.2 Learning capability

Absorbing new knowledge is key for the learning capability. It functions as the link between the data collected from the market and incorporating it into operations. New knowledge needs to be transformed into meaningful and useful information for a company.

A misalignment has been observed between existing educational programs and practice. According to three out of five interviewees, education of staff happens in-house since the existing labor market (and the corresponding educational activity) is strongly focused on linear business activities (Interviewee 1; Interviewee 3; Interviewee 5). Even more so, two interviewees believe that education can only take place in practice (Interviewee 1; Interviewee 3). In addition, they see a competitive advantage in such knowledge being hard to obtain.

In the literature there are gaps regarding the learning capability of remanufacturers. Only one of the articles is fully devoted to learning. It studies a method with the aspiration to learn about consumers' willingness to pay for remanufactured products [18]. Another paper recommends the development of learning materials in general, with an emphasis on cross-disciplinary teaching [21].

Characteristics of the learning capability of this section are:

- The ability to disseminate knowledge to (new) colleagues as a compensation for the fact no formal education exists
- The ability to convert the scarcity of education into competitive advantage
- The ability to (apply methods to) draw learnings from consumer behavior
- The ability to convert learnings from one industry to another

2.4.2.3 Integrating capability

Before knowledge is operationalized it needs to be adjusted to the context, adopted and put into practice by those allocated to the task considered. The interrelations between the entities of groups are central to this capability and determine its success. A thin line exists between this and the previous capability, allowing certain characteristics to fit with both capabilities, for example when looking at product design or education. The capability will be further explained using the following barriers.

In order to maintain a product's original brand identity with regards to product quality, it is vital to produce good quality remanufactured products. Re- certification can be a means to ensure this quality and is in some cases inevitable, often leading to additional costs. Generally, tests to generate proof of sufficient remaining useful life, are scarce or not economically viable [1]. In-house experimentation labs are, possibly, seen as the answer to this problem (Interviewee 1) [28].

Design for remanufacturing is rarely considered during new product development. Occasionally, during disassembly, no other option exists but to destructively break connections between parts, causing damage to an otherwise useful part. As discussed in section 4.2.1, value destruction of this kind can easily be avoided during new product development. Moreover, products have tended to increase in complexity, driving up the difficulty of remanufacturing operations as well, especially in the absence of good alignment with a product development department (Interviewee 1). Since adopting design for remanufacturing guidelines has the potential to increase costs, a balance needs to be found between this investment and the generated value during remanufacturing operations. Options to design for product upgrades, potentially affecting markets positively, are less likely to happen if not taken into account during initial NPD (Interviewee 2; Interviewee 3).

Apart from tendencies of products to degrade heterogeneously, the cleanliness of a product coming back from the market also highly varies. Often, traces of use, oil in particular, contaminate clean transportation and workshop equipment. Some remanufacturers have developed product packaging in order to keep equipment clean.

Technological readiness with regards to closed loop business activities is low. For example, there is limited facilitation to retrieve technical data from the products to support inspection or testing, which also has an effect on the development of metrics for remanufacturing.

Remanufacturing tends to be labor intensive, because of the diversity of tasks and difficulty of implementing automated processes. Therefore, the potential for job creation is often put forward as a one of the positive effects of remanufacturing in academic literature. This is underscored by the research performed by the European Remanufacturing Network [30][13][28][29][31]. However, the exact effect on job creation remains unclear [1]. Besides the question of the number of jobs that could be created, considerations of the working conditions and the quality of work, should not be missed out. Presley argues safety measures need to be always carefully addressed. In particular during disassembly, where worn out, damaged or corroded components can prove troublesome, or when handling chemical and toxic materials [36].

Characteristics of the integrating capability of this section are:

- The ability to demonstrate a certain product quality by means of collecting proof of remaining product lifetime
- The ability to optimize product design for remanufacturing operations

- The ability to find an economically viable balance between increases in product complexity and standardization
- The ability to find an economic optimum between design efforts for remanufacturing and value generated during remanufacturing operations
- The ability to transport cores to the remanufacturing facility, without contaminating surroundings
- The ability to recruit, maintain and develop a team of trained staff
- The ability to provide safe conditions when working with used products

2.4.2.4 Coordinating capability

Once staff are sufficiently trained and developed to the required level, the day-to-day operations need to be effectively executed. The coordinating capability ensures the management of the available resources with respect to tasks which need to be performed. Barriers in relation to this capability are discussed next.

With regards to offering products at lower sales prices, OEMs need to take into account the threat of cannibalization of existing markets [18]. Cannibalization can take place when remanufactured products infiltrate markets of original OEM products, lowering their market share [28]. The real advantage of sales of remanufactured products will become apparent when product remanufacture reaches an economy of scale, which is prevented by various barriers like consumer acceptance and sourcing of cores [13]. In addition, the financial models supporting remanufacturing need dedicated research (Interviewee 4).

Resource information for remanufacturing is hard to obtain. Whereas information like location, availability and price of resources are fixed or predictable for virgin product manufacturing. Information about the time of release of resources from the market, in the form of cores, is highly unpredictable [21][37]. It depends strongly on the real life-time of products and the types of products present in the field. Matching the information regarding the availability of resources with the demand for remanufactured products is an additional challenge. In Business to Consumer (B2C), markets product returns are even harder to control [21]. The products are more difficult to locate and tend to be scattered out through the market than in Business to Business (B2B) markets.

Careful selection prior to collection can prevent unnecessary transportation of cores. Cores which do not meet requirements of a certain product type, such as for quality or timing, can be selected out. Making well-informed acquisition decisions, however, requires extensive data collection, whereas particular data sets might not be available at all. Examples of useful data could, for instance, be maintenance and repair data (Interviewee 1). In the IT industry the requirement for the ability to delete user data is crucial. If this option is not available, then the product is rejected for remanufacturing (Interviewee 2). Further diagnostics and inspection will take place during remanufacturing operations, to prevent sending faulty products to the market and to avoid unnecessary value destruction [10].

Spare parts are ideally sourced from similar end- of-life products since original parts are more expensive [27]. It can be noted, that maintaining a growing inventory of spare parts retrieved the field, can result in a significant increase of costs [1] (Interviewee 2). Close collaboration within the supply chain can help bring back the costs associated with the provision of spare parts, especially when product variety increases (Interviewee 1) [21] [28]. When it comes to collaboration between third-party remanufacturers and OEMs, the relationship could be strengthened. OEMs often do not appoint contact persons responsible for remanufacturing-related issues (Interviewee 1). When this is done, the third- party remanufacturers can receive important information, but in exchange, they can provide valuable user and design feedback to the OEM (Interviewee 2).

Government policy does not support remanufacturing sufficiently. Rules and regulations can prohibit remanufacturers from further developing business activities; one example is the possibility to enter international markets (Interviewee 1; Interviewee 2). A possible rebound effect when new rules are imposed, is that new regulation is mainly developed for large manufacturers, complicating business for smaller remanufacturers (Interviewee 5). Importantly, there are no dedicated standards or certifications available (Interviewee 5). This is likely to be affected by the ambiguous nature of the definition of the field (Interviewee 2). A two-step approach was suggested in an interview, to start with a more widely applicable standard, and to further specify this for different industries (Interviewee 3). It would make a great difference to the perceived quality by the consumer (Interviewee 5).

Characteristics of the coordinating capability are:

- The ability to coordinate sales of remanufactured product, avoiding cannibalization of sales of original products
- The ability to ramp up sales of remanufactured products on a large scale by managing influencing factors like consumer expectations and core sourcing
- The ability to develop financial models to support product remanufacturing
- The ability to obtain information about cores, like location, availability and costs
- The ability to timely locate available cores, matching the customer’s demand
- The ability to make well informed core acquisition decisions

- The ability of having spare parts available when needed
- The ability to collaborate within the supply chain to exchange information or spare parts

4.5 DISCUSSION AND CONCLUSION

In order to grow the remanufacturing industry, businesses need to know what dynamic capabilities they need to develop to overcome the broad range of barriers. This paper presents the results of an analysis of barriers linked to dynamic capabilities, to point out what dynamic capabilities remanufacturers require. The overview resulting from this analysis made clear that the focus in literature thus far has predominantly been on the technical capabilities, developing integrating and coordinating capabilities. Soft capabilities, like sensing and learning, remain less developed. Interviews were conducted to further investigate the need for soft capabilities.

Input found in literature regarding sensing and learning capabilities was limited. The main topics addressed for the sensing capability were determining the right price for remanufactured goods and the potential of integrating design for remanufacturing into the product development process. While additional barriers for the sensing capability found during interviews concerned the ability to develop new value propositions for previously owned products and to anticipating on additional consumer needs, by for example developing services.

Regarding the learning capability market analysis for insights in willingness to pay as well as the development of educational tools and cross- disciplinary learning was present in the literature. Interviewees additionally discussed the need for educational programs tailored to remanufacturers. Fewer discrepancies between theory and practice were identified for the technical capabilities.

The recommendation for further work is the development of tools and methods to improve existing sensing and learning capabilities, to allow remanufacturers make use of them effecitively. Moreover, more empirical research is needed to expand the exploration of the field of soft capabilities and find out whether the overview of soft capabilities is complete.

ACKNOWLEDGEMENT
This paper was made possible by using results of two EU funded EIT KIC Raw Materials projects, called: ‘Key success factors for re-use Networks’ (RUN) and ‘Bridging the raw materials knowledge gap for reuse and remanufacturing professionals’ (ReUK).

Further support from EIT RM project RemanPath is acknowlodged. Prior work from EU Horizons 2020 project European Remanufacturing Network, under grant agreement number 645984, is also acknowledged.

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CHAPTER 3

CIRCULAR BUILDING PRODUCTS, A CASE STUDY OF SOFT BARRIERS IN DESIGN FOR REMANUFACTURING

This chapter has been published as:
Boorsma, N., Tsui, T., & Peck, D. (2019). Circular building products, a case study of soft barriers in design for remanufacturing. In *Proceedings of the International conference of Remanufacturing.*

ABSTRACT

The building industry contributes approximately 40% of the total waste generated in the European Union (EU). Across the EU a shift towards closing product loops, as part of a transition towards a circular economy, is considered as a promising approach to reduce waste and pollution. Remanufacturing is an example of a strategy which supports this approach. It is applied in various industries that are intensive materials users. It has, however, not been applied in the building sector on a large scale. This is unfortunate, given that buildings offer several favorable key conditions for remanufacturing, such as providing access to high volumes of products, containing high material value, at fixed locations. This paper aims to analyze the human, soft issues for design for remanufacturing at the design stage of products used in the built environment. The methodology used consisted of a literature review followed by a workshop with twenty professionals from the building industry. The workshop approach was developed in a series of EU funded projects. The paper concludes by proposing that, even though the technical barriers to remanufacture building products are low, the soft barriers in the shift towards remanufacturing, on a larger scale, appear to remain high.

3.1 REMANUFACTURING DESIGN FOR BUILDING PRODUCTS

The practice of remanufacturing is not new, nor is it novel. In terms of materials and energy, the closing of product loops, in this case extending the life of the product via remanufacturing, is considered a promising approach to cut down pollution and in particular reduce CO2. Together with reducing energy use and pollution production, remanufacturing reduces the dependence of primary (geological sourced) material use.

The closed loop, product life extension, lower impact, approach fits within the frame of the circular economy. Within the EU, Circular Economy (CE) is a relatively new policy concept that has been brought into the spotlight by the European Commission's CE Action Plan in 2015 (EC, 2015). There are diverging views on what the EU, Member States and other stakeholders mean by CE, with no universally agreed definition. CE approaches have only been incorporated in research and innovation activities in recent years.

The EU circular economy approach not only seeks to help meet the EU member states commitments to reducing greenhouse gas emissions and reducing primary material import dependency, but it also supports the commitments to agenda 2030 via the UN Sustainable Development Goals (SDG's). The driver from the policy commitments is well stated, but policy does not translate to business activity easily.

Remanufacturing is an example of a strategy which supports this approach. It is applied in various industries that are intensive materials users. It has, however, not been applied in the building sector on a large scale. This is unfortunate as a building contains high volumes of products, at fixed locations, containing high value materials. Moreover, even though many buildings are bespoke, building products are standardized, creating further opportunities for remanufacturing.

Design activities of companies to develop building products are generally centered around a single use. However, for those companies who actively engage in remanufacturing operations, it might prove profitable to also incorporate 'multiple use' thinking in their new product development process. Designing for multiple use can, for example, incorporate Design for Remanufacturing (DfRem) methods during the new product development process. DfRem is a strategy to design a product that is optimised to be remanufactured. The aim is to restore the products (known in remanufacturing activitities as 'cores') to the original performance specification, with a warranty, in box, as new. To help unpack the factors which influence this process, the following central research question was formulated: *For remanufacturing, what is the role of soft barriers at the product development stage?*

3.2 METHODOLOGY

The methodology to conduct this research is built up in three parts.

Firstly, the description of a generic method for product development was developed to act as a reference point for the study. This was done by consulting literature by leading authors in the field of product development and product design. This was complemented by reviewing the published product development models as applied in education for industrial design engineering at the TU Delft, The Netherlands.

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Secondly, an overview of current design for remanufacturing methods and design rules from literature was consulted. The literature was not specific to the building industry and covered a range of sectors. It was observed that remanufacturing literature from the perspective of the building sector was absent in the searches carried out. An overview of approaches and design rules for design for remanufacturing was selected to give a summary of what is published in literature.

Thirdly, the scope of the research and the framework to analyze the case is introduced. This was also conducted via literature review. The search terms which were used in the search engines of Scopus to find an applicable framework, were 'drivers' and 'product innovation'. For the selection of the framework the following criteria were used:

- The framework should go beyond technical product characteristics
- The framework should be based on literature and tested in practice
- The framework should be acknowledged within the academic field

And finally, a case study approach is deployed, using a case from the building industry, which is analysed using the proposed framework. The case data was collected through an EU funded H2020 workshop and follow up conversations with the company. The case approach follows the structure of shorter case study interviews as described in Yin (2018), by using a protocol in the form of (unpublished) worksheets and structure documents from the EU projects, these are shown in appendix 3-A.

3.3 NEW PRODUCT DEVELOPMENT AND THE BUILDING INDUSTRY

3.3.1 THE NEW PRODUCT DEVELOPMENT PROCESS

In order to determine where and how soft issues influence the design stage, the new product development methodology was consulted. However, before discussing the design methodology, it is important to introduce the supply chain for building parts.

To explain this, the facade equipment manufacturer was used as an example. First, the typical legal process of constructing a building in the Netherlands will be described; then, stakeholders involved in the process of constructing a building will be addressed; and finally, building product manufacturers' position in the system will be explained. Even though an example from the Netherlands was used, the basic frame is applicable in other parts of the world.

3.3.1.1 Constructing a building

To start off with, a building should be seen as an assemblage of products, instead of being one single product. These products have different life cycles, which vary from a few years (services) to a few hundred years (structure), as shown in Figure 3.1 (Brand, 1995). These products include the structure, skin (facade), space plan (such as interior walls, partitions, finishes), and services (such as lighting, water, heating, and ventilation systems) (ibid.) and are designed by different product manufacturers. In this system, a facade equipment manufacturer would provide parts for the "skin" of the building.

When a client, such as a real estate developer, seeks to construct a building, a contract is signed with a contractor. The contractor then commissions an architect and consultants to design the building, as seen in Figure 3.2 (Azcarate-Aguerre et al., 2017). After the building has been designed, the contractor, architect, and consultants jointly select suppliers for the required materials and products in the building, examples of these materials are steel beams, windows, roof tiles and air conditioning systems. Next, architectural drawings are produced, specifying the final selection of products and suppliers for the construction process.

In their turn, suppliers, such as facade equipment manufacturers, manufacture products and sell them to contractors. The product will be mounted onto the building by either the contractor or the supplier. In some cases, companies have their own construction team.

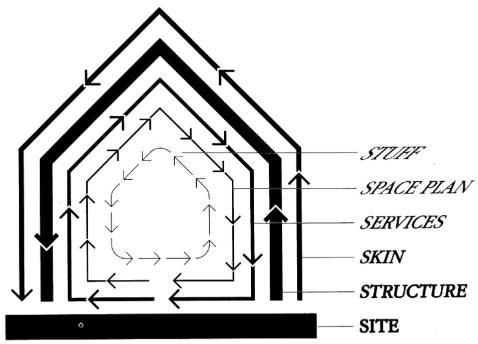

FIGURE 3.1 Shearing layers of products within a building's life cycle (Brand, 1995).

3.3.1.2 The development of building parts

An architect does not design every window, roof tile, column and heater in a building. The architect's role is to design the form, materiality and organization of the building. After this the selection of building products, which fit into the architectural vision, takes place. Although every building looks unique, the products that make up the building are oftentimes mass- produced commercial products. This description is a generalized view of the building industry. The processes to develop a building are not standardized, which means that legal systems and design processes can differ.

Often architects work closely together with suppliers to modify existing products for optimal integration with the building. And, at times, architects design their own building products, such as facades, stairs or doors. However, in general, most building products are not designed by architects: they are designed, manufactured, marketed, sold and distributed like other products in commercial markets.

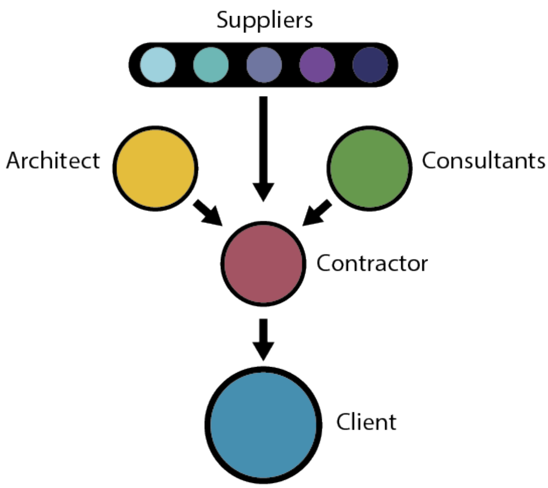

FIGURE 3.2 Legal system of a typical building contract in the Netherlands (Azcarate-Aguerre et al., 2017).

3.3.1.3 New product development in commercial product markets

Several leading authors in the literature of product design engineering have generated theoretical models, and refined each other's models, for new product development. This section will give a short description of product design methodology.

According to Ulrich and Eppinger (1995), characteristics which determine the success of new product development are product quality, product costs, development costs and development capability. Ulrich and Eppinger argue, that the departments carrying out the activities of marketing, design and manufacturing generally take in a central position in the product development process (ibid.). Where marketing forms the link between company and market; design (engineering and industrial design) is the embodiment of the artifact fulfilling the need of the consumer; and manufacturing is responsible for the design of the production process. In the product development flow chart, the authors distinguish six stages within the process, as shown in Figure 3.3, in which each previously mentioned department has its own activities.

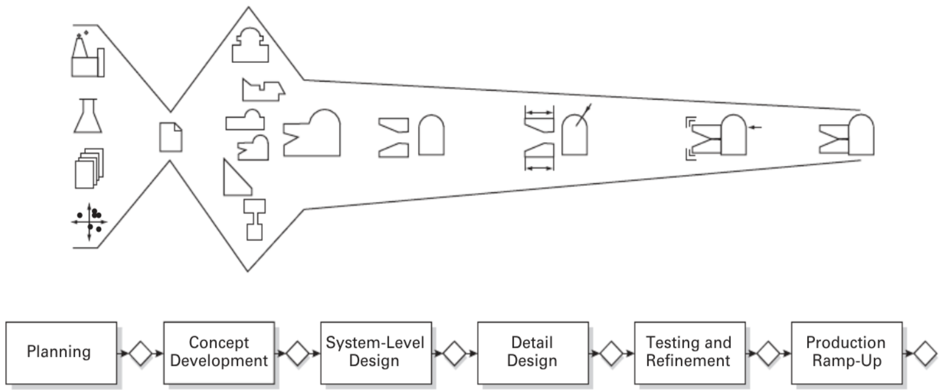

FIGURE 3.3 The product development flow chart, by Ulrich and Eppinger (1995).

Roozenburg and Eekels (1991) have also developed a theoretical representation of the product development process. This model is constructed using the same elements as the model of Ulrich and Eppinger, in which adjustment are made to the process flow, acknowledging that several processes take place in parallel. This model can be found in Figure 3.4, starting from 'Formulation goals and strategies' and ending at 'Use'.

Buijs (2003; 2012) further developed the model of Roozenburg and Eekels, specifying the process steps in more detail and dividing the product development into four phases in his Delft Innovation Model. The four phases he distinguishes are: Fuzzy Front End of innovation, New Product Development, Muddy Back End and Product Use (Buijs, 2007).

- Fuzzy Front End - Identification and anticipation on market opportunities (Buijs, 2007; Koen et al., 2001)
- New Product Development - Transformation of a design brief into a physical product (Buijs, 2012)
- Muddy Back End - Product launch and market introduction (Buijs, 2007)
- Product Use - Origin of need for new product innovation cycle (Buijs, 2007)

Balkenende & Bakker (2018) have adapted the representation of Roozenburg and Eekels to meet the present-day requirements for responsible product development, by adding recovery as a final step (Figure 3.4). This step is added to trigger designers to incorporate decisions about the possible end-of-life scenarios during the design phase.

With this adaptation the stages of the Product Innovation Process are enriched by the task of opportunity and solution finding for recovery operations, allowing a company to discover potential to improve its resource efficiency.

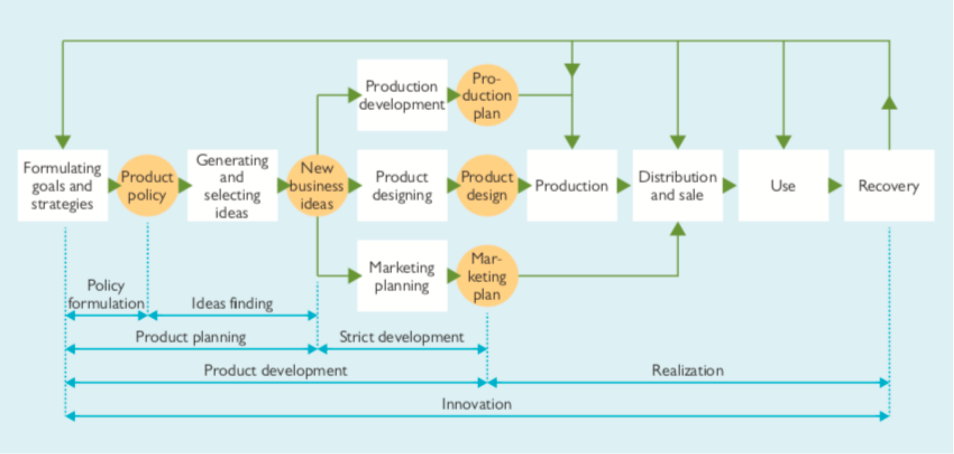

FIGURE 3.4 The Product Innovation Process by Roozenburg and Eekels (1991), with the recovery step added by Bakker, adapted from Balkenende & Bakker (2018).

3.3.2 TECHNICAL DESIGN REQUIREMENTS FOR REMANUFACTURING

Applying technical design for remanufacturing guidelines does not necessarily change the design process, it more likely changes or adds requirements to the product architecture and design. These technical design requirements are extensively described in literature. An overview of approaches and design rules for design for remanufacturing was selected to give a summary of what has been published in literature. The first overview contains approaches for design for remanufacturing as summarized by Hatcher et al. (2011), and can be found in Table 3.1. The second overview contains a list of design rules for X, generated by Bovea & Pérez-Belis (2018) and can be found in Figure 3.5. The second part of the overview consists of detailed design guidelines for designing products for remanufacturing.

TABLE 3.1 Design for remanufacturing approaches table was adopted from Hatcher et al. (2011).

Design for remanufacturing approaches	
Approach	**Authors**
DfRem metrics	Bras and Hammond (1996); Amezquita et al. (1995)
Fastening and joining selection	Shu and Flowers (1999)
RemPro matrix	Sundin (2004)
REPRO2	Zwolinski et al. (2006); Zwolinski and Brissaud (2008); Gehin et al. (2008)
DfRem guidelines	Ijomah et al. (2007a,b); Ijomah (2009)
DfRem metrics	Willems et al. (2008)
Hierarchical decision model	Lee et al. (2010)
Energy comparison tool	Sutherland et al. (2008)
Component reliability assessment	Zhang et al. (2010)
Modularisation	Ishii et al. (1994); Kimura et al. (2001)
FMEA	Lam et al. (2000); Sherwood and Shu (2000)
Platform design	King and Burgess (2005)
Active disassembly	Chiodo and Ijomah (2009)
Design for environment tools	Pigosso et al. (2009)
Quality Function Deployment (QFD)	Yuksel (2010)

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3.3.3 FRAMEWORK OF PREDICTORS FOR NEW PRODUCT PERFORMANCE

Manufacturing companies operating in commercial markets in general, require a diverse set of capabilities to run their operations. These capabilities can be divided into two main categories. The first category refers to soft capabilities, which are routines needed to create new, or redirect existing, operational capabilities in order to support innovation efforts (Daneels, 2011; Pavlou & El Sawy, 2011; Teece et al., 1997). The second category refers to hard capabilities, which are sets of routines needed to execute those business activities which are key to delivering a promised offer to the customers (Pavlou & El Sawy, 2011; Teece et al., 1997).

3.3.3.1 A focus on soft issues

In a previous paper, 16 journal papers revealing barriers to remanufacturing were analysed using the dynamic capabilities model (Boorsma et al. 2018). This analysis pointed out a focus predominantly on the hard capabilities (integrating, coordinating), and limited focus on soft capabilities (sensing, learning). This paper therefore deep dives into the soft capabilities of a case study in the building industry. According to Pavlou & El Sawy, the sensing capabilities include capabilities related to identifying market opportunities and being responsive to market trends. The learning capability comprises capabilities related to obtaining new knowledge and creative new thinking.

3.3.3.2 Predictors of new product performance

An analysis of the soft barriers for the selected case was made using the model for 'Predictors of new product performance' generated by Henard & Szymanski (2001)

(Table 3.2). The assumption supporting this choice, is that even though remanufactured products contain previously used content, when put on the market they are subjected to the same influences as new products are. For this reason, the commercial potential of remanufactured products will be evaluated using a framework of predictors for new product performance. The authors acknowledge that the framework has been adjusted since 2001, more extensive literature review is required to analyze the successive versions.

	(Dowie and Simon, 1994)	(Boothroyd and Dewhurst, 1989)	(Graedel and Allenby, 1996)	(Behrendt et al., 1997)	(Al-Okush and Caudi, 1999)	(*UNE 150062 IN, 2000*)	(Chen, 2001)	(Hata et al., 2001)	(Desai and Mital, 2003)	(Sundin, 2004)	(Sundin and Bras, 2005)	(Active Disassembly Research, 2005)	(Truttmann and Rechberger, 2006)	(Zuidwijk and Krikke, 2008)	(Bogue, 2007)	(Mital et al., 2009)	(ECMA, 2010)	(Ijomah and Chiodo, 2010)	(Hatcher et al., 2011)	(Huang et al., 2012)	(Hultgren, 2012)	(Sundin et al., 2012)	(Peeters et al., 2012)	(Watelet, 2013)	(Pérez-Belis et al., 2013)	(Lee et al., 2014)	(Wang, 2014)	(Poppelaars, 2014)	(Arnette et al., 2014)	(Mulder et al., 2014)	(Smith and Hung, 2015)	(Sawanishi et al., 2015)	(Sihvonen and Ritola, 2015)	(Go et al., 2015)
1. Create a modular design	•		•		•		•	•				•	•		•	•		•										•		•				•
2. Locate unrecyclable parts in areas easy to remove	•			•						•								•			•		•		•									•
3. Minimise the number of components				•	•		•		•		•				•	•		•										•						•
4. Ensure resistance to dirt accumulation										•																		•		•				
5. Use standardised components												•			•										•			•						
6. Minimise product variants	•														•			•																
7. Improve the ratio between the labour required to retrieve a component and its value																		•										•						
8. Avoid moulding or fusing incompatible materials	•																•	•			•				•			•						•
9. Consider the use of an active disassembly															•			•					•					•						•
10. Use standardised joints											•	•						•										•		•				
11. Prioritise latching to screws and bolts						•																												
12. Unify screw heads						•																												
13. Minimise types of connectors	•					•	•			•		•						•		•			•	•	•			•				•		•
14. Use fasteners rather than adhesives	•									•			•		•	•	•	•		•			•	•				•		•				•
15. Make joints visible and accessible	•			•						•	•				•	•	•	•					•					•						•
16. Use fasteners that are easy to remove	•	•		•									•			•		•																•
17. Minimise the number of joints and connections	•			•			•								•	•		•					•										•	•
18. Minimise the number of tools and use push/pull processes																								•								•		
19. Use unseparable joints for components made of the same or a compatible material	•	•					•	•								•		•						•	•			•						•
20. Use materials with low environmental impact										•							•												•					•
21. Use thin walls with nerves (plastics)						•																												
22. Use components made of pure materials			•						•			•														•		•						•
23. Minimise the number of different materials	•		•			•	•	•	•			•			•		•	•		•	•			•		•	•	•						•
24. Avoid secondary finishes and coatings						•						•			•	•					•			•		•		•		•				•
25. Use recycled and recyclable materials	•	•	•		•	•	•			•					•		•				•							•						•
26. Use materials resistant to cleaning processes for components to be reused																		•								•		•						
27. Reduce the material content and energy required in the manufacturing process					•	•	•			•					•													•		•				
28. Ensure the identification of materials using material code marks	•				•	•	•			•						•	•								•		•	•					•	
29. Minimise the use of toxic or hazardous materials	•	•	•	•		•	•								•		•							•				•	•	•				•
30. Use unplated metals for recycling purposes												•																						•
31. Use low alloy metals for recycling purposes												•													•									•
32. Use cast irons for recycling purposes												•													•									

	(Dowie and Simon, 1994)	(Boothroyd and Dewhurst, 1989)	(Graedel and Allenby, 1996)	(Behrendt et al., 1997)	(Al-Okush and Caudi, 1999)	(*UNE 150062 IN, 2000*)	(Chen, 2001)	(Hata et al., 2001)	(Desai and Mital, 2003)	(Sundin, 2004)	(Sundin and Bras, 2005)	(Active Disassembly Research, 2005)	(Truttmann and Rechberger, 2006)	(Zuidwijk and Krikke, 2008)	(Bogue, 2007)	(Mital et al., 2009)	(ECMA, 2010)	(Ijomah and Chiodo, 2010)	(Hatcher et al., 2011)	(Huang et al., 2012)	(Hulteren, 2012)	(Sundin et al., 2012)	(Peeters et al., 2012)	(Watelet, 2013)	(Pérez-Belis et al., 2013)	(Lee et al., 2014)	(Wang, 2014)	(Poppelaars, 2014)	(Arnette et al., 2014)	(Mulder et al., 2014)	(Smith and Hung, 2015)	(Sawanishi et al., 2015)	(Sihvonen and Ritola, 2015)	(Go et al., 2015)
33. Use components and materials with verified reliability																														●				
34. Do not combine components that have different life spans								●																									●	
35. Avoid using parts that require frequent replacement/repair	●		●		●	●	●			●		●	●		●			●						●				●					●	●
36. Minimise length of wires and cables							●																											
37. Minimise weight of components	●						●								●		●							●				●						●
38. Use components sized for easy handing							●				●												●	●				●						
39. Maximise the accessibility of components	●								●	●					●			●	●			●	●	●	●			●						●
40. Avoid dismantling parts from opposite directions							●															●												
41. Simplify the product structure	●			●			●		●				●		●			●				●		●	●									
42. Build monitoring equipment into the system																														●				
43. Ensure that the fewest possible technicians are required to perform a maintenance task																														●				
44. Position components that often need to be maintained closely and in an easily accessible place																														●				
45. Eliminate the need for special disassembly procedures				●						●			●		●	●	●	●																●
46. Use simple and standardised tools	●			●											●		●											●						●

FIGURE 3.5 Design for remanufacturing guidelines table, adopted from Bovea & Pérez-Belis (2018).

3.4 CASE COMPANY: A WINDOW SHADE MANUFACTURER

To gain more insight in the full range of soft barriers affecting remanufacturing operations, the case of a facade equipment manufacturer was analyzed. The selected company for this analysis is a manufacturer of high-end window shades. The company supplies products to the contractors executing the construction of a building. It is a mature company, with 500+ employees, established 50+ years ago and it participates in the Facade Leasing Research project at TU Delft. The company is currently exploring opportunities for remanufacturing within its industry. The case data was collected through an EU funded workshop and conversations with the company during the workshop.

The workshop was given on 22-Jan-2019, in the Faculty of Architecture, TU Delft, the Netherlands. 22 people participated, mostly managers from SMEs in the building industry, but also academics with related research interests.

TABLE 3.2 Predictors of new product performance, adapted from Henard & Szymanski (2001).

Predictors of new product performance	
Predictor	**Definition**
Product characteristics	
Product advantage	Superiority and/or differentiation over competitive offerings
Product meets customer needs	Extent to which product in perceived as satisfying desires/ needs of the customer
Product price	Perceived price-performance congruency (i.e., value)
Product technological sophistication	Perceived technological sophistication (i.e., high-tech, low-tech) of the product
Product innovativeness	Perceived newness/ originality/ uniqueness/ radicalness of the product
Firm strategy characteristics	
Marketing synergy	Congruency between the existing marketing skills of the firm and the marketing skills needed to execute a new product initiative successfully
Technological synergy	Congruency between the existing technological skills of the firm and the technological skills needed to execute a new product initiative successfully
Order of entry	Timing of marketplace entry with a product/ service
Dedicated human resources	Focused commitment of personnel resources to a new product initiative
Dedicated R&D resources	Focused commitment of R&D resources to a new product initiative
Firm process characteristics	
Structured approach	Employment of formalized product development procedures
Predevelopment task proficiency	Proficiency with which a firm executes the pre-launch activities (e.g., idea generation/ screening, market research, financial analysis)
Marketing task proficiency	Proficiency with which a firm conduct its marketing activities
Launch proficiency	Proficiency of a firm's use of technology in a new product initiative
Reduced cycle time	Proficiency with which a firm launches the product/ service
Market orientation	Reduction in the concept-to-introduction timeline (i.e., time to market)
Customer input	Incorporation of customer specifications into a new product initiative
Cross-functional integration	Degree of firm orientation to its internal, competitor, and consumer environment
Cross-functional communication	Level of communication among departments in a new product initiative
Senior management support	Degree of senior management support for a new product initiative
Marketplace characteristics	
Likelihood of competitive response	Degree/ likelihood of competitive response to a new product introduction
Competitive response intensity	Degree, intensity, or level of competitive response to a new product introduction (also referred to in the literature as market turbulence)
Market potential	Anticipated growth in customers/ customer demand in the marketplace

The participants of the workshop were mainly from the building facade sector in Western Europe, and were technical managers, business developers, engineers, and architects. Details about the companies joining the workshop can be found in Table 3.3.

The five-hour workshop started with two presentations by TU Delft, followed by two exercises in which participants got into groups of 2-3 to understand how remanufacturing could be implemented into their own companies using the worksheet in appendix 3-A. The workshop ended with all participants sharing their final thoughts and the most important findings from their day.

TABLE 3.3 Details of workshop participants.

Overview of workshop participants		
Company type	**Description**	**Product example**
Facade shading manufacturer	Manufacturer of high end, bespoke shading products for facades	Motorized sun shading for facades on high-rises
Facade manufacturer	Manufacturer of standardized facade products, including windows and integrated building services	Window unit
Building material manufacturer	Manufacturer of bio-based, non-structural, planar building materials	Bio-based interior wall
Building contractor	Builder and demolisher of buildings on a contractual basis	Service - construction and demolishing buildings
Architecture office	Designer of buildings, with interest on circular design	Service - building design

3.4.1 AN INTRODUCTION TO REMANUFACTURING BUILDING PRODUCTS

Although building products are similar to non- building products, several distinguishing factors can potentially form barriers to remanufacturing. Firstly, building products are part of the large supply chain of an entire building. Since buildings are an assemblage of products, the supply chain of a building highly complex, and therefore includes more stakeholders than for non-building products. Examples of these stakeholders are: the user, the real estate developer, the building contractor, the architect and other building product manufacturers. The facade equipment manufacturer, therefore, is not directly in contact with the client. The only possible channel of communication with the client is the architect or building contractor.

Secondly, the lifespan of building products is relatively long, while the period of ownership generally is much shorter. Therefore, it is likely that the building changes hands several times during its lifetime. This often leads to a disconnect between the building part supplier and the owner, making it difficult for cores to be retrieved for remanufacturing at end-of-life. For example, in the case a certain building product needs replacement, those responsible for maintenance might not know the original manufacturer of that building product. Typically, when a building product needs to be repaired, the user contacts a general repair company, instead of the original equipment manufacturer (Azcarate-Aguerre et al., 2017). Companies like Madaster are trying to create databases for building owners about their products, however these services are not yet widely applied within the building industry (Madaster, 2019). Thirdly, in a broader perspective, in terms of supply and demand, large scale market dynamics are not yet in place. The concept of circular economy is only just emerging in the building industry, therefore there is a lack of awareness about the topic throughout the supply chain. There were no examples found of building products remanufactured at a large scale, in the searches carried out.

3.4.2 ANALYSIS OF SOFT BARRIERS TO DESIGN FOR REMANUFACTURING

Table 3.4 shows the results of the case analysis using the framework for predictors of new product performance. The table only includes those topics which were addressed during the workshop, remaining characteristics are potentially of influence but require more extensive data collection.

TABLE 3.4 Case analysis using the framework for predictors of new product performance**.**

Analysis of soft capabilities of a window shade manufacturer		
Predictor	**Sensing capability**	**Learning capability**
Product characteristics		
Product advantage	Being responsive to market trends The case study company is aware of ways product service systems could potentially create an advantage.	Obtaining new knowledge Offering facade equipment as a service is a novel idea with no precedents.
Product meets customer needs	Identifying market opportunities The company has not investigated potential markets for remanufactured building products (e.g. clients / architect / contractors) who could be interested in circular building products	Obtaining new knowledge The company has no experience in performing tests that a remanufactured product has the same quality and performance as a new product.
Product price	Identifying market opportunities The company has not investigated potential price strategies for remanufactured building products	Obtaining new knowledge The company is concerned about market cannibalization and does not have the knowledge to prevent it
Product technological sophistication	Identifying market opportunities The company produces highly durable products, but lacks information about the market perception of circular products	
Product innovativeness	Being responsive to market trends The company is aware that Circular Economy is of growing importance to the EU. However, sustainability is no main selling points to the company.	

TABLE 3.4 Continued.

Analysis of soft capabilities of a window shade manufacturer		
Predictor	**Sensing capability**	**Learning capability**
Firm strategy characteristics		
Technological synergy	Identifying market opportunities The company has not investigated required technical skills to remarket remanufactured building products	Creative new thinking The product's design allows for the product to be easily constructed, deconstructed, and transported, the company is aware that this supports remanufacturability.
Order of entry	Identifying market opportunities The case study company is unaware of the potential demand for remanufactured products, but does have contact with clients who could supply cores for remanufacturing	
Firm process characteristics		
Marketing task proficiency	Identifying market opportunities The case study company already recycles the aluminum shades in the product, this is not marketed because sustainability is not a main selling point in the market.	
Technological proficiency		See learning creative new thinking under 'technological synergy'
Market orientation	Identifying market opportunities The case study company is unsure if their customers would accept a remanufactured product. Currently, the case study company products are marketed as bespoke, high end products.	
Internal, competitor, and customer input	Identifying customer needs The case study company does not monitor sold products, therefore there is a lack of information for core acquisition.	Obtaining new knowledge The case study company is unfamiliar with strategies to monitor products, such as building passports.

3.5 DISCUSSION

3.5.1 FRAMEWORK OF PREDICTORS FOR NEW PRODUCT PERFORMANCE

In the previous section, the predictors of new product development framework (Henard et al., 2001) is used to evaluate the company's soft barriers to remanufacturing. While most of the barriers to remanufacturing raised by the company could be placed into the new product development framework, some could not. The barriers that did not fit into the framework were all related to the full life cycle thinking that is essential for products and businesses in the circular economy. This suggests that the framework of Henard and Szymanski is more suited for products in the linear economy, where the objective and responsibility of companies is to sell their products, with less emphasis on what happens after these products have been sold. The framework has been adjusted by different authors since 2001, more extensive literature review is required to analyse the successive versions.

The following paragraphs are recommendations on how the Henard and Szymanski framework can be adapted to evaluate a product's success development for remanufacturing. The four main recommended additions are: business model related capabilities of the company, upgradability of the product, consumer input, and collaborations with other stakeholders.

The Henard and Szymanski framework should include how business model related capabilities could affect the performance of a product. The framework focuses on the take, make, dispose business model for products in the linear economy, and therefore does not take into account services that accompany the product after it has been sold, such as maintenance and repair services.

The upgradability or adaptability of a product can be taken into account in the framework. The upgradability of a product is important in a Circular Economy because this makes it easier for products to have multiple lives; to be remanufactured after its first use. In the case study example, this would mean making the products adaptable to different dimensions.

Although customer input is included in the framework, the main focus of the framework is on input before the product is sold. "Customer input" could potentially be split into two parts: pre-sales and after-sales. When operating in remanufacturing markets, information on the products' performance during use, and the time and location of the product's end of life is important. Companies can obtain this information if they focus on customers' after-sales input.

The degree of collaboration and connection with other stakeholders in the supply chain could also be added to the framework. In remanufacturing markets, maintaining a connection with other stakeholders in the supply chain allows for cores to be returned to the original equipment manufacturer, allowing for smooth reverse logistics.

At the same time as the linear approaches seen in the new product development above, there is a dominance of the 'tech will fix it' approach, which even though applied to the circular, closed loop thinking, results in a slow progress of the adoption of remanufacturing and especially the uptake of design for remanufacturing. The combination of the linear thinking in new product development combined with the circular hard tech frameworks leaves the human soft aspects missing. This is an important gap as it can be observed that the absence of the human drivers and barriers can be more powerful than those from the hard tech aspect. At the same time the frames for the soft side are documented and applicable to the case of DfReman.

3.5.2 CASE EVALUATION

The case study company's main barriers in identifying market opportunities is caused by limited investigation into markets for circular building products, or remanufactured building products. The company has not identified existing or potential customers who may be interested in a circular building product, and does not know of many clients, architects, and contractors who are interested in transitioning to a circular economy. The company is also unsure of whether its existing customers would be interested in any product that could be perceived as "not new", such as a remanufactured product. Because of the complexity of a building project, the case study company has barriers in identifying customer needs. The company does not maintain close enough relationship with the user of the product after it has been sold, which prevents it from knowing when a product can be collected. The company also provides limited maintenance and repair service to users, due to the complex legal nature of the building industry.

The case study company is also encountering learning barriers to remanufacturing, specifically in the process of obtaining and transforming knowledge. In terms of obtaining new knowledge, the company is missing knowledge in ensuring that remanufactured products have the same quality and performance as new products, in preventing market cannibalization, in offering facade equipment as a service, and on strategies of monitoring cores, such as using building passports.

The company also has existing knowledge that could be transformed. The product's design allows for it to be easily assembled and disassembled, since all the connections within the product are mechanical, no connections with glue. The company recognizes that it could explore how this product design could make the remanufacturing process simpler. The company is aware of the increasing importance of Circular Economy in the EU, and has therefore started to explore future strategies with TU Delft, attending the Workshop and participating in the Facade Leasing Project led by Professor Tillmann Klein and PhD candidate Juan Azcarate-Aguerre. By participating in the Facade Leasing Project, the case study company is also aware of the potential benefit of product services systems to businesses as well as its customers.

3.6 CONCLUSION

Case study research was done to help answer the central research question: *For remanufacturing, what is the role of soft barriers at the product development stage?* The analysis of the selected case company, a window shade manufacturer, was done using the model for 'Predictors of new product performance' drafted by Henard & Szymanski (2001). Prior to the analysis, the supply chain dynamics for the building industry, the theoretical model for product development, as well as the technical requirements for design for remanufacturing were discussed. The data collected during an EU funded workshop was used to do the final analyses of soft barriers.

The conclusions which can be drawn from this analysis are as follow. Firstly, regarding the framework, the main conclusion would be that the framework of Henard and Szymanski is more suited for products in the linear economy, where the objective and responsibility of companies is to sell their products, with less emphasis on what happens after these products have been sold. The four main recommended additions to the framework, to make it relevant to remanufacturing, are: business model related capabilities of the company, upgradability of the product, after-sale consumer input, and collaborations with other stakeholders.

Secondly, the case study company's main soft barriers were identified. In relation to the sensing capability, the main barrier is limited investigation into markets for remanufactured building products. The company is also encountering learning barriers to remanufacturing, main barriers are missing knowledge about the performance of remanufactured products and missing strategies to monitoring cores.

The results from this paper can be used to draft an encompassing framework for characteristics for the success of remanufactured products. Such a framework can be used to reflect on the extent in which existing new product development efforts support product remanufacturing, from both a technical and human perspective, and helps finding gaps for improvement. This allows opportunities for a shift in focus for design for remanufacturing, from a predominantly technical one towards a combined one, including human, soft capabilities.

ACKNOWLEDGEMENTS

This paper was made possible by using results of EU funded EIT KIC Raw Materials projects, called: 'Remanufacturing Pathways' (RemanPath), under grant agreement number 17087, and Catalyse Remanufacturing through Design Bootcamp (CARED), under grant agreement number 18024. Prior work from EU Horizons 2020 projects 'European Remanufacturing Network' (ERN), under grant agreement number 645984, 'Key success factors for re-use Networks' (RUN), under grant agreement number 15078, and 'Bridging the raw materials knowledge gap for reuse and remanufacturing professionals' (ReUK), under grant agreement number 15023, are also acknowledged.

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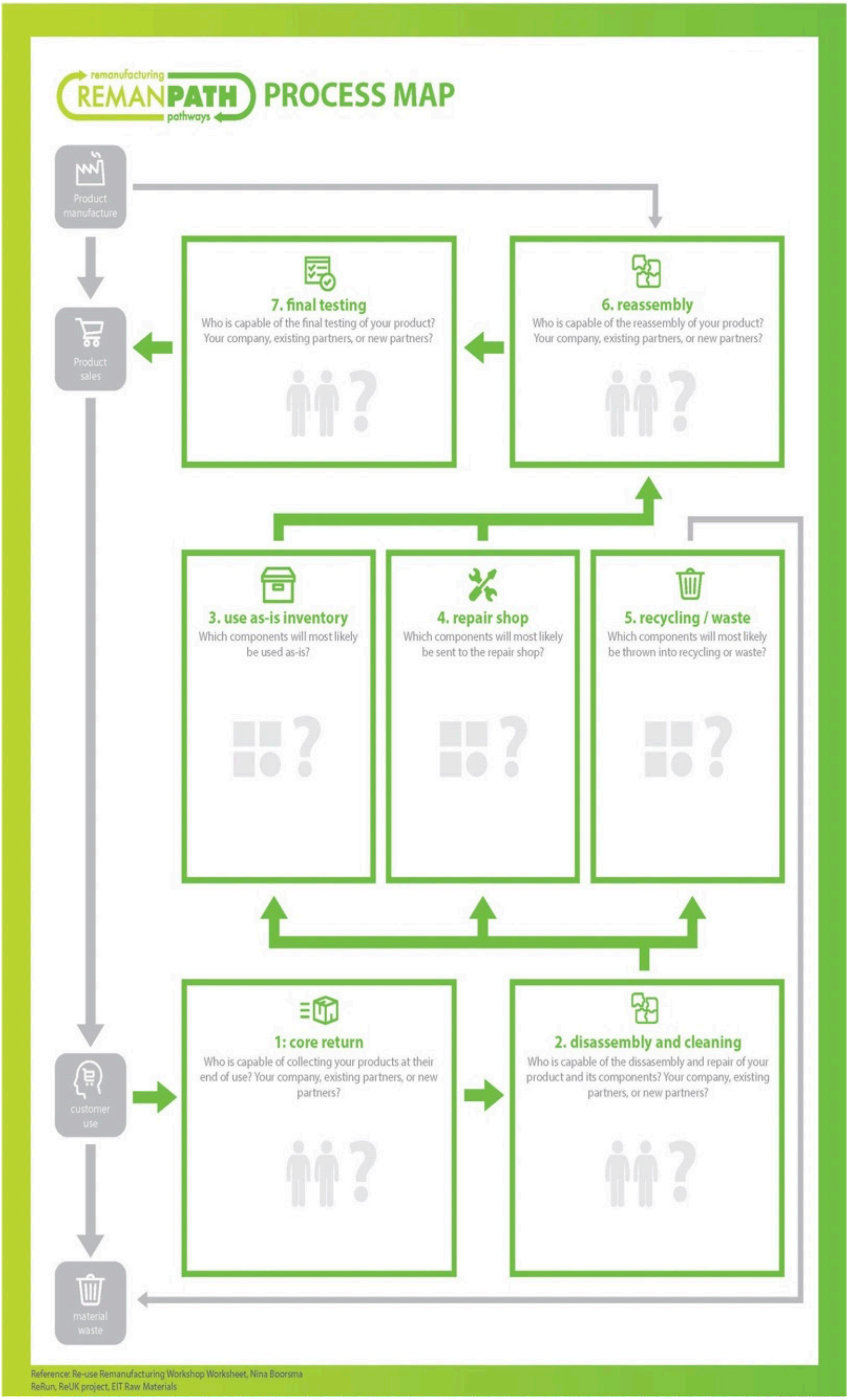
APPENDIX 3-A

Worksheets and structure documents from the EU projects: workshop schedule and exercise sheets: reman process map and reman checklist.

I. WORKSHOP SCHEDULE

13:00	Introduction of participants
13:30	Introduction to Remanufacturing by David Peck, TU Delft
14:00	Remanufacturing case study by Tanya Tsui, TU Delft Technical process Business model
14:30	Coffee break
15:00	Remanufacturing workshop 1. Reman process map: what are the processes in remanufacturing and is your product ready for it? 2. Reman checklist: what are the conditions favorable to remanufacturing? How can your company overcome barriers and utilize opportunities?
16:30	Final sharing

II. EXERCISE SHEET: REMAN PROCESS MAP



III. EXERCISE SHEETS: REMAN CHECKLIST

remanufacturing REMANPATH pathways

THE REMAN CHECKLIST

Is your product or company suitable for remanufacturing? When it comes to remanufacturing, what are your existing opportunities? What are the barriers that need to be overcome? Answer the following questions to find out.

MARKET POTENTIAL

CUSTOMERS & MARKETS	Y	N
could remanufacturing improve the brand, recognition, and reputation of your company?	×	×
are customers accepting of remanufactured products?		
is there a separate target market for remanufactured products?		
OTHER ISSUES	**Y**	**N**
does legislation allow for remanufacture goods?		
is sustainability seen as the company's way of doing business?		

PRODUCT AND PRODUCTION

PRODUCT STRUCTURE & DESIGN	Y	N
is the product modular, or designed to be (easily) dismantled?		
has the product been designed from the perspective of life cycle costs?		
are the safety requirements relating to the product low?		
SUPPLY & DELIVERY CHAIN	**Y**	**N**
is there a relationship between sales and after-sales?		
is the testing of remanufactured products straightforward?		
PRODUCT CHARACTERISTICS	**Y**	**N**
does the product have a high retained value?		
is the rate of change for the product slow?		

REVERSE LOGISTICS

BUSINESS MODEL & MARKETS	Y	N
is the recovery of products included in the business model?		
are there good logistical connections in the market?		
is the recovery of products unrestricted by customs, tariff, or other border formalities?		
LOGISTICS	**Y**	**N**
is the length of the product's life possible to predict?		
is the storing of products (cores) possible / affordable?		
can the existing sales and distribution channels be utilised for remanufactured products?		
is there an efficient system of reverse logistics with which products can be collected?		
is there an incentive system that encourages customers to return their products?		

1

Translated and modified from DemaNET project report, VTT (https://www.vtt.fi/inf/pdf/technology/2015/T207.pdf, appendix C)

CHECKED "YES"?

Transitioning to remanufacturing can start from small steps and opportunities. If you answered "yes" to any of the questions above, your company already has existing opportunities that could be favourable for remanufacturing. Pick any point on which you answered yes, and go through this exercise.

MY OPPORTUNITY IS...

COULD THIS OPPORTUNITY IMPROVE THE USER EXPERIENCE IN SOME WAY?

HOW DOES THIS OPPORTUNITY FAVOR REMANUFACTURING?

HOW MIGHT THIS AFFECT MY BUSINESS STRATEGY AND FINANCIAL NEEDS?

2

Reference: Circular Opportunities Worksheet, Circular Design Guide, The Ellen MacArthur Foundation

3

remanufacturing REMANPATH pathways

CHECKED "NO"?

Remanufacturing is a complicated process. In order to overcome barriers, new skills and resources are needed. Pick any point on which you answered "no", and use this worksheet to work out how to overcome this barrier.

MY BARRIER IS...

WHAT ARE THE RESOURCES I NEED TO OVERCOME THIS BARRIER?

TECHNICAL RESOURCES	HUMAN RESOURCES

WHAT COLLABORATIONS DO WE NEED TO MAKE THIS HAPPEN?

WHAT ARE THE NEXT STEPS TO GET THIS PROCESS STARTED?

3

Reference: Circular Opportunities Worksheet, Circular Design Guide, The Ellen MacArthur Foundation

CHAPTER 4

INCORPORATING DESIGN FOR REMANUFACTURING IN THE EARLY DESIGN STAGE: A DESIGN MANAGEMENT PERSPECTIVE

This chapter has been published as:
Boorsma, N., Balkenende, R., Bakker, C., Tsui, T., & Peck, D. (2021). Incorporating design for remanufacturing in the early design stage: a design management perspective. *Journal of Remanufacturing*, 11(1), 25-48.

ABSTRACT

Adopting design approaches that allow products to last multiple use-cycles supports European Commission objectives to reduce greenhouse gas emissions and reduce primary material impacts. Remanufacturing is an example of an appropriate circular strategy and it can be applied in a variety of industries that are intensive materials users. However, most companies have not yet adopted design strategies facilitating remanufacturing at scale. In this paper, we explored how design management can facilitate the implementation of Design for Remanufacturing, based on a literature review and in-depth interviews. Seven companies active in business-to-business markets were interviewed about the design-related opportunities and barriers they see for remanufacturing. We found that access to technical knowledge is not a barrier, whereas integrating this knowledge into the existing design process is. We conclude that design management can contribute to the uptake of Design for Remanufacturing for the following reasons: by making the value of Design for Remanufacturing to the company at large explicit, by building bridges between internal and external stakeholders, and by embedding Design for Remanufacturing into existing processes by means of Key Performance Indicators (KPIs) and roadmaps.

KEYWORDS

Design for Remanufacturing, Design management, Implementation, Circular product design, Product development, Multiple use-cycles, Closed loop supply chains.

4.1 INTRODUCING STRATEGIC DESIGN FOR REMANUFACTURING

For decades, the practice of remanufacturing has been used as a tool to create economic benefits from previously used products. From an environmental sustainability perspective, extending the life of a product via remanufacturing is a promising approach to reduce pollution, in particular CO2 emissions, and our dependence on primary (geologically sourced) material use.

The closed loop, product life extension, lower impact, approach fits within the frame of the circular economy. In the EU, Circular Economy (CE) is a relatively new policy concept that came into the spotlight following the European Commission's 2015 CE Action Plan [22].

Remanufacturing is an example of a strategy which supports CE. It is applied in a range of intensive material using industries. Technical solutions for remanufacturing are extensively discussed in the literature and are centered around product design to facilitate the remanufacturing process, which includes disassembly, cleaning, testing, and reassembly [26, 28, 31, 46]. The emphasis is on optimising part re-use by minimising the possibility of parts being damaged during the process. This helps in maintaining high product quality at a low cost, and reducing production time. To tap into the full potential of these technical solutions, integration within the new product development process is crucial, yet uncommon in practice [46].

Strategic design solutions may advance this integration, however their development is much less reported in the literature [29, 37]. Strategic design takes place during the early phase of product development and is concerned with concept development based on, for example, market analysis, consumer behaviour, product portfolio management, and the available innovation capacity. The body of literature on topics like market analysis and consumer behaviour is growing [25, 49], however discussions are rarely linked back to early stage design activities.

In this study, therefore, we investigated the opportunities and barriers to implementing Design for Remanufacturing in early stage product development. We aimed to build a better understanding of these early stage dynamics by taking a design management view. Design management provides a structural approach to exploring the value created through design by taking different perspectives like a customer perspective and learning perspective [7]. This allowed us to explore the full potential Design for Remanufacturing can have for the entire company.

In the background section, we introduce the concept of design management in more depth and present the corresponding roles found in the literature with regard to remanufacturing. In the methods section, we explain how we collected data through in-depth interviews. Lastly, we analyse the results and finalise with a discussion and the overall conclusion.

4.2 STRATEGIC OPPORTUNITIES AND BARRIERS

4.2.1 FRAMEWORK

The objective of giving products multiple use-cycles through remanufacturing is to create benefits for the target market, the environment, and for profitability [3, 21, 27, 36, 55]. The better a product's design is adjusted to serve multiple use-cycles, the greater these benefits will be [26, 28, 50, 52, 54]. In this paper, we use the following definition of remanufacturing, as described by the International Resource Panel [32]:
"[Remanufacturing] refers to a standardized industrial process that takes place within industrial or factory settings, in which cores are restored to original as-new condition and performance, or better. The remanufacturing process is in line with specific technical specifications, including engineering, quality, and testing standards, and typically yields fully warranted products. Firms that provide remanufacturing services to restore used goods to original working condition are considered producers of remanufactured goods."

Design for Remanufacturing literature is primarily concerned with finding the optimal alignment between product properties and the remanufacturing production process [26, 28, 46, 55]. In their paper, Prendeville and Bocken [51] highlight the importance of strategic design as a wider frame to add to the technical design solutions. Strategic design takes place in the early stage of product development and is expected to lay the foundation for a more integrated remanufacturing design strategy. Formulating an innovation direction requires expertise and input from different disciplines, including business development, marketing, manufacturing, and product development. In line with this, Lindkvist Haziri and Sundin [39] also explored the opportunities to include insights from the remanufacturing department in these early stages of product development. In their study, they assessed both the current, and ideal, level of information exchange at a manufacturer of electro-mechanical machines. To achieve this, they used design tools like visualisation techniques. In the following step of the study, they identified concrete actions to implement the ideal scenario. One of the important factors they mention in building up a relationship between departments is to sensitise employees to each other's work. One of their proposed solutions was to give designers first-hand experience by having them visit the remanufacturing production line.

The importance of strategic design for remanufacturing was already recognized in studies from the 70s, where, for example, Lund and Denney [42] reported the success of effects of customer perception, product planning, and innovation management. The authors highlight that customers should be well- informed about benefits like cost savings, and that product parts should, where possible, be standardized across different models alongside product innovation. Calabretta and Gemser [10] define strategic design as the following: to "co-determine strategy formulation and implementation toward innovative outcomes that benefit people and organisations alike". This definition shows that besides using design to implement a strategy, it can also be of use to formulate a strategy.

To get an understanding of the full potential strategic design can have within an organisation, we have turned to the field of design management. This field revolves around more generic values of design: value creation, problem solving, skill improvement, and design as leadership (to reach company goals) [13]. Design management makes use of design competencies to connect market needs with company goals in creating products and/ or services. This can, for instance, be directed at improving product performance or durability, or be applied to the integration of new design requirements, or to creative thinking to find new business opportunities. Other roles associated with design management are creating competitive advantage, improving customer perception, and increasing market share [6]. Its value becomes particularly evident in multidisciplinary environments involving complex problems [14]. Borja de Mozota [7] created a balanced score card for design managers. She formulated four capacities for design: design as differentiator, design as integrator, design as transformer, and design as good business. Design as differentiator takes a customer perspective and focuses on design's abilities to be distinctive from competitors and to be easy to recognize for customers. Design as integrator takes a process perspective, and focuses on design's abilities to function as an innovator of the product development process, by, for example, implementing new tools or methods. Design as a transformer takes a learning perspective. It is about the ability to assist a company in adapting to change, in, for example, finding new business opportunities. Lastly, design as good business takes a financial perspective and focuses on design's ability to increase financial gains and actualise sustainable growth for the business by, for example, increasing the market share.

Using Borja de Mozota's design capacities and perspectives, we developed a framework for design management roles for remanufacturing (Table 4.1). For each of the four design capacities and perspectives (i.e. Design as Differentiator/ Customer perspective, etc.), the remanufacturing literature was reviewed to identify opportunities and barriers for design management. After grouping the opportunities and barriers, sub-categories for each perspective emerged. For example, based on the literature, the Customer Perspective was further subdivided into market assessment, customer acceptance, and customer relationships. For each of these sub-categories, we then assigned a number of design management roles. We would for instance find in the literature that a clear definition of suitable markets for remanufactured products is important, but that companies often do not prioritise the activities of defining markets and collecting market insights for remanufactured products [24, 58]. Based on this finding, we concluded that a role for design management would be to 'identify customer needs that can be met by offering remanufactured products'. We have applied this approach for all the roles included in Table 4.1. In the following section we describe our approach in more detail. The findings of the literature review can be found in Table 4.4 in Appendix 4-A.

TABLE 4.1 Design management roles for remanufacturing (based on literature).

Design as differentiator (Customer perspective)	
Sub-categories	**Design management roles**
Market assessment Analysing a market for a product/ service offer to make predictions about the market size and ideal product price [38]	Identify customer needs that can be met by offering remanufactured products [25, 59] Identify the added value of remanufacturing to the marketing department [17, 29]
Customer acceptance Customer's agreement that a product and/ or service fits in the category that meets a customer's standard or needs [2]	Identify and document product specific information that could support the purchasing process of customers [1, 17, 30] Increase awareness and trust by developing a marketing and branding strategy for remanufactured products [30, 35] Communicate the need for certifications for remanufactured products to trade unions [35, 47, 48]
Customer relationships The behavioural patterns, and feelings linked with those patterns, a company and its customer(s) have developed over time in relation to the company offer [15]	Instruct customers about the desired return procedure [16, 42] Engage customers and stakeholders in the timely return of products [16, 42]
Design as integrator (Process perspective)	
Sub-categories	**Design management roles**
Information management The company's internal approach to collect, organise, store and provide information [33]	Specify and communicate product information required by both the remanufacturing department and the product development department [29, 39, 40, 55]
Collaboration The combined efforts of two of more stakeholders to complete a task or assignment [11]	Identify opportunities to create value in collaboration with supply chain partners [28, 29, 53] Organise interdisciplinary workshops to co-create and exchange experiences, preferably at a location where the participants can gain first-hand experience [53] Promote the development of routines and channels for internal collaboration and information exchange [40, 53]

TABLE 4.1 Continued.

Design as integrator (Process perspective)	
Sub-categories	**Design management roles**
Organisational support Work conditions of an organisation such as behaviours and routines that allow an action to take place [57]	Involve management in developing and communicating a clear vision on remanufacturing [29, 40]
Commitment The willingness of a person to dedicate time and effort to a particular task in order to complete it [12]	Identify departments and the employees that need to be involved in the tasks [29, 39]
Integration with existing processes The process of introducing new knowledge into a previously established routine to accomplish new or adjusted goals [34]	Identify potentially conflicting product requirements (in relation to remanufacturing) at an early stage [28, 53] Integrate remanufacturing knowledge into existing methods and tools, throughout the whole product development process [24, 28, 61]
Design as transformer (Learning perspective)	
Sub-categories	**Design management roles**
Innovation A new approach with regards to product design, production or the marketing of products and/ or services, which adds value, and brings competitive advantage to the company [38].	Identify target parts and components at an early stage [42, 49] Identify business value of short lead times for product availability [45, 49]
Business development The process of advancing the way a company sells its products and/ or services [8, 18]	Explore the opportunities to adopt access or performance business models [35, 52, 56]
Design as good business (Financial perspective)	
Sub-categories	**Design management roles**
Financial drivers Incentives related to money that influence the decision-making process to advance business growth [19, 23]	Explore the possibility to use remanufacturing for quality and brand management [41, 45, 53]
Market share The percentage of customers in a particular market accommodated by a company [44]	Assess the risk of cannibalizing new sales by offering remanufactured products [35, 40, 53]

4

4.2.2 OPPORTUNITIES AND BARRIERS TO IMPLEMENTING DESIGN FOR REMANUFACTURING

Design management roles were identified based on opportunities and barriers to implementing Design for Remanufacturing; these are discussed below for each of the four perspectives. The design management roles derived from these opportunities and barriers are listed in Table 4.1.

4.2.2.1 Design as differentiator - the customer perspective

This perspective discusses the connection of the company to its market. Understanding market dynamics and customer needs allows a company to develop products and/ or services that fit its market. When remanufacturing is concerned, efforts to define markets and collect market insights are usually not prioritised within companies

[25, 59]. A growing market demand for remanufactured products is expected to positively influence the marketing teams' commitment to perform such studies [17, 29]. However, the risk of cannibalizing new sales is often highlighted as a drawback in promoting remanufactured goods [40]. For market assessment, possible roles for design management therefore are identifying target markets and identifying customer needs that can be met through remanufacturing.

From the customer's point of view, the interest in remanufactured products is affected by the lack of information about product history, the remanufacturing process, and/ or product quality [1, 17, 26, 30, 58]. Financial risks most prominently influence the purchasing intention [42, 48, 53, 58]. Improved information transparency and certification or quality labels are expected to improve the quality perception [1, 30, 35, 47, 48].

Lastly, customer cooperation can influence the success of remanufacturing (e.g. proper use of products or timely product returns) [42]. The customer relationship can be improved by instructing customers about the desired use [16]. This can for example translate into the design management role of engaging customers and stakeholders in returning products timely.

4.2.2.2 Design as integrator - the process perspective

The process perspective focuses on all actions required to get from a business idea to market introduction. It involves the actual product development and the design competencies needed to fulfil the tasks. To develop remanufacturable products, the development department needs to receive input from the remanufacturing department. An important factor is that the required information should be carefully specified [40]. In turn, the remanufacturing department requires detailed product information from the product development, manufacturing and servicing, to produce high quality output [29, 55]. Currently, channels for information exchange are often non-existent or rely on informal exchanges [39, 53].

What could help improve these exchanges is setting up interdepartmental collaborations. Organising workshops, for example, is a way of bringing different stakeholders together. These workshops can also take place with external stakeholders, for example, with part suppliers. These collaborations can help in taking a lifecycle perspective during product development [29, 53]. It is important to carefully coordinate these collaborations [29]. Coordinating these workshops has been identified as a role for design management.

In support of collaborations, it helps to have a clear strategy formulated by top management and that this is communicated throughout the company [29]. This can also help spread awareness and knowledge of remanufacturing, which tends to be concentrated at the remanufacturing department [39].

In addition to acquiring information, people's task-commitment is expected to be at least as important [29]. Companies with a clear overall vision, and task division, motivate their employees to take action [29]. This motivation can be enhanced by giving employees first-hand experience of a subject [29, 39]. This can be achieved by, for example, inviting them to the production line and scheduling regular follow ups [29, 39]. From the employee's point of view, a lack of trust in product quality and the absence of leadership have negative effects on motivation [29]. A role for design management in getting employees committed is identifying and assigning relevant tasks.

To ensure improved integration of remanufacturing guidelines into the existing process, the literature notes the importance of early stage design [24, 29, 35, 53, 61]. Early stage involvement can also assist in signaling and solving the unwanted effects of adding new requirements (e.g. increased environmental impact) [28, 51, 53]. The use of design tools can also be of value; familiarity with, and the complexity and accuracy of these tools is essential for a seamless integration [28]. Roles for design management therefore are the early identification of potentially conflicting product requirements and improving the compatibility of new design tools.

4.2.2.3 Design as transformer - the learning perspective

The learning perspective focuses on finding new ways to design, manufacture, or market products. In this context, it is important to design products that are suitable for the remanufacturing process. Remanufacturing can also be used as a tool to innovate. For example, from a marketing point of view, since remanufacturing allows for shortened time- to-market lead times compared to that of new products, it can be used as a tool to react to a sudden market demand [45, 49].

Another important aspect is the return flow of products, as input for the remanufacturing process. One way to support this is through product development: by identifying and standardising (target) parts and components to create more homogeneous volume [42]. Another way is to adopt different business models. A shift from sales models to access or performance business models, for example, can increase the return flow of products [4, 35, 55, 56]. To support such a shift, setting up new supply chain collaborations may be valuable [35, 53]. A role for design management is, therefore, to explore the opportunities for adopting access or performance models.

4.2.2.3 Design as good business - the financial perspective

The financial perspective is the fourth perspective; its value is related to the way a company optimises its profit from remanufacturing. Improving product design can help to increase profit margins and ecological benefits [9, 29, 41, 53]. The most promising scenarios to initiate remanufacturing are those where costs for initial production are high and costs for remanufacturing are low [17]. The required labour, and more frequent servicing, however, can add significantly to the costs of remanufacturing [51].

Competing remanufacturers are the main drivers for Original Equipment Manufacturers (OEMs) to start up remanufacturing [29, 48]. OEM remanufacturing can prevent third party remanufacturers from entering the market [53]. Yet, companies producing low-budget or counterfeit products can also be a threat [35, 53]. At the same time, OEMs perceive cannibalisation of their own new product sales to be a risk [35]. A role for design management is to explore the possibility to use remanufacturing as a tool for quality and brand management.

4.3 METHODOLOGY

To set the starting point for this study, we reviewed the literature for barriers and opportunities for design management for remanufacturing. A combination of the search terms ‘remanufacturing’, ‘product design’ and ‘management’ was used to find articles in the Scopus search engine; this yielded 102 documents. We narrowed this number down by selecting articles focussed on non-engineering barriers and opportunities affecting the design process, from a consumer, process, learning, and financial perspective. We based this on the titles and abstracts, and by looking for keywords such as: integration, implementation, acceptance, knowledge, demand, needs, value, awareness, risks, costs and coordination. The resulting papers were read in more detail and additional papers were found through snowballing. In the end, 26 papers were selected for the literature overview (Appendix 4-A), of which 22 formed the basis for the design management roles for remanufacturing presented in Table 4.1, column 2. This table was structured according to the four capacities of design described by Borja de Mozota [7]. The sub-categories that emerged by grouping the input from literature were defined using additional references, see Table 4.1, column 1.

Figure 4.1 Research process steps.

After developing the framework, we conducted in-depth interviews to further explore the possible roles for design management in the implementation of Design for Remanufacturing. Figure 4.1 shows the research process.

Seven companies operating in business-to-business markets were selected for inclusion based on their product properties, their level of influence on the product design, and their interest in (setting up) remanufacturing activities. The first criterion was that the company's product properties had to have the potential for remanufacturing. Examples are durability, the possibility for long term part standardisation, and the use of a stable technology [43]. The second criterion was that the companies could influence decisions made in the product development process; there had to be a link with the product development department. The last criterion was the level of interest in recovery activities; a basic interest in setting up remanufacturing was required. The final selection included four OEMs, two OEMs with recovery activities in place, and one third party remanufacturer. A summary of the case details can be found in Table 4.2 and the company descriptions can be found in Appendix 4-B.

TABLE 4.2 Company details.

Ref.	Activities	Product	Role of interviewees	Company size
A1	OEM	Air treatment units for buildings	R&D	Medium-sized enterprise
A2	OEM	Outdoor furniture	Head product management and design	Medium-sized enterprise
A3	OEM	Vessel and maritime equipment	Manager R&D, Innovation consultant	Large enterprise
A4	OEM	Window shades	R&D, Business developer	Large enterprise
B1	OEM, remanufacturer	Electro motors	Sales engineer key-accounts	Large enterprise
B2	OEM, refurbisher	Professional coffee machines	Supply Chain Manager, Bid Manager/ Sustainability Officer	Large enterprise
C1	Third party remanufacturer	Electro motors	CEO	Small enterprise

Interviews with these companies were conducted following the structure for shorter interviews described by Yin [60]. They were semi-structured and lasted approximately one hour each. The interview protocol led discussions around opportunities and barriers to remanufacture products from a product design perspective, and can be found in Appendix 4-C. The interview recordings were then transcribed.

The data for the company producing window shades (A4) was collected in a four-hour workshop, followed up by conversations with the company. This workshop was set up using a protocol in the form of worksheets and structure documents from an EU project [5]. Elements discussed were the opportunities for remanufacturing the product in relation to market potential, product and production, and the remanufacturing process.

Data analysis was performed using the framework of design management roles for remanufacturing presented in Table 4.1. The researcher carefully went through the transcriptions in order to develop themes that reflected the respondents' meanings. These were related to opportunities and barriers for design management and addressed market issues, customer perspectives, product design issues, and finances; the findings are summarized in Table 4.3. Themes found for design as a differentiator, for example, were: market assessment, customer acceptance and customer relationship. In the following step, we compared these opportunities and barriers to the design roles in Table 4.1. This led to the identification of a number of new roles for design management; these are described in the discussion.

4.4 RESULTS

In this section, we describe the findings from the interviews for each of the four design capacities. The list of opportunities and barriers is presented in Table 4.3, column 1. The details for the case references can be found in the methods section in Table 4.2. In the discussion section, we reflect on how the opportunities and barriers link to the earlier-identified design management roles (Table 4.3, column 2).

When analysing the interviews, we added the new sub-category called external drivers to the capacity of design as good business (the financial perspective). External drivers are defined as incentives out of the company's control that influence the company's way of doing business [19, 20].

TABLE 4.3 Design management roles for remanufacturing (based on interviews).

Design as differentiator (Customer perspective)	
Opportunities and barriers per sub-category	Design management roles
Market assessment	
The market is not actively seeking remanufacturing. (A2, A3, A4, B)	Increase awareness and trust by developing a marketing and branding strategy for remanufactured products
Customers are often unaware of the possibilities to have their products remanufactured. (A1, A3, A4, B1)	" "
Customers are unaware of the possibility to use remanufacturing as a tool for spare part supply. (A1, B2, C1)	" "
Customers are unaware of the additional advantages of remanufacturing, for example, the possibilities to make modifications (e.g. improving energy efficiency). (A1, A3, C1)	" "
Product take-back for parts harvesting or recycling is not considered valuable. (B1)	
For customers, economic benefits form the main driver to remanufacture, resource savings, is not considered a priority. (A2, A3, A4, B1, C1)	" "
Companies are unaware that initial time and costs to set up remanufacturing operations can be fairly low. (C1)	" "
Customer acceptance	
Economic benefits are not prioritized above the perceived risk. (A1)	Identify and document product specific information that could support the customer purchasing process
Customers' decision-making process is based on both ratio and emotions. (A4, B1, C1)	" "
Circular offers are new to certain markets, customers need time and resources to explore the benefits of remanufacturing. (A1, A2, A4)	" "
The conservative nature of certain markets prevents acceptance of new types of offers. (A1, A2, A3, A4, B2)	" "
Customers settle for lower grade materials to get short term price benefits. (A2, C1)	" "
The lack of confidence in a product's suitability for remanufacturing is a major barrier to starting up remanufacturing (with a contractor). (C1)	" "
There is no remanufacturing certification to convince customers of product quality. (A2)	The need for certifications for remanufactured products to trade unions
Customer relationship	
Certain industries (e.g. the building industry) have no existing direct communication channels with end-customers. (A1, A2, A4)	No role assigned
The dynamic and complex nature of the supply chain leaves companies with little to no influence after initial sales. (A1, A4)	No role assigned

TABLE 4.3 Continued.

Design as a integrator (Process perspective)	
Opportunities and barriers per sub-category	**Design management roles**
Information management	
Product data is collected for providing services, but not to make product design improvements. (A1, A2)	Specify and communicate product information required by product development department
Collecting product use-data is essential to improving remanufacturing quality. (B4, B1)	Specify and communicate product information required by the remanufacturing department
There is no existing feedback loop with the development department. (B1)	Promote the development of routines and channels for internal collaboration and information exchange
Collaboration	
Organising workshops is an effective way to get people acquainted with new initiatives, however it does not ensure continuity. (A3)	Organise interdisciplinary workshops to co-create and exchange experiences, preferably at a location where the participants can gain first-hand experience
Product developers do not feel they have the power to influence other departments like business development. (A2)	Promote the development of routines and channels for internal collaboration and information exchange
A lack of effective communication between the procurement department and product development department can cause a significant barrier. (C1)	" "
Procurers have a strong focus on short-term financial gains. (C1)	Identify departments and the employees that need to be involved in the tasks
Organisational support	
Companies have limited Full-Time Equivalents (FTEs) available dedicated to (design for) remanufacturing. (B2)	Identify departments and the employees that need to be involved in the tasks
Companies fail to adopt remanufacturing in their strategic goals. (A1, A3, A4, C1)	Involve management in developing and communicating a clear vision on remanufacturing
Commitment to change is needed to transform linear to circular organisational structures, as they are absolute opposites. (A2, A3, B2, C1)	" "
Commitment	
Engineers do not embrace sustainable or circular design because of the preconception that it is more expensive to produce. (A3)	Involve management in developing and communicating a clear vision on remanufacturing
A clear vision, personal commitment and perseverance are required to initiate remanufacturing activities and to get colleagues on board. (A3, C1)	" "

TABLE 4.3 Continued.

Design as a differentiator (Customer perspective)	
Opportunities and barriers per sub-category	**Design management roles**
Integration with existing processes	
For it to be effective, Design for Remanufacturing should be put on the agenda in the early stages of the design process. (A3)	Integrate remanufacturing knowledge into existing methods and tools, throughout the whole product development process
Most actions towards implementing Design for Remanufacturing originate from bottom-up initiatives. (A3, A4, B2)	Identify departments and the employees that need to be involved in the tasks
Concrete and practical actions to for implementation are missing. (A3)	" "
Design for Remanufacturing is expected to be a trade-off with initial product quality. (B1)	Identify potentially conflicting product requirements (in relation to remanufacturing) at an early stage
Careful selection of products to remanufacture can save time and money. (B1, C1)	Identify target parts and components at an early stage
Design as transformer (Learning perspective)	
Opportunities and barriers per sub-category	**Design management roles**
Innovation	
Rapidly changing product portfolios form a barrier to adopt (design for) remanufacturing. (B1, B2)	Identify target parts and components at an early stage
Uncertainty about future market and technological developments makes designing for the long term risky. (A3, A4)	No role assigned
Designing products for remanufacturing can assist in solving production errors of new products by allowing product modifications. (B1)	No role assigned
Business development	
Only few companies are aware of the benefit of controlling their brand image through product take-back. (A1, B2)	Explore the possibility to use remanufacturing for quality and brand management
New partnerships are necessary to shift to access-based models. (A2, B1)	Identify opportunities to create value in collaboration with supply chain partners
Supply chain collaboration is key to come up with truly circular concepts. (A2, A3, A4, B1)	" "
The required business processes for remanufacturing are considered to be too complex. (C1)	No role assigned
Access models are difficult to set up when the customers are manufacturers. (B1)	No role assigned
Being highly dependent on suppliers is likely to become riskier over time. (A2, B2, C1)	No role assigned
For our company to explore a new business opportunity, a business case is required. For remanufacturing, a feasible business case is required. (A3)	No role assigned
Feasibility studies for new product development tend to be based on direct costs and profits only. (B2)	No role assigned
It can be hard to attain long term competitive advantage by use of labels, standards and certification. (A2)	No role assigned
Setting up the remanufacturing operation is not the most difficult part; setting up the business and logistics around it is most difficult. (A4, C1)	No role assigned

TABLE 4.3 Continued.

Design as good business (Financial perspective)	
Opportunities and barriers per sub-category	**Design management roles**
Financial drivers	
Financial decision makers are not necessarily product experts, but have great power. (A1, A4)	Promote the development of routines and channels for internal collaboration and information exchange
Company reward systems in sales departments are attuned to new product sales. (A3)	No role assigned
Remanufacturing is generally labour intensive. (A4, B2, C1)	No role assigned
Market share	
The fear of market cannibalization is a barrier to remanufacturing. (A4)	Assess risk of cannibalizing new sales by offering remanufactured products
External drivers	
Companies benefitting from economies of scales of mass-produced new products form strong competition to remanufacturing. (B1)	No role assigned
Certain markets have such a strong competitive nature that parties with radical new ideas are unlikely to survive. (B2)	No role assigned
Once a product is installed in the public domain, it is impossible to retain ownership. (A2)	No role assigned
The cost of raw materials, especially for those involved in electronics, is expected to become a driving force for remanufacturing. (A2, A3, B1, B2)	No role assigned
A shift is taking place toward tenders based on predetermined price asking for the best set of requirements. However, circularity is often not included. (A2)	No role assigned

For each of the four capacities we were able to identify opportunities or barriers that were not mentioned in the literature reviewed for this paper. We will discuss these opportunities and barriers in more detail, starting with the sub-category customer relationship. The barriers found here are the result of operating in highly complex supply chains. Due to this complexity, companies may not have existing channels to communicate with their (end) customer and therefore experience difficulties when initiating circular models. To illustrate this, an interviewee from company A1 describes their customer relationship as follows:

> "We do not deliver our products to the end user or the building investor, but to the installer. Once the system is installed, the end user is out of our sight. This is where we try to make a connection, to stay in the picture. Only then can we start offering circularity."

In the next sub-category, innovation, the interviewees from companies A3 and A4 mentioned the risk of designing products for the long term because of the difficulty of assessing future market needs and uncertainties regarding technological developments. The interviewee from company A3 shared the following:

> "Our assets last for many decades, but at one point they become outdated, written off, or too expensive to maintain. How can we deal with this? One thing to consider is the difficulty of looking into the future. Most people say: 'I don't believe in [circular design]. You don't know anything about what's going to happen after five years.' And the challenge is that a lot of our products are custom built, so how do you approach remanufacturing when every part is slightly different to the other? This is a big challenge."

In the business development sub-category, many barriers have to do with the complexity of setting up circular business models. Companies A3 and B2 point out the misalignment of exploring circular business opportunities with the existing way companies develop new business cases. The existing process is strongly driven by direct costs and profits, and leaves very little room for exploration. In addition, companies A2, B2 and C1 sense that it is important to collaborate with supply chain partners, yet they experience dependence as a risk for the longer term. The interviewee from company C1 noted the following:

> "Many potential customers were initially very interested in remanufacturing. But once they headed back to their company, they experienced a lot of resistance; it was not a priority and it was expected

> to be too complex. Which it is. Any business expert knows that a linear process is simpler than a circular process. But, in the end, you will earn more money with it."

A quote from the interviewee from company C1 illustrates the need for collaboration with supply chain partners to make remanufacturing feasible:

> "We were in the process of remanufacturing a very expensive pump, when we realised that replacing the worn-out component would be incredibly expensive. This was due to the price the supplier charges for spare parts. Buying a new pump would almost cost the same."

Another example, with regard to the dependency of suppliers, was given by the company B2 interviewee:

> "The design of our machines changes every five years. If we extend the product lifetime even further, there is a big chance we will run out of spare parts. The supplier simply no longer produces those parts. By refurbishing a second or third time, we would risk not being able to service the machines in field properly. That is why we only refurbish our machines once."

The sub-categories financial drivers and external drivers also yielded several new barriers. While the external barriers mentioned are difficult to influence through design management, the financial barriers can be influenced. One of the barriers relates to the company reward system for product sales. The company A3 interviewee explained the following:

> "[In selling remanufacturing products] the main obstacle, internally, would be the reward-system. [The way it is organised now,] sales people get paid as a percentage of the new-build products. When you stop selling new-build, how should the reward structure for sales be organised so that that they will accept and work with it? The reward-system has to change."

4.5 DISCUSSION

In this section, we compare the opportunities and barriers found in the interviews with the earlier- identified design management roles for remanufacturing. Most of these barriers and opportunities have been addressed in similar forms in previous studies in literature and can therefore be linked to design management roles identified in the background section (Table 4.3, column 2).

A number of opportunities and barriers were linked to the same design management roles because they share an underlying cause, for example, for the opportunities and barriers related to customer awareness under the sub-category market assessment. The role linked to these opportunities and barriers is to 'increase awareness and trust by developing a marketing and branding strategy for remanufactured products' and covers all of the barriers in this sub- category.

Several barriers from the interviews did not show clear links with the reviewed literature. For these, we formulated additional roles for design management based on insights from the cases and by reflecting on the literature review in the background section. We discuss these additional roles in more detail in this section.

Firstly, for design as a differentiator, the new role is to 'Identify what new channels are suitable to start up communication with customers in complex supply chains'. This role addresses the difficulty for companies in complex supply chains to communicate with their (end-) customers. The importance of communication with customers, as well as the type of information to be communicated, have been thoroughly discussed in the literature [1, 30, 35, 47, 48]. In industries with complex supply chains, however, there are often no existing communication paths with these customers; therefore these need to be developed (A1, A2, A4).

One new role was identified for the process perspective: 'Identify the added value of remanufacturing to the manufacturing department'. The importance of the exchange of product/ production information between the manufacturing department and remanufacturing department is addressed in the literature [29, 40, 55]. In our study, we found that remanufacturing can also add value in other ways, for example by resolving production errors (B1).

For the learning perspective, we found one additional role: 'Compile technological roadmaps to make estimations of the duration certain technologies will be used'. To include remanufacturing in early stages of the product development process has proven to be important, for example, when identifying which component can be standardized

[24, 28, 35, 53, 61]. In line with this, and to support portfolio management, drafting an early stage technology roadmap is essential for identifying design opportunities (B1, B2).

For the financial perspective, we added two new roles for design management. The first of these is to 'Identify the non-financial benefits of remanufacturing'. While the literature discusses the costs and profits, the non-financial benefits are also likely to have a valuable impact [9, 17, 29, 41, 53]. A shift towards a value-based view in, for example, feasibility studies, by including aspects like brand management, parts harvesting, and the possibility to reduce time-to-market, will demonstrate the full potential of remanufacturing (A1, B1, B2).

The second role is to 'Identify existing KPIs which are directly or indirectly unsupportive of remanufacturing, and formulate new KPIs where possible'. The topic of KPIs is not exten- sively discussed in the literature due to the fact that remanufacturing is often not yet embedded in the company. One of the case study companies addressed this topic by noting that company reward systems in sales departments are attuned to new product sales, while no reward system is in place for the sales of remanufactured products (A3).

For this study we interviewed seven companies in addition to the literature review. Even though this number is limited, it resulted in the formulation of several new roles. This implies that either 1) the topic requires a more extensive literature review to cover the remaining roles, or 2) there is much more to be expected from design (management); it is an overlooked capacity that might be instrumental in making remanufacturing more successful.

4.6 CONCLUSION

The use of a design management approach leads to a good understanding of the importance of strategic design for remanufacturing and it leads to formulating concrete actions. As a starting point, we were able to formulate a number of design management roles based on the literature review. This was reviewed using a design management framework based on four capacities of design: design as differentiator, design as integrator, design as transformer, and design as good business. The frame-work was further developed by adding sub-categories to these capacities, based on grouping the opportunities and barriers found in remanufacturing literature. After conducting in-depth interviews with seven different companies, we defined several additional roles for design management.

Design for Remanufacturing has been thoroughly discussed in literature in recent decades. Its implementation in practice, however, has not followed at the same pace. The (early) integration of the knowledge into existing company processes is considered important. Current literature has revealed numerous points for improving the uptake of this knowledge in the early design stage. Our study contributes by initiating an exploration for concrete design management roles, as a next step in finding a structured approach for implementing Design for Remanufacturing.

As a result, we found that the roles for design management can contribute in three ways. Firstly, they make explicit the added value of Design for Remanufacturing for an organisation. Additionally, the roles aid in building bridges amongst both internal and external stakeholders. And finally, they contribute to embedding Design for Remanufacturing into existing processes by means of KPIs and roadmaps.

The exploratory work in this paper yielded a detailed list of concrete design management roles for remanufacturing. To get insights in the added value of these roles in practice, further research is needed. In-depth studies with companies have the potential to provide a more detailed description of the added value of these roles. They can also help in further detailing and finetuning, as well as increasing our understanding of their effect on information exchange and collaboration amongst stakeholders. Lastly, in-depth case studies may reveal opportunities or knowledge gaps for further development of (early stage) design tools to aid OEMs in the development of remanufacturable products.

ACKNOWLEDGEMENTS

This paper was funded through EU-funded H2020 project 'Resource-Efficient Circular Product Service Systems' (ReCiPSS), under grant agreement number 776577-2. The results were collected in EU-funded EIT KIC Raw Materials projects, called: 'Remanufacturing Pathways' (RemanPath), under grant agreement number 17087, and Catalyse Remanufacturing through Design Bootcamp (CARED), under grant agreement number 18024.

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APPENDIX 4-A

TABLE 4.4 Literature review summary: Opportunities and barriers to implement Design for Remanufacturing.

Design as differentiator (Customer perspective)
Opportunities and barriers
Market assessment - There is a lack of knowledge about the effect of market dynamics on the success of remanufacturing [25, 59]. - Recognizing customer demand for remanufactured products as a customer need should trigger - implementation of Design for Remanufacturing into the product development process [29]. - Remanufactured products are less likely to thrive in a market where demand is concentrated at the lower end, mainly due to an expected strong competition in this lower segment [17]. - Market demand for remanufactured products results in support from the marketing department [29]. - The marketing department may be guarded about promoting remanufacturing offers, because of the risk of cannibalizing new sales [40].
Customer acceptance - Remanufactured products are perceived to have a lower value than new products [17]. - Customer perception on product quality is a significant determinant for demand for remanufactured products [17, 26, 35]. - The perceived quality of remanufactured products is strongly related to the expected total costs of ownership, product performance, safety, and serviceability [1, 30, 58]. - The perceived financial risk was found to be the most prominent factor influencing the purchasing intention of remanufactured products, where, besides the purchasing price, future maintenance and servicing costs are considered as well [42, 48, 58]. - Quality perception can be improved by introducing a reference, like certification or a quality label, to inform customers when buying remanufactured products [1, 35, 47, 48]. - Transparency about the origin and production process of a remanufacturing product towards the customer significantly influences customer acceptance [30, 35]. - Customers' value perception of new products decreases when they are informed about the environmental benefits of a remanufactured equivalent [48]. - Customers' willingness to pay is higher for new products than for remanufactured products, especially when information about the recovery process, product quality, and/ or environmental impact is not provided [30, 48].
Customer relationship - The success of remanufacturing is heavily dependent on customer cooperation in remanufacturing business models [42]. - Product durability is related to customer behaviour during use and can be affected by instructing customers [42]. - Not all remanufacturers are confident about their customers' willingness to cooperate (e.g. in returning products, taking good care of products) [16]. - A strategy for remanufacturers to build good customers relationships is to lead by example by initiating the behaviour they would like their customers to mirror [16].
Design as integrator (Process perspective)
Opportunities and barriers
Information management - The channels for information feedback from the remanufacturing department to the development department are missing [40]. - The remanufacturing department should have access to product information [55]. - The remanufacturing department can benefit from formal channels to receive information from service technicians [29]. - Disintegration of Design for Remanufacturing can result from a disconnect between the sales organisation and the production facilities of a company [39]. - In-depth knowledge about remanufacturing is often restricted to the remanufacturing department [39]. - It should be clearly defined what exact remanufacturing information the development department can benefit from [40]. - Informal routines and exchanges (e.g. experience and social relations) store important procedural knowledge and information [53].

4

TABLE 4.4 Continued.

Design as integrator (Process perspective)

Collaboration
- Collaboration between the remanufacturing department and product development department is likely to require improved levels of coordination [29].
- OEMs do not develop all of their parts in house [29].
- There is a lack of knowledge about the product information exchange between OEM and a contract remanufacturer to improve business results [28].
- Interdisciplinary and/ or stakeholder workshops are needed to find innovative solutions for remanufacturing [53].
 	
Organisational support
- (Top) management is in charge of decision making on Design for Remanufacturing implementation [29].
- The company definition and objective of remanufacturing should be clear throughout the whole company [29].
- Awareness of, and knowledge about, remanufacturing is generally not spread throughout the organisation, but concentrated at the remanufacturing department [40].
 	
Commitment
- Design engineers can be sensitized to the implementation of Design for Remanufacturing by giving them a first-hand experience on the remanufacturing shop-floor [39].
- Motivation for design engineers to use Design for Remanufacturing guidelines is dependent on individual values, but is also strongly dependent on company incentives [29].
- Motivation for design engineers to implement Design for Remanufacturing is expected to be more critical than having knowledge about Design for Remanufacturing [29].
- A lack of trust in remanufactured process and product quality can lower the motivation of design engineers [29].
- Frequent touchpoints with the remanufacturing department motivate design engineers to prioritise Design for Remanufacturing [29].
- It is not clear who should be in charge of the implementation of implementing Design for Remanufacturing [29].
 	
Integration with existing processes
- Trade-offs between Design for Remanufacturing and further design requirements should be addressed [28].
- Design for Remanufacturing should be considered in an integrated way with other product requirements to avoid unwanted effects like an increase in cost or increased environmental impacts [28, 51, 53].
- Lifecycle thinking improve the uptake of Design for Remanufacturing [28].
- The use of existing tools is likely to be beneficial beyond remanufacturing [28].
- Design for Remanufacturing implementation is most effective when considered at an early stage of the product development process [24, 28, 35, 53, 61].
- By considering remanufacturing during the product planning process, improved levels of implementation of Design for Remanufacturing can be achieved [39].
- The amount of investment available to implement Design for Remanufacturing may be dependent of the company's size [29].
- Calculations for the amount of required spare parts needs to be adjusted when products are being remanufactured; this should take place at the early stage product development [49].
- Subjectivity in existing Design for Remanufacturing guidelines should be reduced to a minimum [29].
- Ways to adjust Design for Remanufacturing guidelines to fit a specific product should be addressed [29].
- Most design tools from literature are complex and mainly support later stages of product development [28].
  - Links with, and the use of, existing design tools is beneficial because of familiarity in industry [28].
  - Instructions as to how Design for Remanufacturing design tools should be integrated in existing processes is missing [28].
  - Many tools as presented in literature are too complex and technical to apply in early stage product development [28].
  - Guidelines for Design for Remanufacturing are present in literature, yet in low volume [28].
  - Proof needs to be collected about the effectivity for businesses of existing Design for Remanufacturing [28]. - Design for Remanufacturing tools do not meet the need of the users of the tools (e.g. high complexity or time consuming) [28].
  - The uptake of Design for Remanufacturing tools is expected to improve along with the product engineers' awareness of remanufacturing operations [29].
    - Implementing Design for Remanufacturing can only take place effectively with the right tools and under the condition that those implementing it have acquired deep knowledge of the subject [61].

TABLE 4.4 Continued.

Design as transformer (Learning perspective)
Opportunities and barriers
Innovation - With the production of durable products, or products lasting multiple lifetimes, the turnover rate of the product stock decreases and therewith slows down the possibility of introducing new innovations, which may have an effect on market demand and the implementation of sustainable innovations [42, 49]. - New market introductions in some cases rely solely on renewed aesthetics to boost sales, independent of improvement in functionality [42]. - New market introductions are often characterized by having both improved aesthetics and functionality [42]. - Time-to-market lead time can be decreased significantly by remanufacture [45, 49]. - Without interfering with product innovation, standardization of components should be maximized [42].
Business development - Access models, performance models, or other product-service systems, are business models enabling higher volumes of retuning products for remanufacturing [35, 55, 56]. - Design for Remanufacturing can be used to make the business approach of remanufacturing more efficient [28]. - Setting up new collaborations and partnerships within the supply chain can improve the efficiency of remanufacturing activities [35, 53].

Design as good business (Financial perspective)
Opportunities and barriers
Financial drivers - Good alignment between a product's design and the remanufacturing process improved efficiency and, with that, profit margins [9, 29, 41]. - Remanufacturing activities contribute to the environmental goals of companies [29]. - The effects of providing warranties for remanufactured products are unclear (e.g. increased servicing costs) [51]. - A more expensive design may increase short-term costs [42]. - Labour costs for remanufacturing are high [51]. - By combining the purchase of testing equipment for both manufacturing and remanufacturing, cost savings can be achieved [53]. - The more integrated a remanufacturing strategy is, the higher the ecological benefits, and the more likely it is to receive (future) tax credits or governmental support [53]. - A key driving force for remanufacturing is a high initial production cost in combination with low costs to remanufacture [17]
Market share - Competitors with remanufacturing activities may also activate OEMs to start up remanufacturing [29]. - The entry of non-contracted third-party remanufacturers into the market forms a risk for OEMs [48]. - Low-budget entries, or competition from emerging economies, can form a threat to remanufacturing businesses [35, 53]. - OEM remanufacturing can keep third party remanufacturers out of the market [53]. - The possibility of cannibalization of new product sales is seen as a threat [35].
External drivers - Environmental regulations demanding higher levels of Extended Producer Responsibility (ERP) posed by governments are likely to become more stringent over time [53].

APPENDIX 4-B

Company descriptions:

Air treatment units for buildings – This company offers customised solutions for air treatment systems for buildings. The products have high potential to be remanufactured as they are built up out of standardised parts, with varying dimensions. The design is highly modular, upgradable and made of long-lasting materials. The product technology is relatively stable, and functionality and costs are the main selling points.

Outdoor furniture – This company develops products for the public domain. Examples of such products are street furniture, bike parks, infrastructural devices, and equipment for sports and play grounds. The products are made from highly durable, wear-resistant materials, from both a functional and aesthetical point of view. The products are designed according to the specifications in a tender.

Vessel and maritime equipment – This company offers a range of products used in the maritime industry. These large systems typically have extremely long lifetimes, lasting for many decades. Activities for the application of these systems range from dredging, oil and gas, offshore wet mining, etc. Large amounts of high-grade materials are used requiring enormous investments.

Window shades – This company develops and manufactures high-end, bespoke shading products for facades of buildings. The products are made from durable and well-recyclable materials, and the design allows for ease of disassembly and replacement of parts. Main selling points of the products are the aesthetics, the functionality, and costs.

Electro motors – This company offers customised electro motors for a broad range of applications, from all sorts of conveyers to industrial mixers, grinders and cranes. The lay-out of the production process for new products is set up in a way that it allows for integration of remanufacturing in the same process. Existing customers can make use of this to remanufacture their products, which offers benefits like maintaining exactly the same product specification, as well as cost-saving.

Professional coffee machines – This company retains ownership of their products and offers access or performance models to customers. The machines are installed at the preferred location and offers are based on either a monthly fee (access model) or a price per served beverage (performance model). The machines are designed for service and maintenance and therefore enable ease of replacement of parts and ease of recovery to return the product to its original state.

Electro motors – Using their knowledge of producing new electro motors, this company remanufactures used electro motors as a contractor. The company has a dedicated production line for high-grade recovery of each of the parts of this product, allowing their customers to make efficient use of their resources. Since the company has gained experience in, and developed a method for, remanufacturing, they are also expanding to other product groups.

APPENDIX 4-C

Interview protocol:

Can you describe your current offer?

- What product functionality do you offer?
- To what target market?
- To meet what market needs?
- Do you offer performance related services (e.g. maintenance, quality control)?
- Do you offer any additional services?
- In what way is the value proposition for remanufactured products different from newly produced products? Or in what way would it be different?

What are barriers to remanufacture your product?

What are drivers to remanufacture your product?

What are enablers to remanufacture your product?

What type of investments are required for remanufacturing? *If applicable*

How are your products developed?

- What process steps do you follow?
- Which departments/ functions outside of the product development department contribute to product development? And why?
- Do you Design for Remanufacturing? In what way?
- How do you deal with (future) technological developments during product design (in relation to remanufacturing)?
- Do you make use of critical materials?

What does your remanufacturing process look like? *If applicable*

- What are the most time-consuming steps? And why?
- What are the costliest steps? And why?
- Do you improve the product during the process?

Are you planning to implement new business models, like service-based business models?

- Would this be desirable?
- Can you give an example?
- Who would be involved in this process?
- What prevents this from happening now?

What additional services could you offer your clients through remanufacturing?

- Would this be desirable?

- Can you give an example?
- Who would be involved in this process?
- What prevents this from happening now?

How do you market your remanufactured products? (/ How do you ensure customer acceptance?) *If applicable*

- Do you target the same customer segment for remanufactured products as for new products?
- Through which channels?

CHAPTER 5

THE STRATEGIC VALUE OF DESIGN FOR REMANUFACTURING: A CASE STUDY OF PROFESSIONAL IMAGING EQUIPMENT

This chapter has been published as:
Boorsma, N., Peck, D., Bakker, T., Bakker, C., & Balkenende, R. (2022). The strategic value of design for remanufacturing: a case study of professional imaging equipment. *Journal of Remanufacturing* 12, 187–212.

ABSTRACT

Remanufacturing offers an approach to extend product lifetime beyond its first use. After restoring products to original quality, they are reintroduced to the market. To make products more suited for this approach, and to increase resource-efficiency, design for remanufacturing can be incorporated for new product development. Academic literature points out opportunities for improved implementation particularly through early-stage design activities. This paper presents an in-depth, single case study into the opportunities and barriers to incorporate design for remanufacturing in early-stage design. The selected case company is a producer of professional imaging equipment with an internal remanufacturing division. The company has decades of experience in remanufacturing and has introduced a company standard on design for End-of-Life. For data collection, employees from different departments were interviewed and observed. Design management theory was used to combine findings from all perspectives into a company-specific strategy map. This map shows departmental interrelations and dependencies, and exposes the opportunities for creating new value through design. At the case company, remanufacturing was found to be separate from, and secondary to, the development of newly manufactured products. If the strategy of a company is not attuned to developing products that serve multiple use-cycles, its execution will remain sub-optimal and remanufacturing will be a value-retention strategy in isolation. These findings may be valid for other companies that have remanufacturing operations, which are separate, as well.

KEYWORDS

Circular economy, Circular product design, Printers, Design strategy, Sustainable design, Soft barriers.

5.1 INTRODUCTION

In seeking pathways to increased levels of sustainable production through remanufacturing, which is a value-retention strategy in the circular economy [1], design has a pivotal role to play [2, 3]. Remanufacturing activity takes place within a factory, where products are restored to original 'as-new' condition and performance, or even better, with full warranty, through following prespecified technical quality, engineering, and testing criteria [1]. The suitability for lifetime extension and the way prod- ucts are designed prescribes the period they can be used effectively [4]. Literature has highlighted the benefits of designing products for remanufacturing as an opportunity to further increase resource productivity [5, 6]. Yet, the implementation of, for example, design guidelines, often finds significant resistance in design teams, as optimising costs, time-to-market, and functionality for the first use-cycle are prioritized [7–10]. Understanding the benefits and value of strategic, early-stage, design for remanufacturing is key and can help improve the level of sustainable production [11–13]. The need for early-stage design integration is also acknowledged in the field of eco-design, which remanufacturing can be considered part of [14, 15]. Adjustments to product design, however, only pay off if the products are returned to the original equipment manufacturer, or a partnered third-party, after use. The choice for a business model influences to what extent a company can regulate the number of products returning from the market. Bakker et al. [4] describe five archetypes of business models that are frequently used in circular settings. The archetypes that offer products-as-a-service tend to ensure highest return rates [16, 17].

To improve products' circularity in the context of remanufacturing, academic literature suggests aligning a product's design with the activities of the remanufacturing production process [18, 19]. Much of the literature, [20] and case studies, adopt an operational perspective, for example: the development of engineering design guidelines, improvement of informational flows, or End-of-Life decision-making [21–23]. Design for remanufacturing is not, however, being widely applied in practice [24, 17]. There is a lack of cases that provide sufficient insights to facilitate addressing the strategic aspects, including how to develop the organizational environment so that it supports and drives remanufacturing towards more successful outcomes [25]. This research aims to look beyond the scope of detailed, operational design engineering and moves into the field of early-stage, strategic design, in order to help answer the following research question:

How can design management support the strategic integration of design for remanufacturing in industry?

This question has been addressed through the analysis of a single case study. The aim of this study is to explore how remanufacturing is integrated in the earlier design stages in a real-world context and what lessons can be learned from this case that are relevant for other industries. The selected case company is an original equipment manufacturer of professional imaging equipment. The company has remanufactured products for over three decades. To analyse the case, a design management perspective is taken. The use of a design management framework helps in recognising the opportunities and barriers to the strategic integration of design for remanufacturing.

In the second section, the background section, this paper provides a theoretical background on early-stage design activities and the role of design management. In the third section the methodology is presented. The fourth and fifth sections introduce the case study company and show the case analysis. The final sections discuss the main findings and the conclusions.

5.2 BACKGROUND

Even though there is a lack of dedicated cases, the function of early-stage design has been recognized in literature. This can be seen from the acknowledgement that the early- stage design phase, which includes strategic and conceptual design, can be valuable to the integration of remanufacturing [26, 18].

There are a number of studies describing the functions of early-stage design for remanufacturing. Concerning product conceptualization, Gehin et al. [26] observed that companies should identify potential future markets for remanufactured products during the early phase of the original design process. Singhal et al. [3] recognized an opportunity for design strategies like upgrading, which require early-stage conceptualisation, to generate profit for the company. Subramoniam et al. [27] particularly bring up integration in early-stage design to prevent decisions that go against building a good remanufacturing business case. The authors promote cross-departmental collaboration to help identify possible design barriers or trade-offs. In their paper, Lindkvist-Haziri & Sundin [22] explore strategic ways to allow design engineers to learn from insights gained at the remanufacturing department, and with that seek to increase commitment to improve designs. The study identified four steps that will help transfer design information from the remanufacturing to the design department. First, the current situation is assessed, then an outline for a future vision is created, feedback actions are implemented, and finally an evaluation takes place. Early-stage design was also highlighted by Krikke et al. [28] with regards to the need for identification of high-value parts with a sta- ble technology, since these are critical in making the business case for remanufacturing viable. Strategic design elements related to marketing and business development were marked as critical by Copani & Benham [12] in allowing for future-proof remanufacturing concepts.

Several studies highlight the barriers to early-stage design integration. Hatcher et al. [5] found that companies are primarily focused on cost savings, optimizing designs for a single/ first use-cycle, and have difficulties predicting customer demand for successive use-cycles. Another major barrier from the same study was the lack of designers' motivation, which is linked to the absence of remanufacturing objectives in design briefs. In case it is adopted, Hatcher et al. [5] argue that commitment towards applying remanufacturing design guidelines decreases when time pressure to develop products increases. With regards to market potential, D'adamo & Rosa [29] identified having the expertise to effectively position remanufactured products on the market as an industry knowledge gap. The importance, and value, of early-stage design is widely acknowledged, yet its application in industry, and an understanding of what barriers and opportunities companies may encounter, has not been researched in detail.

Design management is a cross-disciplinary research field that tries to bring together design-based and management-based knowledge and practices. Situating this study at the intersection of design and management is deemed useful, because it allows us to ask questions such as "What do specific design solutions demand from management in terms of strategic attention, managerial priority, organizational change, investment or relationship management?' [30]. Moreover, design management is a field of study that is concerned with developing and integrating design, and bringing awareness to its stra- tegic potential [31, 32]. In a previous paper, an initial set of design management roles for remanufacturing was defined based on literature and interviews with companies [11]. Key roles were 'connecting different disciplines within the company to develop relevant, high-quality offers', 'making technology roadmaps at an early design stage', and 'identifying the intangible value of remanufacturing to a company'.

This paper builds upon Borja de Mozota's [33] balanced scorecard for design management. A balanced scorecard is a tool that measures how well an organisation's intangible assets support the outlined strategy and pinpoints opportunities for improved effectiveness [34]. It is a management system that relaxes the primary focus on financial objectives and shifts it to one divided over four perspectives: the customer, process, learning, and financial perspective. These four perspectives are used to analyse the case study of this paper. Borja de Mozota assigned values of design to each of these perspectives within the scope of design management.

Before describing these values in the context of remanufacturing, an adaptation to one of the perspectives will be explained. The term 'financial perspective' was found to be too narrow for the type of value this perspective covers in the context of sustainable production. The term 'value perspective' is considered more suitable. In addition, a new value descriptor was added to this perspective to acknowledge the importance of creating environmental and societal value in addition to making profit, which is the descriptor 'Improve triple bottom line'.

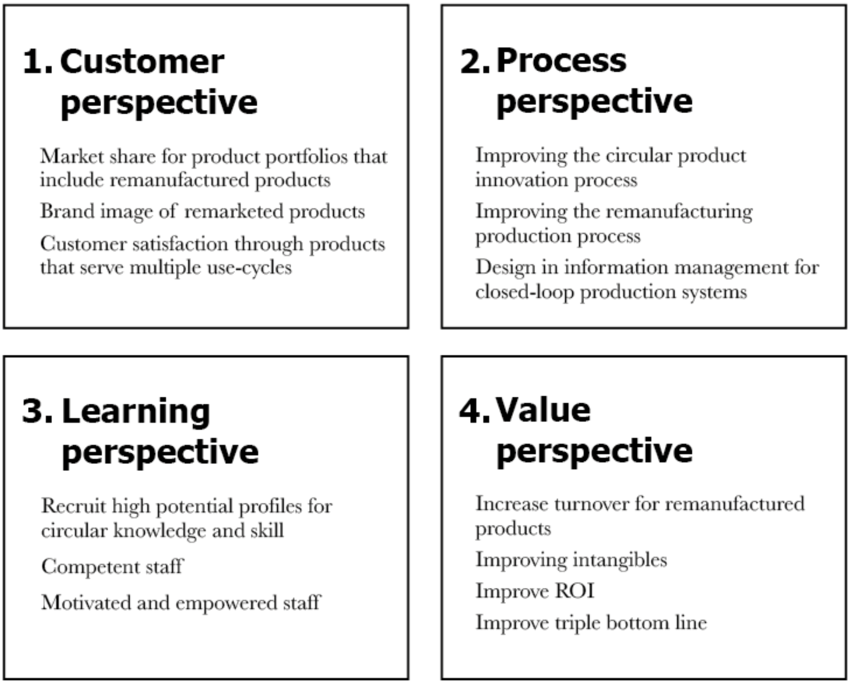

FIGURE 5.1 Balanced scorecard for design management applied to remanufacturing, adapted from Borja de Mozota [6].

The functions of the perspectives will now be described in more detail, in particular, describing the way they relate to remanufacturing (Figure 5.1). The customer value perspective evaluates the way to create value to the market through remanufacturing. It addresses the company's current approach in finding opportunities to remanufacture products and increase market share. It also addresses how assets are used to satisfy market needs. The process perspective covers the activities that take place in the design and production processes. It focuses on innovative product improvements that take remanufacturing into consideration, it optimises products for the remanufacturing process, and manages the required product information. The learning perspective is the key perspective in finding novel ways of operating. This perspective is about developing new skills and expertise to make the most value out of remanufacturing. It focuses on renewing (design) visions, explores new ways for design to add value, and cultivates the mind-sets needed to take remanufacturing a step forward. The value perspective connects remanufacturing design with business metrics. This perspective is focused on expressing how designing for remanufacturing contributes to increased turnover, intangible value, and improved return on investments, as well as improvements in the triple bottom line.

5.3 METHODOLOGY

This section presents the methodology applied for the study, including the selection of the case, data collection, and data analysis.

5.3.1 CASE STUDY RESEARCH

This paper took an exploratory approach in finding the opportunities and barriers to the strategic integration of design for remanufacturing in industry. A single case study research was selected to understand what remanufacturing means to its wider strategic context, related to product design, and in what ways additional value can be created [35]. Moreover, case study research offers diverse and rich data from multiple sources, with the possibility to follow up on topics that are brought up during the inquiry.

The selected case company is a producer of professional imaging equipment that operates in a business-to-business industry. It is a frontrunner in the field of remanufacturing, which has been applied for over three decades. The company has a large in-house design department and follows a design-driven approach to produce complex and durable products. The company's experience, as well as attempts to mature their remanufacturing approach, formed a rich basis for a case study. The company has the required level of awareness, ambition, and knowledge concerning the topic.

5.3.2 DATA COLLECTION

The case data was collected over four weeks by conducting on-site interviews and by making observations (Figure 5.2). Four departments were included for this study: the business development, product development, remanufacturing, and compliance departments. A total of 35 interviews were conducted in a semi-structured face-to-face setting, and lasted between 40 and 80 min (Table 5.1).

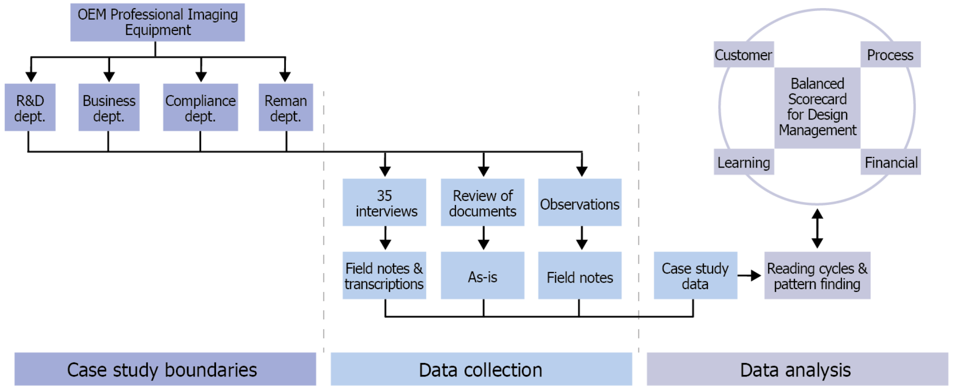

FIGURE 5.2 Methodology flow chart.

Additional open, short interviews were carried out with the remanufacturing technicians. The interviewees were selected based on their role within the departments and their specific experience with the product life-cycle (including End-of-Life). The following topics were discussed during the interviews: processes in place to support Design for Remanufacturing; technical and strategic barriers and opportunities; good practice examples of successful remanufacturing, and; examples where remanufacturing could not or would not be applied, see Appendix 5-A.

5

TABLE 5.1 Case company interviewees.

Departments	Roles interviewed	Time spent on interviews
Business development, sales and marketing (Bus.)	Product Line Manager; Product Manager; Strategic Planner; Sales & Operational Planner; Marketeer; Marketing & Communications; Manager; and Sustainability Officer.	6 hours and 50 minutes
Product development department (Prod.)	Project Lead (2x); Process Architect; Domain Architect – mechanical; and Domain Architect – electrical.	5 hours and 20 minutes
Compliance & quality (Compl.)	Department Lead; Environmental Policy & Eco-Design; Product Safety Expert (2x); and Quality Lead.	5 hours and 50 minutes
Remanufacturing (Reman.)	Program lead; Program Manager; Project Manager; Industrial Engineer; Sustainability Manager; Supply Chain Engineer; Remanufacturing Technician (6x); and Compliance Engineer.	8 hours and 50 minutes

The interview data from the first week was collected through making field notes. The interviews in the second, third, and fourth week were recorded and transcribed. In several instances, follow-up interviews were planned to let the interviewees respond to topics brought up by other departments, ensuring internal validity [35].

Central to the study is the professional imaging equipment that the company produces. Data about these products were collected through company documentation, observations, photos/ images, and interviews; including multiple sources of evidence enabled data triangulation [35]. Additional data were collected through participant and non-participant observations and by reviewing company documents. The observations concerned the operations at the remanufacturing workshop with its different stations, from inbound to disassembly to cleaning, the quality and types of systems remanufactured, as well as the detailed operations (such as the way remanufacturing technicians would consult the information system to get access to specific instructions). These observations were documented in a field diary, structured following date and type of event, and by taking photographs. The events were described in short notes about the activities of employees, the process set-ups, atmosphere, insights and ideas from the note taker, possible follow-up questions, and remarks by employees.

5.3.3 DATA ANALYSIS

The balanced scorecard, introduced in the background section, was used for the case analysis, by providing four main themes. The method for thematic analysis proposed by Castleberry & Nolen [36] was used to analyse qualitative data in detail.

As a first step, the compiled data was coded to group similar data using an open coding scheme. After this step, codes that revealed patterns or relations were linked to one of the themes. To move towards interpretation, a narrative was created for each theme based on the causal sequences found during the reading-cycles. This narrative was further detailed and improved upon by iterating and revising early tentative statements. Creating such a narrative was a helpful way to convey all the details, interdependencies, and relations of the events observed at the case company, see the example in Table 5.2. This process was repeated several times with all co-authors, as well as a company-contact. As a last step, conclusions were drawn from the narratives to formulate an answer to the research question.

TABLE 5.2 Narrative development based on the interview transcripts.

Sentences from transcript	Case narrative
- The market maturity curve largely determines the possibilities for remanufacturing - Remanufacturing is a low-effort option to provide products to customers as we do not need a new development cycle to do this. - We plan to replace one technology by a new version for this category. Remanufacturing is used to cover the remaining customer demand.	At the case company, remanufacturing is seen as a very effective strategy to fill gaps in the product portfolio for newly manufactured products. It is used when products, that are already on the market, are taken out of production, while there appears to still be market demand.

The results were reviewed by key informants from the case company to corroborate the findings. This took place in two stages. In the first stage, after an initial round of data analysis, a short report with key findings was shared and reviewed by the company; in the second stage, after structured analysis, a more elaborate and detailed set of findings was shared and reviewed in several rounds.

5.4 CASE DESCRIPTION

The case company is a globally operating original equipment manufacturer in the imaging equipment industry with a long history of remanufacturing. The remanufacturing production facility is located in Europe, next to the development and manufacturing plant for new products. The brand is known for its high standards with regards to product safety, quality and environmental impact, which helped in initiating its first remanufacturing production line in the 80' s. The case company is strongly technology-driven, its product development department employs over 500 people.

The case company was highly successful in combining manufacturing and remanufacturing back in the 80' s. To give an example, for one of the products the company produced 120 new printers, and 100 remanufactured printers, each day. The remanufacturing department employed about 200 people spread over different locations. At that point, the product portfolio was relatively uniform. With an increase in variety in the product portfolio over the years, the opportunities for product and part remanufacturing diminished. Remanufacturing activities did continue, yet on a smaller scale. This increase was caused by a strong focus on the rapid development of new printing technologies to increase speed and improved user workflows. The remanufacturing process got decentralised and shifted to the regional divisions of the company, weakening the link with new product development.

In 2018, the company took a step towards renewed integration of remanufacturing by again centralising, refocusing, and renaming the remanufacturing department, as well as developing a company standard for ease-of-disassembly. The remanufacturing production capacity did scale up after renewing the operations. The product portfolio of newly developed products of this division contains about thirty products. Two of these products are remanufactured in full, two to three each month. And an additional 1200 spare parts are remanufactured each month. At the moment, around thirty people are employed at the remanufacturing department.

5.5 RESULTS

The results section follows the four design management perspectives that were introduced in the background section: the customer, process, learning, and value perspective. For these perspectives, the ongoing processes related to design management to support remanufacturing are described, as well as their associated barriers and opportunities. To put the case into context, four product types are introduced and referred to throughout the results section. The descriptions of the products can be found in Table 5.3.

TABLE 5.3 Description of products at the case study company.

Products	Type	Characteristics	Example of application
Product A	- High-volume, black-white printer - Introduced in 2006 - Fit for remanufacturing	- Large-sized market - Market demand is stable for longer than expected - Long lasting from both a commercial and engineering perspective - Low in maintenance, requires only a few part replacements during the use-phase - Product architecture has been stable for decades.	On-demand printing of books
Product B	- Wide-format, colour printer - Introduced in 2008 - Fit for remanufacturing	- Hard-to-mimic toner cartridges - Low interest from competitors and brokers because of the exclusive technology - High return flow of products	Architectural blueprints of buildings
Product C	- Flatbed, large-format printer - Introduced in 2002 - Not fit for remanufacturing	- The required stack-up tolerances of parts cannot be ensured for remanufacturing - The stack-up only succeeds for certain sets of parts put together by highly-qualified technicians. - Remanufacturing was not a feasible business idea according to the lead developer of this product, for this reason the fundamental architecture of the design does not support it	Printing on a solid area, like a glass door.
Product D	- High volume colour printer - To be introduced - Currently under development	- This printer is the successor of Product A and thus replaces Product A - Products A and D have technological synergies, main differences are full colour printing and increased printing speed	On-demand printing of books in full-colour.

5.5.1 CUSTOMER PERSPECTIVE

All of the activities at the case company are essentially designed to create value for their customers. In what way remanufacturing is used to create this value is discussed in this section. Firstly, by explaining the current market opportunities the company sees, as well as discussing the frictions present in early-stage design.

5.5.1.1 *Remanufacturing as an afterthought*

At the case company, remanufacturing is seen as a very effective strategy to fill gaps in the product portfolio for newly manufactured products. It is used when products, that are already on the market, are taken out of production, while there appears to still be market demand. In such a situation the company appeals to the potential of products to be remanufactured and reintroduced to the market. The following examples of products A and B illustrate the value thisit generates rto customers.

In the case of Product A, the company expected the market to have switched to full colour printing. However, market demand for black-white printing remained unexpectedly high. To meet this unanticipated market demand, a remanufacturing production line was initiated. This way, customers would still have access to a product for black-white printing.

In the other example, the company did not have a fitting successor for Product B at the time it was taken out of production. To provide the market with a similar offer, a remanufacturing line was set up. A significant enabler was the product's hard-to-mimic technology of this specific product, which kept competitors and brokers out of entering the market. This way, the customers' need for the wide-format colour printers was met.

These examples show that the company sees remanufacturing as an option only if market demand is proven to remain high after the product is out of manufacturing production. The risk of competing with new products was given as the main reason not to consider remanufacturing earlier on in the design process; this was based on the premise within the company that the target groups for remanufactured products and their newly designed successor have significant overlap. To illustrate this, at the moment Product D, the successor of Product A, will enter the market, the remanufacturing line of Product A will be halted. The two products are considered too similar to be produced simultaneously, causing the threat of market cannibalisation, which is perceived as a risk, especially for this expensive product type.

5.5.1.2 *Early-stage design integration considered impossible*

A closer look into the dynamics of early-stage design may help in understanding the exact opportunities and barriers for the company experiences to use remanufacturing to meet customer demand. Where initially there does not seem to be much room for this early-stage design integration, some opportunities did arise.

The Product Line Manager (Bus.), who oversees and manages the development process from start to finish, considers using remanufacturing as a tool to meet customer demand in early-stage design as nearly impossible. This is due to the risks associated with predicting future market demand, where estimations for market dynamics, technological development, and competitor behaviour all need to be considered at once. Besides, interviewees from both the business development and product development mention that the customer's mind-sets are typically programmed for new features, improved performance, and aesthetics. Such new features are improved levels of user workflow integration, improved customer experience, and increased productivity.

Closely related to the perspective on market demand is the market segmenting approach applied at the case company. This has to do with how the company divides the market into different customer segments. Currently, the dominant parameter in the segmentation approach is based on printing speed against costs. While this may indeed be important to customers buying the latest technology, it may not represent customers interested in remanufactured products well. According to the Product Manager (Bus.), a very limited amount of research is done to collect insights from the market for remanufacturing, which complicates defining market segments for such products. This also means that the level of differentiation between these customer segments has not been substantiated through customer research.

A reflection from the sales forces with regards to remanufactured products, is that they are used to offering customers new features instead of existing technology. Remanufatured products are therefore considered a difficult sell. Besides, the company incentives the sales of newly manufactured products significantly more than selling remanufactured products. This means that customers are not likely to hear about remanufactured product offers in the first place.

An opportunity for using remanufactured products to meet market needs was pointed out by the Strategic Planner (Bus.). He proposes a strategy where newly manufactured products, containing the latest printing technologies, are used to target new markets, whereas remanufactured products can be offered to the more mature markets. According to him, combining remanufactured and newly manufactured products would allow the company to focus their innovation capacity and still serve the needs of all customer segments. This way, careful management of the product portfolio could allow Products A and D to be sold simultaneously. In such combined portfolios, the stability of the product technology becomes the main driving force for remanufacturing.

5.5.1.3 Fragmented efforts deliver suboptimal results

To make remanufacturing attractive to the market, input from all departments is required. An example would be the need for marketeers to inform the market about possible remanufactured product offers. To inform the market in time, the sales organisation needs to be well-informed about the available offers. Their commitment is crucial for the commercial success of remanufacturing. The Program Lead (Reman.) notices that most departments are mainly concerned with developing and selling new printing technologies. According to him, making a greater financial impact through remanufacturing would be an effective way to get other departments committed.

To summarise, the case company uses remanufacturing to bridge gaps caused by unforeseen market demand, which cannot be met with newly manufactured products. Although remanufacturing is used to meet customer demand, early-stage design activities, like customer research and product portfolio management, do not consider remanufacturing. Commitment from other departments, and their orientation towards remanufacturing, would be important to successfully serve the market. In addition, having greater financial impact would draw out increased levels of commitment.

5.5.2 PROCESS PERSPECTIVE

Understanding how early-stage design decisions influence operationalising design for remanufacturing is the next step. This section dives into the processes in place and early- stage activities that ensure design integration. Besides covering the company standards for design, this section looks into product performance and required design competencies. It will also shed light on what part categories require early-stage involvement to support remanufacturing. This is essential for maintaining high product quality over the long term.

5.5.2.1 Operationalising design for remanufacturing through company standards

Under guidance of the compliance department, about 50 company standards help in designing compliant (to legislation), high-quality, and safe-to-use products. One of these standards is concerned with the End-of-Life of products. The first version of this standard was purely about being compliant to the European Union's Waste Electronics and Electrical Equipment (EU WEEE) directive, the EU Battery directive, and the compulsory markings that need to be applied to plastic parts.

To make designs better suited to End-of-Life scenarios, like remanufacturing, a new section on ease of dis- and reassembly was added to this company standard in 2018. About 30 design guidelines were added to Appendix 5-A. These 30 guidelines were developed in a multi-disciplinary team that involved the remanufacturing department, the compliance department, the business development department, and was led by the product development department. The team aimed at reducing the environmental impact of, and reducing labour- and material costs during, remanufacturing. It was also aimed at improving the alignment between stakeholders across the remanufacturing value chain. Examples of the guidelines are the following: to minimize variation of material types, to apply easy-to-see handles, to design light-weight units (<12 kg), to use standard screws, and to avoid the need to turn units during disassembly.

A certain level of flexibility is required for the guidelines, since their implications differ from product to product. Therefore, the guidelines are formulated qualitatively. This can be illustrated for the case of Product C. Enforcing these guidelines would require changes in the product architecture. Such impactful changes would drive up the design budget significantly. The Process Architect (Prod.) working on the design of Printer D is optimistic about the design guidelines, as he states: "From my point of view, these [guidelines] are relatively easy to integrate into the design process."

A downside of not having quantitative guidelines is that the level of implementation is hard to assess; yet, the design engineers fully rely upon these company standards. Without any tools for measurement, however, the effectivity of the company standard cannot be monitored. New versions of the standard proposing quantified design guidelines for remanufacturing have found significant resistance from the product development department.

Personal perspectives of lead engineers, and their affinity to remanufacturability, also affect the level of implementation. One of the Domain Architects states the following: "I have less affinity with this subject, so it wouldn't be my focus. Even if this has been written down in a [company standard]. Everything becomes fluid when under pressure." He continues by saying that the implementation of new requirements should take place before the end of the conceptual phase; after this point the product functionality and budgets are frozen, which means that it is costly or technically impossible to make big changes.

5.5.2.2 Remanufacturing process performance is hard to capture through key performance indicators

When it comes to operationalising through measurements, the Program Manager (Reman.) shares that there are no key performance indicators (KPIs) that impact remanufacturing directly. This means that the existing KPIs of the company do not support or counteract remanufacturing. He expresses no concerns about the absence of these KPIs and explains that the department does have targets for the product return rate, which is the fraction of products returning from the market, and the delivery performance. The return rate for some products turns out to be relatively low, about 30 %. The department is currently looking for ways to increase this number.

Drafting new KPIs is a challenge, according to the Program Manager. It is easy to cause unwanted side-effects, “One of the unwanted side-effects is poor quality. KPIs do not easily help steer this process in the right direction. In some way they can always be avoided or fulfilled with the least possible effort.”

5.5.2.3 Managing the quality and safety of products that serve multiple use-cycles

In producing products, high quality and safety are core values to the case company. All processes are optimised to ensure these values throughout a product’s first use-cycle. In what ways these high-quality and safety levels are maintained during remanufacturing will be explained based on the interviews with the development, compliance, and remanufacturing departments. Out of these interviews, several categories of parts were identified that primarily determine the quality and safety levels beyond the initial use-cycles. These are the identified part categories: (1) high-value parts; (2) software-related parts; (3) safety-critical parts; (4) procured parts; and (5) spare parts.

1. **High-value parts**

Professional imaging equipment often contain several high-value parts that make the reverse logistics and remanufacturing process viable from a cost perspective. For instance, for Product B, these are the printheads containing the print nozzles. This printer contains a number of print heads which make up the largest share of the printer’s value. For this product, a combination of parts harvesting (e.g. taking back printheads) and full product remanufacturing makes the process viable.

Identifying high-value parts at an early design stage can help to identify opportunities for remanufacturing early on. One of the Domain Architects (Prod.) explained: “I don’t think making an estimation about the remanufacturability of the different parts is time-consuming. Besides, any estimation is better than the non-estimation we are making now. I would estimate an average remanufacturing potential of about 80% of the parts. Important to keep in mind is, that the most valuable parts should be included in this 80 % for the process to be viable.”

2. **Software-related parts**

Another essential category includes the software-related parts. Keeping operating systems up to date and secure is of increasing importance to companies working with products connected to networks and the internet. Since imaging equipment connects to such networks, their operating systems need to be secure too. Product B, for instance, may be used by companies to print blueprints for the building industry. This may contain sensitive information which should not be accessible through hacks and other data leaks.

The operating systems of the printers are currently optimized to serve a single use-cycle, according to one of the Project Leads (Reman.). This means that the operating systems may not allow for software updates after this first use-cycle of about 7 years. If this is the case, the printer is not suited for remanufacturing. An interviewee from the product development department stated that "upgradable software-support-life is not a go/ no-go criterion for the product definition." Introducing such a standard would let more products be suitable for remanufacturing.

3. Safety-critical parts

To provide as-new product quality, the information about the safety-critical parts needs to be managed carefully. The remanufacturing department is confident about their level of information management concerning these aspects. According to the Program Manager (Reman.) and remanufacturing technicians, qualification tests are the same ones as used for newly manufactured products.

The Product Safety Expert (Compl.) expresses his concerns regarding the evidence collected about lifetime expectations of safety-critical parts. He estimates that about 10% of a printer's parts are safety-critical, most of which are the ones containing electronics. He is, for example, uncertain about the duration of the effectiveness of fire retardants in printer covers. According to the him, lifetime tests are needed to get a proper understanding of the behaviour of these parts. The remanufacturing department only reuses the safety-critical parts when they pass the original qualification tests.

4. Procured parts

Another, less critical, yet important category of parts was again pointed out by the Product Safety Expert (Compl.), which contains the procured parts. According to him, managing and tracing certificates of these parts is important to guarantee as-new quality. This information about externally sourced sub-assemblies, however, is often harder and costlier to acquire than for in-house parts. The Program Lead (Reman.) is in charge of monitoring certificates of these parts.

Procured parts can also become scarce when suppliers for any reason shut down pro- duction. In those cases, a 'last time buy' is often still an option. This, however, does generally not include the scenario to remanufacture.

5. Spare parts

The final category of parts is spare parts. Spare parts are essential for remanufacturing and for fulfilling service agreements. During the development of new product platforms, an estimation of the number of required spare parts is made. This is done based on expected production levels and the duration of the service agreements. Since the company does not plan for remanufacturing from an early stage on, the calculations for spare parts do not include a scenario for remanufacturing. When the company decides to remanufacture a product, it relies either on an extension of the production of newly manufactured spare parts, or on parts harvested from the market. In the case of product B, the need for spare parts was fulfilled by setting up a remanufacturing line for the print nozzles.

To summarise, this section describes the processes to manage product quality beyond the initial use-cycle. By introducing new design guidelines in 2018, the company tried to improve the ease-of-disassembly of products. The development and implementation of (additional) quantified or hard requirements remains a challenge, as not all stakeholders support this. Apart from several KPIs regarding the acquisition of products from the market, indicators are not used to regulate processes supportive of remanufacturing. The case company has a clear idea of the part categories critical to remanufacturing, however, the design and production (quantity) for these parts do generally not consider a remanufacturing scenario.

5.5.3 LEARNING PERSPECTIVE

This section dives into current mind-sets towards remanufacturing, the skills and training needed to transition towards circular thinking, and the ways to create awareness and acceptance of remanufacturing. Organisational change towards circular production systems at the case company is largely driven by bottom-up initiatives.

5.5.3.1 Competences for high-quality remanufacturing through experience-based learning

The skills needed to remanufacture products are developed through experience, there is no external educational track to train remanufacturing technicians. To reach the objective of delivering high-quality products, the remanufacturing technicians require extensive experience and expertise. Such experience is built up over the years while working at the production line of newly manufactured products. The technicians need to be familiar with the information system that is used: to know where product information is exactly located, but also to know how the products are constructed. Rebuilding a high-volume black-white printer (Product A), is more likely to succeed with having the experience of putting it together at an assembly line. These skills, therefore, are difficult and time consuming to transfer to new employees. Skilled technicians are therefore recruited from within the company, based on specific expertise profiles. The same is true for non-engineering skills for remanufacturing. The experience and knowledge from working with newly manufactured products form the basis for remanufacturing competencies.

5.5.3.2 Linear thinking remains the norm

Previous sections already touched upon customers' critical mind-set towards remanufacturing. The design engineers' mind-sets are just as critical. Most interviewees from the product development department recognize that there is a lack of awareness and interest in remanufacturing amongst engineers, including themselves. The Process Architect (Prod.) and Domain Architects (Prod.) argue that this one of the main reasons that remanufacturing is not included in the assignment they receive from the business development department. And if the business development department does not prioritise remanufacturing, it does not end up into the design brief, like was the case for Product C. The Process Architect (Prod.) notes that actions taken towards the integration of remanufacturing either comes from the remanufacturing or compliance department, or from individual initiatives driven by intrinsic motivation. The lack of integration and prioritisation is also reflected in the fact, that the central remanufacturing department was shut down for a number of years in the previous decade. The ease of halting the operations is a sign that this department's strategy and mission are relatively independent and detached from the development of new products.

5.5.3.3 Branding as a tool towards acceptance

Internal and external acceptance of remanufacturing are difficult to cultivate. The Program Lead (Reman.) is well aware of the attitude towards remanufacturing within the company, i.e. the level of internal acceptance, and within the market, i.e. the level of external acceptance. A common barrier is uncertainty about the quality potential and/or quality offered through remanufactured products. The Program Lead (Reman.) explains that this perception can be influenced by building a separate brand image for remanufactured products. According to the Program Lead (Reman.), trust is generated through building an image of the quality and performance of the products, as well as providing sufficient information. Renaming and repositioning the remanufacturing department several years back, was a first step in the department's branding strategy. The activity of creating this brand currently lies with the Program Lead (Reman.) himself and his direct colleagues.

To summarise, adjusting mind-sets and having clear drivers are needed to integrate design for remanufacturing in ways that not only underpin the engineering value, but also the strategic value. Lead engineers have indicated a need for a strategic direction, which should be provided by the business development department. This would allow remanufacturing to be adopted in the design brief. When it comes to the development of skills and expertise, informal educational pathways are the norm. Lastly, to move towards increased levels of commitment and trust from all departments, the first step is to use branding as a tool.

5.5.4 VALUE PERSPECTIVE

This section discusses the tangible and intangible value of remanufacturing, and what collective efforts are needed to optimise the business cases. In more detail, this section covers the process of setting up business cases for remanufacturing and it shows how the remanufacturing department seems to be a rather separate entity within the company.

5.5.4.1 Business case calculations may not reflect the actual potential

The impact the remanufacturing department makes within the company is indirectly related to the investments the company is willing to make in Design for Remanufacturing. Having high product volumes and high numbers of product types that are remanufactured, increases the company's willingness to invest in adjusting designs. From a value perspective, there are several factors that influence the development of business cases for remanufacturing.

The initial business case of new products does not include a remanufacturing scenario. The reason for this, is that remanufacturing does not create any revenues in the first years after the new product is launched. The calculations for remanufacturing business cases are therefore made separately.

The Program Manager (Reman.) expresses that there is room for optimization when it comes to developing these business cases. The most significant costs for the business case include transportation costs, production costs, and the costs of return credits. The Program Manager (Reman.) argues that it would be beneficial to exclude the return credits from these calculations, since this is a transaction made within the company itself. The revenues, on the other hand, are made up from the sales of the remanufactured product. The Program Manager (Reman.) argues here, that use-phase revenues, i.e. revenues from the sales of toner and from the service agreement during a printer's use-cycle, should also be included for the revenue calculations, since they are enabled through remanufacturing. The reason why they are excluded at the moment, is because the remanufacturing department is seen as a production department that produces durables and does not produce consumables (i.e. toner) or offer services. The reason why the Program Manager is concerned about the details of the business cases is, that the department does not receive a production budget, and is fully dependent on the success of business cases.

The level of product return rates also influences the success of a business case. This can be significantly improved through timely communicating the needs for certain types of products to the sales organisation. In the case of Product B, this was done effectively, causing the return rates to be higher than usual.

The Program Manager (Reman.) continues by saying that the business case for reman- ufacturing spare parts (e.g. parts that are used inside the company in servicing and reman- ufacturing operations) is made at an earlier stage than that of full printers. The enabler here, is that spare parts are already needed from the start of the first use-cycle in ser- vicing and can directly contribute to lowering operational costs. Another enabler here, is that end users do not interact with these servicing parts directly since they are posi- tioned behind the printer covers. Acceptance of using remanufactured spare parts, there- fore, does not play a significant role. Having a spare part remanufacturing line in place, however, may also support the business case for full remanufacturing, like in the earlier mentioned example of the print nozzles for Product B.

The constraint the department has when it comes to scaling up the production of remanufactured spare parts, is that they are not allowed to charge market-conform prices for the internal pricing. This is decided by the business development department. In other words, even though the department is the single supplier of these parts, after they are taken out of manufacturing production, the pricing of spare parts remains unchanged. As a result, the remanufacturing department does not have the advantage of being the single supplier.

To summarise, this section describes how the value of (design for) remanufactur- ing is influenced by the development of business cases. The business case calculations for remanufactured products are secondary to newly manufactured products and leave room for improvement in terms of effectiveness. They are primarily focused on tangible value, i.e. euros. Therefore, the additional strategic value brought in by design is not separately assessed or considered.

5.6 DISCUSSION

The data analysis of the previous section was based on Borja de Mozota's [33] balanced scorecard for design management. The results discuss remanufacturing from each of the four perspectives of this balanced scorecard. This section discusses and visualises the links and interrelations between the four perspectives by means of a strategy map. A strategy map is a framework that puts together the main results of the four company perspectives into one visual [34]. The focus of this framework is to examine the value creation by linking the intangible assets of the perspectives. This map helps in clarifying the contributions of this study.

Several adaptations were made to the lay-out of the strategy map prior to use. The reason for these adaptations was to ensure an optimal fit within a context of improved sustainable production. The process, customer, and value perspectives were rotated to all be connected to the learning perspective, to acknowledge the fact that this perspective supports the activities in the other perspectives (Figure 5.3). The resulting strategy map, which is presented in the form of an advice, can be seen in (Figure 5.4). All perspectives are equally important and the elements included in this map are not prioritized according to the order of implementation. They form a mix of shorter- and longer-term solutions. The map shows how design management theory can be used to identify elements that can feed into a design strategy that is attuned to developing products that serve multiple use-cycles.

Currently, the case company's remanufacturing design guidelines do not get prioritised during new product development. Where other recent case studies on the topic focus on operational aspects, such as optimising the transfer of process knowledge to optimise product design and process planning [22, 21], the strategy map presented in this paper suggests a strategic approach towards increased effectiveness of design. A first important link that this map shows is that of the strategic value of remanufacturing to the product requirements. This value stretches beyond seeing remanufacturing merely being a last resort to fill a gap in the product portfolio; its strategic value is acknowledged. Ansari et al. [37] list many possible advantages, i.e. creating market opportunities, saving resources, improving the brand image, increasing competitiveness, and increasing productivity. Similarly, advantages were found in studies by Kerr & Ryan [38], with regards to reduced environmental impact of photocopiers, and Östlin, with regards to applying new business strategies to ensure product returns from the market [39]. The strategy map presented in this paper describes the ways to develop such advantages through connected actions.

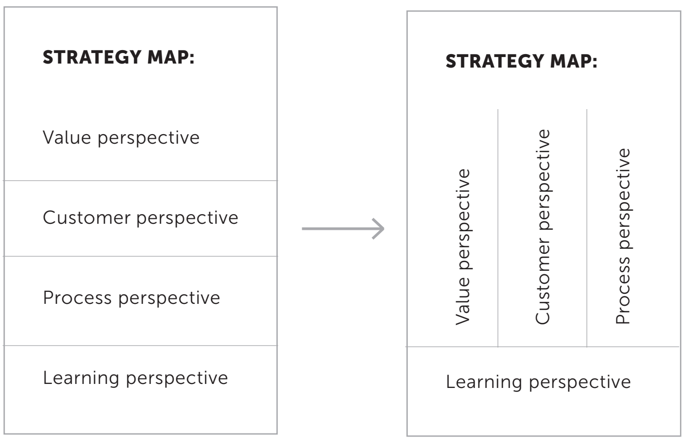

FIGURE 5.3 Adaptation to the strategy map lay-out.

The process perspective of the strategy map connects to the customer perspective as follows. New product requirements find their origins in customer research. The strongest argument to adopt a new feature is that it meets market demand. If the case company does not investigate the market needs for remanufactured products, evidence that supports the development of remanufacturable products will be lacking. In their paper, Chouinard et al. [40] stress the importance of researching customer needs in cir- cular product design as well. Bressanelli et al. [41] similarly found a lack of considering user needs for circular design in WEEE-industry research. This paper shows why and how this affects the integration of Design for Remanufacturing. Secondly, directly linked to customer research, is the product identity with which the company presents remanufactured products, i.e. how it promotes quality and relevance, but also how it wins customers' trust. Without this identity, customers, as well as employees, build their own perceptions around remanufactured products (possibly based on inaccurate information or information that is not specific to the case company).

The customer perspective connects to the value perspective, in which the central opportunity for improved implementation is to move towards an integrated business strategy, that includes both newly manufactured and remanufactured products. Early-stage integration allows the case company to anticipate on the earlier mentioned strategic values of remanufacturing. In this way, remanufacturing design guidelines can be included in the design brief, and because of that, receive a design budget. Previously, no budget was allocated to Design for Remanufacturing and it was listed as a recommended activity. This resulted in remanufacturing design requirements being neglected, caused by normal product development time pressure and the traditional focus of engineers. This tendency has been brought up in previous research [7, 5]. This paper explains the underlying causes related to the design brief and design budgets. There is another layer of depth to the business aspects within the value perspective that drives design; the case company focuses on business cases for product designs that will pay back within several years after market introduction. This period only covers a part of one full use-cycle and will therefore be optimised to only serve customer needs in this initial cycle. This means that remanufacturing is already factored out by aiming for a short pay-back period. Stretching this pay-back period would only make a difference when remanufacturing business cases are drafted early on in the process as well, i.e. in the early stages of new product development.

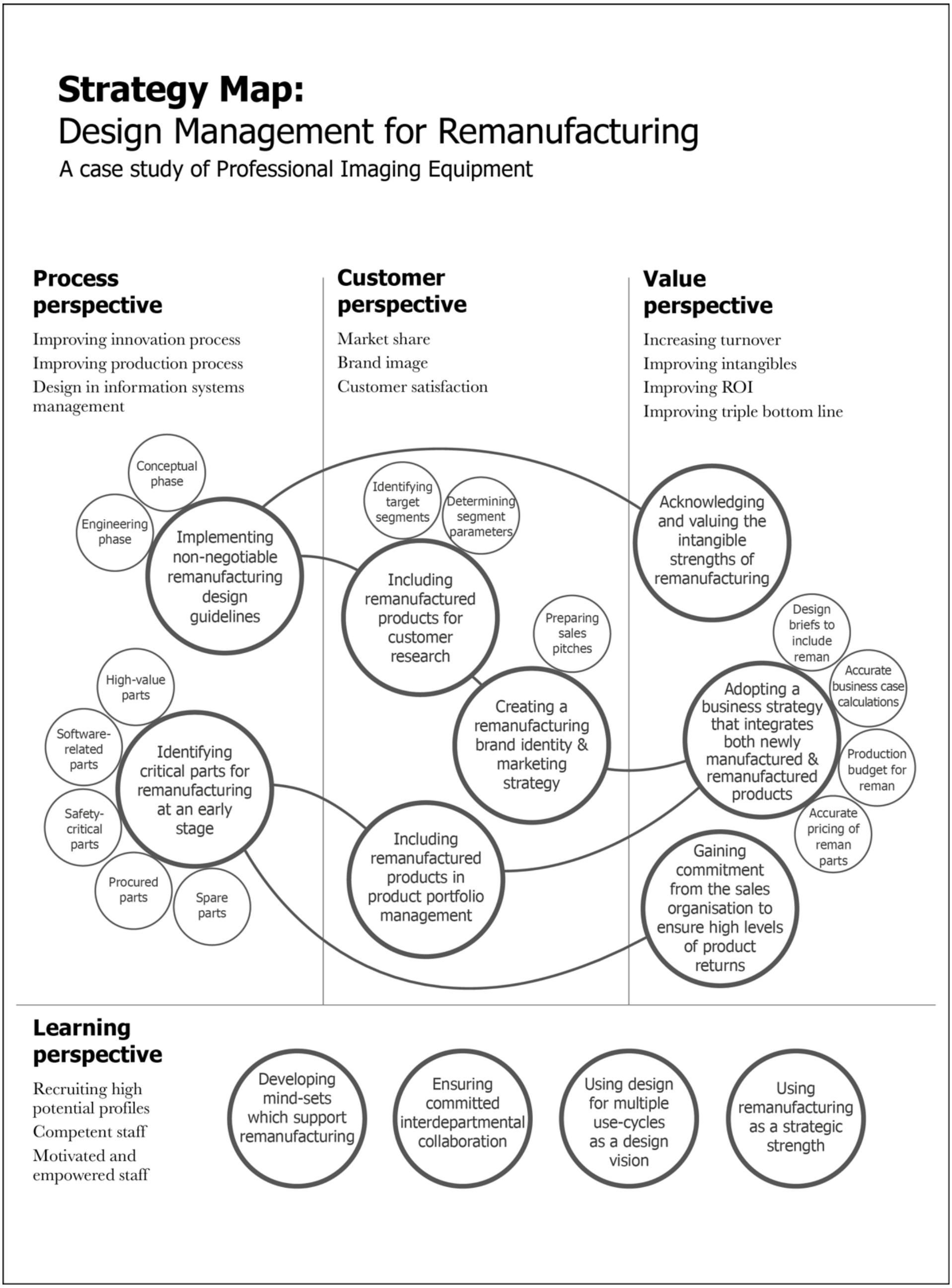

FIGURE 5.4 Strategy Map: An overview of strategic elements, and their interlinkages, of design management for remanufacturing.

The value perspective links back to the customer perspective through product portfolio management in the early design stage, in which both newly manufactured and remanufactured products should be included. Abbey et al. [42] propose differentiation strategies based on price and brand image to support such a combined portfolio. This paper revealed a need for collaboration with the marketing and sales department, to let strategic designers determine the most optimal way of serving customers, by making use of both product types. The customer perspective requires information originating from the process perspective to accurately build the product portfolio. This information concerns the remanufacturing potential of products and parts. Besides knowing what high-value parts a product contains [28], this study found additional important categories, like software-related and safety-critical parts. Identifying critical parts, again at an early design stage, helps to identify the remanufacturing potential.

Key in offering remanufactured products is to have a predictable inflow of products returning from the market. This is the final link in the strategy map between the process and value perspective. The flow of products returning from the market can be regulated by making early stage agreements with the sales organisation about the product types and targets needed, based on the estimated remanufacturing potential of products.

A fundamental part of the advice in the strategy map is captured by the learning perspective. Making use of the strategic strengths remanufacturing requires supportive mind-sets, design visions, and committed personnel. Instilling this from an early stage will activate employees and give them awareness of the topic, and a sense of ownership and commitment.

The practical value of this research may extend beyond this one case study, because of the rich and deep understanding it provides of the complexity of making remanufacturing part of the company strategy. The scientific value of this study is the contribution to the body of literature on Design for Remanufacturing – this is one of the first extensive case studies that takes a non-operational perspective and that elucidates the importance of combining a managerial and a design perspective through design management.

Recommendations for further research would therefore be to focus on strategic design elements through (longitudinal) case studies and action research, focused on implementing the proposed solutions in practice, and monitoring their effects. In more detail, this could mean setting up experiments about how to manage product portfolios that include both newly manufactured and remanufactured products. This could also mean building sector-specific insights of customer segments and their needs for remanufactured products. A third option would be to analyse products for their (strategic) potential to be remanufactured in the future in terms of their expectancy to meet customer needs in consecutive use- cycles. And a last recommendation would be to further investigate the effect remanufactuing business cases can have for a company, including its strategic value, and how to make them accurate. This would also mean investigating ways to adopt Design for Remanufacturing as a central part of future circular business models.

5.7 CONCLUSION

The study of this paper is an exploration as to how design management can support the strategic integration of Design for Remanufacturing in industry, and it demonstrates opportunities for further development in other company cases. Unique to this case study is the view on remanufacturing through four different perspectives by means of the balanced scorecard for design management. Combining these multi-angle findings led to a company-specific strategy map that shows the departmental interrelations and dependencies, and thereby exposes the opportunities for creating new value. Bringing together the four perspectives is crucial for successful product development [34].

In academic literature, product remanufacturing is often viewed as a goal in itself. To obtain increased levels of sustainable production, it could also function as an integrated approach for companies to address not only climate goals and resource efficiency, but let it be part of a wider circular system. To this end, remanufacturing should become more mainstream as it currently is. The extent to which product design can support this, is determined in the early design stage. This case study helped in shedding light on the many soft barriers that are still there.

At the case company, remanufacturing was found to be separate from, and secondary to, the development and production of newly manufactured products. Because of this implicit status, there is a gap when it comes to a design vision and an integrated business strategy for remanufacturing. Closing this gap can be done by using design management to draw up a design strategy that is attuned to developing products for multiple use-cycles. Not addressing this gap will produce suboptimal results and the risk of leaving remanufacturing to be a value-retention strategy in isolation. In its current form, the case company utilizes only a part of the possible value that design for remanufacturing can bring. Selecting business models that support optimal product return rates from the market, like offering product-as-a-service, could support the case company to develop such circular design strategies.

Having a design vision and an integrated business strategy that considers both manufacturing and remanufacturing simultaneously, would open up the possibility to find alignment with new product design, take advantage of the strategic value of remanufacturing, and improve upon across-company buy-in for remanufacturing. Deploying the approach of a learning organisation towards such circular economy activities can be adopted through developing supportive mind-sets. These findings may be valid for other companies that have remanufacturing operations, which are separate, as well. This, however, would need to be corroborated through further research.

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APPENDIX 5-A

Interview protocol

Case study: Producer Professional Imaging Equipment

1. General questions

- What is your role within the company? What are your responsibilities? What do you deliver?
- Are you familiar with the different levels of product recovery at your company? Is it clear what these levels mean?
- In your view, what is the general mind-set towards remanufacturing within your department?
- How often is the topic of remanufacturing brought up in your team meetings? For what purpose?
- Do you have targets for remanufacturing?
- What could improve the implementation of Design for Remanufacturing?

2. Questions specific to the remanufacturing department

- Can you describe the remanufacturing process?
- What barriers and opportunities do you see that influence this process?
- Who is responsible for creating business value for remanufacturing?
- How are remanufactured products branded?
- How do you assess the quality remanufactured products?
- Is there a difference in service costs for remanufactured products? If so, what factors
- are of influence here?
- What market needs does a remanufactured product need to meet?
- What is needed to get customers interested in remanufactured products?
- How do you manage core acquisition?

3. Questions specific to the compliance department

- Who initiated the development of the company standard for ease-of-disassembly?
- Can you describe the process of developing the company standard for ease-of-disassembly?
- In what way was the company standard introduced and implemented?
- What is the mind-set of the product development department towards this standard?
- What are legislative barriers and enablers to remanufacturing?
- What opportunities do you see for improved implementation of Design for Remanufacturing?

4. Questions specific to the business development and marketing
- Who is responsible for creating business value for remanufacturing?
- What is the process of developing business cases for remanufacturing?
- What is the role of remanufactured products within the product portfolio?
- What are the differences in meeting customer needs when comparing remanufatured products to newly manufactured product?
- What do customers value most about remanufactured products? What is the unique selling point?
- How can you get customers interested in buying remanufactured products?
- What target segments buy remanufactured products?
- To what extent are end-users willing to accept remanufactured products?
- What are reasons to sell remanufactured products?
- What are reasons not to sell remanufactured products?
- What can be learned from past success stories of remanufacturing?

5. Questions specific to the product development department
- What product functions do you design for?
- To what extent does your department have knowledge to design a product for remanufacturing from a technical viewpoint?
- To what extent does your department have knowledge to design a product for remanufacturing from a strategic viewpoint?
- For product X, what are the parts that could serve multiple use-cycles? What parts
- cannot be reused?
- Do you have product examples of ten years ago for which it is possible to retrofit
- current-day technologies?
- What market needs does a remanufactured product need to meet?
- How can you get customers interested in buying remanufactured products?
- What is the role of the business development department in designing remanufacturable products.

DECLARATIONS

Funding

This paper was funded through EU-funded H2020 project 'Resource-Efficient Circular Product Service Systems' (ReCiPSS), under grant agreement number 776577-2. The study was conducted in consul- tation with EU funded EIT KIC Raw Materials projects, called: 'Remanufacturing Pathways' (RemanPath), under grant agreement number 17087, and Catalyse Remanufacturing through Design Bootcamp (CARED), under grant agreement number 18024.

Data availability

The data is not publicly accessible due to sensitivity reasons.

Code availability Not applicable.

Conflicts of interest/Competing interests Not applicable.

Ethics approval

The ethics approval was covered by signing an NDA with the case study company.

Consent to participate

The purpose for data collection was explained to all participants before every interview or observation. The participants were asked for approval to be included in the study separately.

Consent for publication

The case study company reviewed the final version of the manuscript and approved it before submission.

Open Access

CHAPTER 6

REMANUFACTURING WORKSHOPS WITH PROFESSIONALS TO OVERCOME BARRIERS -OUTCOMES OF TWO EU PROJECTS

This chapter has been published as:
Boorsma, N., Peck, D., Fischer, S., Bakker, C., & Balkenende, R. (2018). Remanufacturing workshops with professionals to overcome barriers-outcomes of two EU projects. *Proceedings of Conference Going Green—Care Innovation.*

ABSTRACT

Remanufacturing is seen as a key strategy as part of the transition towards a circular economy. Remanufacturers encounter various barriers in their operations, even after being applied in various for over decades. These barriers, along with propositions to overcome them, are discussed extensively in academic literature. This paper focuses on the process of translating the barriers found in literature and field studies into lifelong learning materials for remanufacturers. In this process, a workshop for remanufacturing entrepreneurs and practitioners was developed, aimed at overcoming the barriers identified in literature and in two European Union KIC EIT Raw Materials funded projects. More widely, the outcomes aim to foster the further development and exploitation of remanufacturing practice. The workshop was based on literature and case studies that highlighted barriers to remanufacturing. The workshop exercises support participants in developing company specific solutions, and simultaneously provides a framework for discussion. Based on participants' evaluations, exercises discussing product design, selecting a business model and planning reverse logistics were considered most insightful. Lower rated aspects, included offering more services around products and offering products as services.

6.1 INTRODUCTION

Over recent decades, governments and companies are increasingly interested in product recovery strategies. This increase is propelled by numerous internal and external drivers. On a governmental level the increase is caused for example by the need to secure critical materials and to comply with international climate goals. On a company level this is mainly driven by the need to secure resources, maintain competitive advantage and to meet regulatory requirements and actions by the government. Previous studies in the two KIC projects called 'Key success factors for re-use Networks' (RUN) and 'Bridging the raw materials knowledge gap for reuse and remanufacturing professionals' (ReUK), have introduced barriers to remanufacturing, which practitioners encounter on a daily basis. In support of this work, the development of lifelong learning tools should be developed to help remanufacturers overcome the found barriers.

This paper aims to address this gap through the development of a workshop which can assist organisations in developing specific product recovery solutions. To support the workshop development, a selection of workshop topics was made and the learning goals were listed. These goals include ways to identify business opportunities and the ability to test if a product can be remanufactured.

To tailor the contents to the target audience, an iterative design process was set up, using a circular economy expert panel. Multiple sessions with this panel helped to further develop the content with respect to the exercises, the structure and the usability.

The workshop includes exercises in which companies are challenged to create new value propositions for remanufactured products, aimed at customer acceptance, with the primary focus to reduce the perceived risk of buying previously owned products. Part of this offer is to build in an incentive for the consumer to return the products at the end-of-use. Simultaneously, the company needs a plan to roll out the reverse logistics to facilitate these returns and look into the requirements to set up re-use and remanufacturing operations.

The exercises perceived by the participants as most useful, are those focused on the suitability of a product for remanufacturing, setting up reverse logistics and the types of business models. A topic companies found to rate lower is offering more services to customers, including offering products as services.

6.2 METHODOLOGY

The literature on the field on existing barriers was supplemented by field research executed in the EU funded project ReUK. The workshop aspect of the project was developed in conjunction with the research, to provide suitable results for analysis.

The workshops were run in Germany (x2) and the Netherlands (x1) with this workshop providing ten evaluation forms, which are analysed in more detail. The development of the workshop consisted of several consecutive and iterative phases. During the first phase, the boundary conditions of the workshop were determined. This was done based on the project objectives and a report on knowledge gaps, compiled by Wuppertal Institute [5]. The project objective, originated from the ReUK project proposal, was realised via workshops for professionals, along the following three learning goals

- how to identify opportunities for re-use and remanufacturing
- how to test if a product can be reused or remanufactured, from a design, logistics and business perspective
- how to develop a reuse or remanufacturing business

Although these learning goals are central to the workshops, an important expectation was to bring professionals together to allow them to exchange knowledge and to network.

The workshops were developed using a 'framework of barriers. The report on knowledge gaps generated the following table of barriers, adopted from [5], using the framework for technological innovation systems of Hekkert et al. (2007) [10] (Table 6.1). The seven system functions which make up the framework are: F.1. Entrepreneurial activities and technology, F.2. Knowledge development and information management, F.3. Cooperation, F.4. Policy and regulation, F.5. Market, F.6. Resources and F.7. Creation of legitimacy. The F.2 column ('knowledge development and information management') was selected as it judged by the researchers to be the best fit. Based on their relation with this function (F.2), the barriers are divided into three tiers. The first-tier barriers have the strongest relation with this function, the second-tier barriers are related to this function, yet have a stronger relation with another function and the third-tier barriers have a weak relation with this function. The gray cells indicate the strongest function relation with the barriers.

TABLE 6.1 Adopted from 'Report on ten knowledge gaps' by Fischer, Benke & Wilts (2017) [5].

1st tier barriers	F.1	F.2	F.3	F.4	F.5	F.6	F.7
B.1.1 Definitions, standards and classification	X	X	X	X			X
B.1.2 Mind-set, commitment and awareness	X	X	X				X
B.1.3 Understanding the customer	X	X	X		X		X
B.1.4 Economic benefits, risks and resource prices		X	X	X	X	X	X
B.1.5 Raw material savings and externalities		X	X	X	X	X	X
B.1.6 Skills and education	X	X	X				X
B.1.7 Product design	X	X	X				X
B.1.8 Product-related data	X	X	X				X
B.1.9 Exchange platforms	X	X	X				X
B.1.10 Metrics	X	X	X				X
2nd tier barriers							
B.2.1 Trade barriers	X	X		X	X		X
B.2.2 Market demand	X	X		X	X		X
B.2.3 Supply of components	X	X	X	X	X		X
B.2.4 Communication and collaboration	X	X	X				X
B.2.5 Legal framework	X	X	X	X			X
B.2.6 Reverse supply chain	X	X	X		X	X	X
B.2.7 Public procurement	X	X		X	X	X	X
B.2.8 Innovation dynamics and technological progress	X	X			X		
3rd tier barriers							
B.3.1 Competition	X			X	X		X
B.3.2 Costs	X			X		X	X
B.3.3 Lobby	X						X

6.2.1 WORKSHOP CONTENT DEVELOPMENT

In the second phase, the development of the workshop content was key, which is based on the selected workshop focus: the learning goals and the first-tier barriers. The workshop content is designed in iterative steps, by using a panel of fourteen circular economy experts (Figure 6.1). The first concept was put forward in a series of one-on-one discussion, where the content and structure were evaluated and adjusted multiple times. Then the preliminary version 1 was presented to a panel of six PhD researchers and four senior researchers. From the feedback collected during this session a new version (2) was made. Next, a small- scale dry-run of the workshop followed, with again, based on the feedback, a new version (3) as the result. The final round existed of two dedicated one-on-one session to evaluate and finetune the usability and structure of the exercises. The final result of the workshop content is presented in the results section.

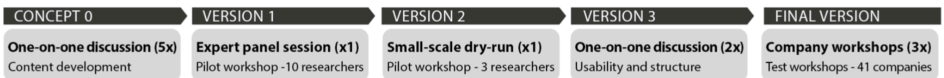


Figure 6.1 Iteration phases of workshop content development.

6.2.2 SELECTION OF PARTICIPANTS

The main results data was derived from the Netherlands based workshop. The project team determined that participants would be invited from an existing Delft based, raw materials network. A selection requirement was that the participants had an interest in developing reuse and remanufacturing activity. An invitation was posted to the network and ten participants responded. The participants were from the following sectors; Construction and Real Estate, ICE and Electronics, Electrical Equipment, Electro mechanics, Cooling Equipment, Transport and Logistics and Home Appliances.

6.2.3 WORKSHOP SET-UP

All workshop participants received a printed version of the exercise sheet shown in Figure 6.2. The workshop was run three times, with a total of 41 professionals. The workshop is called the 'RR Workshop' and the materials included the exercise sheet, a presentation slide deck, practice examples, an evaluation form and the facilitator's manual. The workshop structure is described in Table 6.2.

TABLE 6.2 Workshop structure.

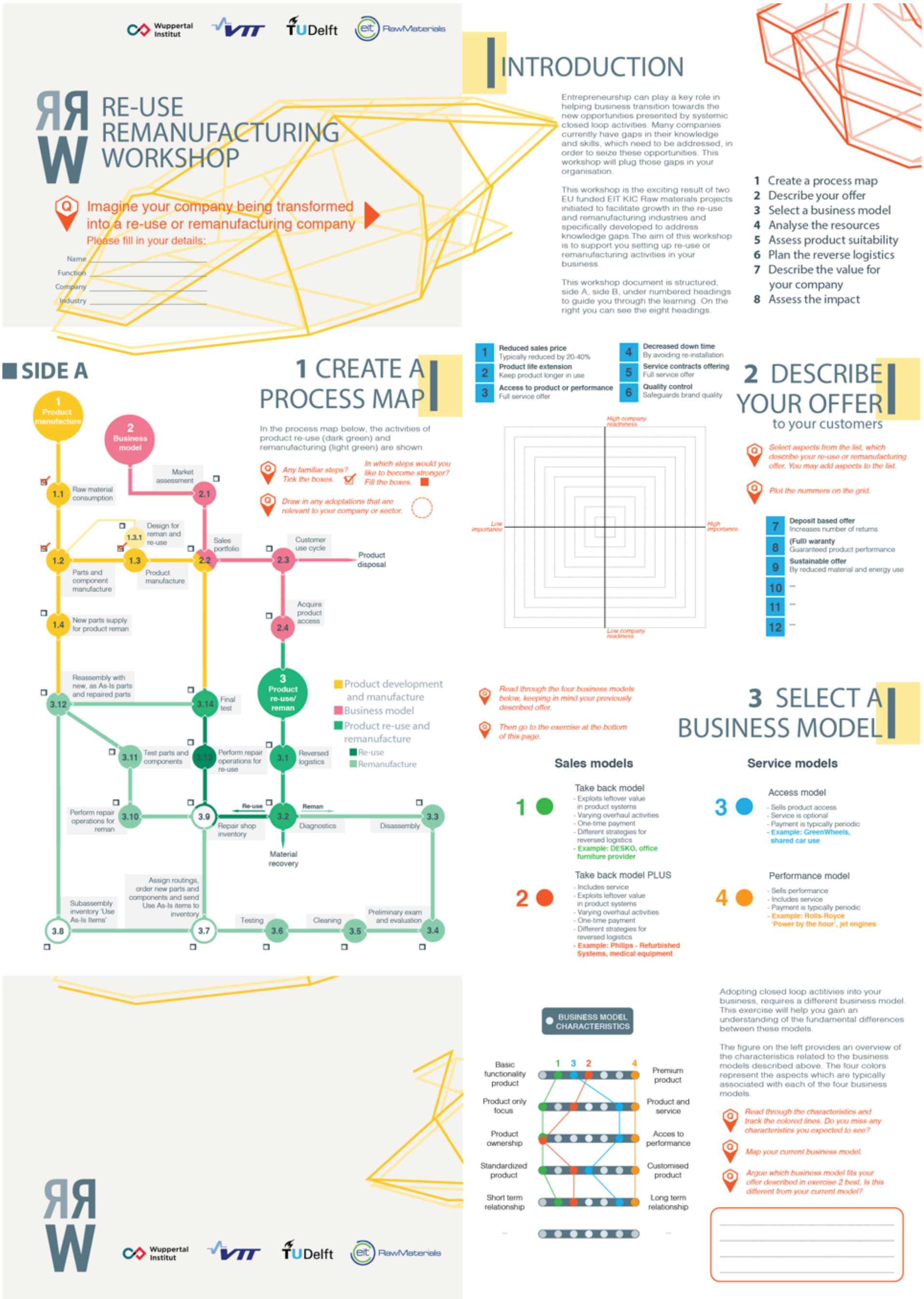
Workshop structure			
	Exercises	**Description**	**Learning objective**
1	Introduction	Introduction of the objective of the workshop as part of ReUK project.	
2	Exercise 1: Create a process map	The definition and proceedings of both remanufacturing and re-use activities are discussed in depth. Participants are also asked to mark the activities they are familiar with and those they want to investigate further. [7][8][9]	Distinguish circular processes Being able to name three main differences between product remanufacture and re-use.
3	Exercise 2: Describe your offer	Remanufactured products typically have a different value proposition from virgin products. In this exercise participants are asked to compose their value proposition using the elements from the list and to map the elements on the quadrants, indicating their importance and the company readiness to pursue them. [13]	*Understand customer needs* Recognising different customer needs for product manufacture, remanufacture and re-use and understanding their consequences for the business model.
4	Exercise 3: Select a business model	In this exercise four types of business models are presented. The participants are asked to take a look at the different possibilities and argue which one fits their products best by looking at business model characteristics (functionality, service, ownership, standardization, etc.). [2]	Distinguish business models The ability to name different characteristics of the business models and their effect on product design and the return flow of products.
5	Exercise 4: Analyse the resources	The purpose of this exercise is to dive deeper into the remanufacturing operations. The participants are asked to describe what resources are required to execute the activities found in the process map of the first exercise as well as indicating their complexity. [1][3][11]	Perform a resource analysis The ability to perform a resource analysis using the provided tools.
6	Exercise 5: Assess product suitability	By means of eight statements the participants evaluate how suitable their product is for remanufacturing. The statements can be valued on a 5-point scale, the outcome of the exercise is a spider diagram. [6]	Design for remanufacturing and re-use The ability to name eight guidelines to evaluate the product's suitability for product re-use and remanufacturing.

TABLE 6.2 Continued.

Workshop structure			
	Exercises	**Description**	**Learning objective**
7	Exercise 6: Plan the reverse logistics	Participants are asked to go through a decision-tree of three questions, to find their most appropriate solution area. The three solution areas discussed are: utilizing existing channels of the forward supply chain, looking at customer touchpoints which allow product drop-off and pick-up or by developing up new partnerships.	Plan development for reverse logistics The ability to recognize and name three different strategies to set up reverse logistics.
8	Exercise 7: Describe the value for your company	The set-up is equal to the set-up of exercise 2. However, this time the purpose is to identify the value remanufacturing can have for the company instead of for consumers. In other words, here too are participants asked to select elements from the list and to map the elements on the quadrants, indicating their importance and the company readiness to pursue them. [4]	Strategic leadership in circular business Recognising a company's strengths by looking at its resources.
9	Exercise 8: Assess impact on environment and costs	Re-using materials has an impact on the amount of materials needed for production. This exercise was designed to let participants reflect on their possible impact in terms of material, energy, water and CO_2 use. [12]	Understand effects on savings The ability to name at least thee material characteristic, which enable material re-used.
10	Workshop evaluation	Completion of the evaluation form by the workshop participants	

TABLE 6.3 Participants' evaluation results.

Participants' evaluation results	- -	-	- +	+	+ +	N/A	Totals
Workshop exercises							
Exercise 1: Create a process map			4	2	1		4
Exercise 2: Describe your offer			4	1	1	1	3
Exercise 3: Select a business model			2	2	3		8
Exercise 4: Analyse the resources			4	2		1	2
Exercise 5: Assess product suitability			1	3	4		11
Exercise 6: Plan the reverse logistics			3	2	2		6
Exercise 7: Describe the value for your company			2	2	1	2	3
Exercise 8: Assess impact on environment and costs			2	3		2	3
Importance of elements of remanufacturing							
The product architecture: how the elements of each of your products fit together				5	2		9
Having the skills and knowledge tod esign new products				7			7
Changing your offering/ value proposition			1	2	3	1	8
Taking a broader perspective on how your firm creates value, e.g. people, planet, profit				3	3	1	9
Offering more services around your products, for example maintenance or repair services			3	2	1	1	4
Offering your products as services			3	2	1	1	4
Creating your business model and product design in an integrated way			2	4	1		6
Engaging with your suppliers				3	3	1	9
Creating new products/ services together with your suppliers			1	3	2		7
Investing in reverse logistics, for example remanufacturing or dealing with take-back rates of your products				1	5	1	11
Convincing your existing customers of your new circular offerings			1	2	4		10
Finding new customers for your circular offerings			1	1	5		11



Wuppertal Institut
VTT
TU Delft
eit RawMaterials
RE-USE
REMANUFACTURING
WORKSHOP
Imagine your company being transformed into a re-use or remanufacturing company
Please fill in your details:
Name
Function
Company
Industry
INTRODUCTION
Entrepreneurship can play a key role in helping business transition towards the new opportunities presented by systemic closed loop activities. Many companies currently have gaps in their knowledge and skills, which need to be addressed, in order to seize these opportunities. This workshop will plug those gaps in your organisation.
This workshop is the exciting result of two EU funded EIT KIC Raw materials projects initiated to facilitate growth in the re-use and remanufacturing industries and specifically developed to address knowledge gaps. The aim of this workshop is to support you setting up re-use or remanufacturing activities in your business.
This workshop document is structured, side A, side B, under numbered headings to guide you through the learning. On the right you can see the eight headings.
1 Create a process map
2 Describe your offer
3 Select a business model
4 Analyse the resources
5 Assess product suitability
6 Plan the reverse logistics
7 Describe the value for your company
8 Assess the impact
SIDE A
1 CREATE A PROCESS MAP
In the process map below, the activities of product re-use (dark green) and remanufacturing (light green) are shown.
Any familiar steps? Tick the boxes.
In which steps would you like to become stronger? Fill the boxes.
Draw in any adoptions that are relevant to your company or sector.
1 Product manufacture
2 Business model
3 Product re-use/ reman
Product development and manufacture
Business model
Product re-use and remanufacture
Re-use
Remanufacture
2 DESCRIBE YOUR OFFER to your customers
1 Reduced sales price Typically reduced by 20-40%
2 Product life extension Keep product longer in use
3 Access to product or performance Full service offer
4 Decreased down time By avoiding re-installation
5 Service contracts offering Full service offer
6 Quality control Safeguards brand quality
Select aspects from the list, which describe your re-use or remanufacturing offer. You may add aspects to the list.
Plot the nummers on the grid.
7 Deposit based offer Increases number of returns
8 (Full) waranty Guaranteed product performance
9 Sustainable offer By reduced material and energy use
3 SELECT A BUSINESS MODEL
Read through the four business models below, keeping in mind your previously described offer.
Then go to the exercise at the bottom of this page.
Sales models
Service models
1 Take back model
2 Take back model PLUS
3 Access model
4 Performance model
BUSINESS MODEL CHARACTERISTICS
Basic functionality product
Premium product
Product only focus
Product and service
Product ownership
Acces to performance
Standardized product
Customised product
Short term relationship
Long term relationship
Adopting closed loop actitivies into your business, requires a different business model. This exercise will help you gain an understanding of the fundamental differences between these models.
The figure on the left provides an overview of the characteristics related to the business models described above. The four colors represent the aspects which are typically associated with each of the four business models.
Read through the characteristics and track the colored lines. Do you miss any characteristics you expected to see?
Map your current business model.
Argue which business model fits your offer described in exercise 2 best. Is this different from your current model?

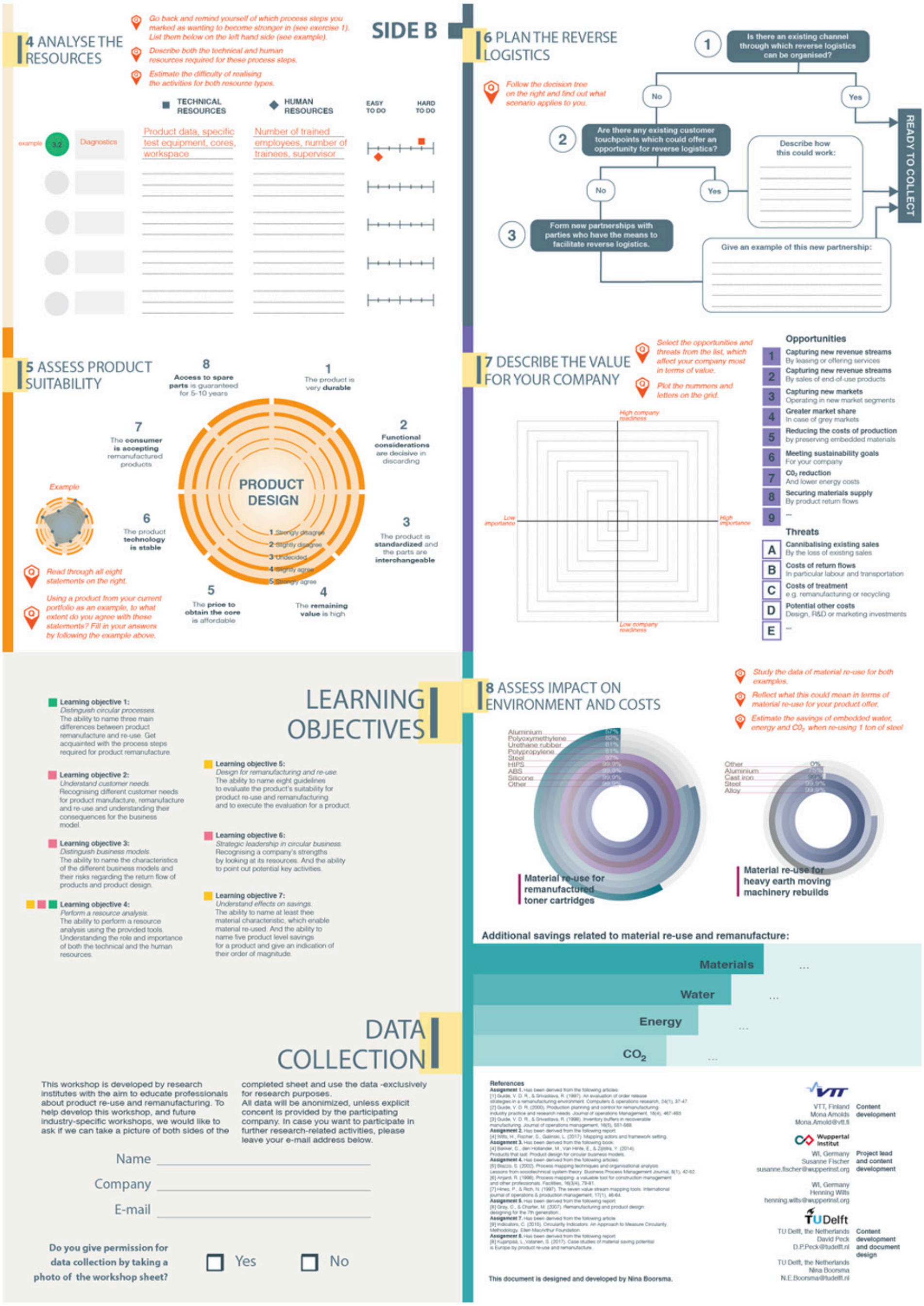


FIGURE 6.2 Exercise sheet Re-use and Remanufacturing workshop.

6

6.2.4 WORKSHOP EVALUATION FORM

After finishing the Netherlands based workshop, ten participants filled in an evaluation form, providing detailed insights. In addition, the workshop facilitators were asked to write an evaluation about the workshop. The participants' workshop evaluation form included the following headings:

- Company details
- Rating of the workshop exercise
- Rating of the elements of remanufacturing - Selection of business model type
- Ideal re-use and remanufacturing tool

6.3 RESULTS

The insights from the evaluation with the participants and facilitators, are presented in this section. Due to bias of three of the participants who worked for TUDelft, these three were excluded from the results, meaning only seven participants' results were used.

6.3.1 PARTICIPANTS' WORKSHOP EVALUATION

The order in which the exercises and the elements for remanufacturing were rated, are shown in Table 6.3. The business model the participants' indicated to be most promising to their companies, are shown in Table 6.4. The answers to the question what the ideal tool would be for three of these companies were:

- "A tool to help convince colleagues internally in the company about the importance of product re-use, but also to help implement circular ideas into the real world." – Machinery and equipment sector
- "We would like a tool containing practical advice, about for example product design, what is it exactly that should be repairable? What are legal requirements and legal pitfalls that re-use companies need consider? In general, when using the workshop material, we would recommend to give participants extensive time to exchange knowledge, discuss and really understand the needs from a customer perspective." – ICT and electronics sector
- "Session with examples and solutions to common barriers. Activities where you can learn from other people's experiences." – ICT and electronics sector
- "Tools for overcoming company culture, tools for creating a business case based on the different business models out there." – Professional cooling equipment

TABLE 6.4 Most promising business model.

Type of business model	1	2	3
Take back model	X		
Take back model incl. service	X		
Access model		X	
Performance model			X

6.3.2 FACILITATORS' WORKSHOP EVALUATION

The evaluation of the workshop according to the workshop facilitators was as follow. The main take- away of the workshop was that the exercise sheet helped start, structure and deepen the discussion amongst participants. Participants enjoyed the way the materials were presented. Some exercises provided several bits of complex information, which required the participants to take more time before being able to continue the discussion. Therefore, in case the tool should become accessible for a broader audience within companies, the language needs to be simplified and translated as much as possible in the native language. The tool is relatively general and not tailored to specific functions, which results in rather general discussions.

6.3.3 WORKSHOP SET-UP EVALUATION

Table 6.5 indicates which of the boundary conditions have been met by the current workshop set-up.

TABLE 6.5 Workshop evaluation table.

Workshop boundary conditions		
	List of first-tier barriers	**Boundary conditions met?**
1	B.1.1 Definitions, standards and classification	Briefly addressed in *Exercise 1*
2	B.1.2 Mind-set, commitment and awareness	No dedicated exercise
3	B.1.3 Understanding the customer	Addressed in *Exercise 2*
4	B.1.4 Economic benefits, risks and resource prices	Addressed in Exercise 7 and 8
5	B.1.5 Raw material savings and externalities	Addressed in *Exercise 8*
6	B.1.6 Skills and education	Addressed in *Exercise 4*
7	B.1.7 Product design	Addressed in *Exercise 5*
8	B.1.8 Product-related data	No dedicated exercise
9	B.1.9 Exchange platforms	The workshop itself can be considered and exchange platform, however there is no post-workshop continuity
10	B.1.10 Metrics	No dedicated exercise
	Project objectives	
11	how to identify opportunities for re-use and remanufacturing	Addressed in Exercises 2, 3 and 7
12	how to test if a product can be reused or remanufactured, from a design, logistics and business perspective	Addressed in Exercises 2, 3, 5 and 6
13	Although how to develop a reuse or remanufacturing business	The totality of the tool should provide a starting point, briefly addressed in more detail in *Exercise 4*
14	Allow knowledge exchange	Discussions and examples during the workshop contributed to this point, however there is no post-workshop continuity

6

6.4 DISCUSSION

Generally seen, the extent to which the workshop set- up meets the boundary conditions is high. Seven out of ten barriers, and all of the project objectives, are addressed through the workshop exercises. The remaining three barriers which are not addressed through the workshop exercises are barriers 2 ‘Mind- set, commitment and awareness’, 8 ‘Product-related data’ and 10 ‘Metrics’. Barrier 2 is not directly addressed in any of the exercises. However, attending a workshop in itself contributes to this topic, at least on an individual level. To solve this barrier on a wider level, for example on a company level, conducting multiple company-specific workshops could have an effect. Barriers 8 and 10, are not addressed in the workshop exercises either. These topics require additional dedicated research and could be addressed for example during in-depth workshops.

Even though the remaining barriers and project objectives are covered by the workshop materials, this particular workshop set-up allows only limited time per topic. For the participants to get a thorough understanding of the workshop topics, especially in relation to their companies, more time and more elaborate tools are required.

TABLE 6.6 Workshop participants’ highest and lowest rating of exercises and elements of remanufacturing.

	Exercises	Elements of remanufacturing
Highest rated	Eexercise 5: Assessing product suitability	Investing in reverse logistics, for example remanufacturing or dealing with take-back rates of your products
	Exercies 3: Selecting a business model	Convincing your existing customers of your new circular offerings
	Exercise 6: Planning the reverse logistics	Finding new customers for your circular offerings
Lowest rated	Exercise 4: Analysing the resources	Offering products as services
	Exercise 2: Describing your offer	Offering more services around your products, for example maintenance or repair services
	Exercise 8: Assess impact on environment and costs	Creating your business model and product design in an integrated way

6.5 CONCLUSION

This paper focuses on the development of a workshop for remanufacturing entrepreneurs and practitioners, aiming to overcome barriers in the field. Firstly, the results show that most of the barriers, which formed part of the boundary conditions, were addressed during the workshop. The question whether this resulted in helping companies to overcome the barriers, however, is more nuanced. To be able to answer this question thoroughly, the workshop should have included several surveys over time with the participants; one prior to the workshop, to determine the company-specific barriers, one right after the workshop, to determine the alignment of the exercises with the company-specific barriers and one several months after the workshop, to investigate whether the companies have actually overcome these company-specific barriers. Since only the second survey has taken place, the absolute effect could not me measured. Conclusions which could be drawn from this single survey, are the following.

The top 3 of highest-rated exercises can be found in Table 6.6 and are the ones covering topics around product design, business model types and planning the reverse logistics. Besides, the top 3 of highest rated elements of remanufacturing, are investing in reverse logistics, convincing existing customers and finding new customers.

Even though, convincing existing customers and finding new customers were rated relatively high, workshop exercise 2, which was focused on specifying the value proposition to the customer, scored relatively low. This indicated that either the exercise did not use the right language to convey the learning or the exercise set-up was not useful to the participants to reach their goal of convincing customers.

Also, elements related to 'offering products as services' and 'offering more services around your product' received lowest ratings, whereas the business model types 'take back model incl. service', 'performance model' and 'access model', all including services, were identified as most interesting by six out of seven participants. Even after going through the exercises, there appears to be a lack of understanding regarding the services included in these business models.

The final conclusion is, that to be able to meet the needs of companies in overcoming barriers in remanufacturing, the company-specific needs have to be identified prior to the development of the workshop. Also, the overview of barriers needs to cover the full range barriers, including both hard and soft barriers, to allow holistic and tailored solutions.

The current workshop set-up offered materials to facilitate a broad discussion on topics related to remanufacturing, whereas every exercise could be a workshop topic in itself. In other words, more topic dedicated workshops have the potential to add value for the workshop participants. Generic workshops are particularly effective for companies who are still in the exploratory phase with regards to remanufacturing. Companies who have reached the implementation stage, often look for knowledge to refine their business and are more likely to look for case specific or in-depth knowledge. For future use, it would be interesting to tailor the tool to different functions, to enable a more dedicated knowledge exchange.

In addition, the quality and quantity of received feedback can be improved in two ways. The first way is to take in a more longitudinal approach with several, potentially affecting insights in follow-up actions positively. Secondly, the maturity of the participating companies is not considered for the interpretation of the participants' evaluation. This evaluation is potentially correlated with company maturity.

Lastly, to be able to draw more general conclusion, more workshops and completed evaluation forms are needed.

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CHAPTER 7

DEVELOPMENT OF THE CIRCULAR PRODUCT READINESS METHOD IN CIRCULAR DESIGN

This chapter has been published as:
Boorsma, N., Polat, E., Bakker, C., Peck, D. & Balkenende, R. (2022). Development of the Circular Product Readiness method in circular design. *Sustainability*, 14 (15), 9288.

ABSTRACT

Design indicators can be used by companies to track circular design implementation, which can yield insights into their performance and opportunities for improvement. Yet, existing indicator methods either lack depth with regard to circular design, are incomplete, or do not use design semantics. This study explores product-level circularity indicators, with the aim to develop a comprehensive circularity indicator method specifically aimed at designers. The method development process follows a Design Science Research approach. Within this approach, literature re-view is conducted; knowledge coproduction sessions with circular design experts are organized on topics such as durability, repair, remanufacturing, and recycling; and company evaluations are carried out with two multinational corporations operating in the white goods and automotive industries, respectively. The study delivers the first indicator method that assesses circular product design on a broad range of aspects to indicate levels of readiness, company strengths, and opportunities for improvement. The method uses product design semantics to evaluate design aspects, takes a comprehensive view of the full life cycle, and is developed for industry use.

KEYWORDS
Sustainable manufacturing, sustainable design, design roadmap

7.1 INTRODUCTION

There appears to be increasing interest from companies in developing their circular design readiness by using indicators to monitor their progress [1,2]. The literature on circularity indicator methods is diverse, with indicator methods ranging from industry-level, meso approaches to product-level, micro approaches [2,3]. Product-level indicators tend to focus on resource circularity, usually using material flow analysis models to derive indicators [2–4]. Specific product-related indicators have been collected, categorized, and reviewed in several academic studies that, for example, assessed the product performance in circular settings and the circularity of a product's materials [5,6]. Other studies assessed the performance of specific design aspects, usually expressed in quantitative units, such as with longevity expressed in time, the recycling rate in percentage terms, or a remanufacturability score expressed as an aggregate of multiple variables [7–9]. After a review of product-focused indicators, Linder et al. [6] concluded that the Material Circularity Indicator scheme by the Ellen MacArthur Foundation contains the most ambitious set of indicators [10]. This tool measures the effectiveness of a company's transition based on material flows.

Despite the usefulness of this approach, and given that different sets of existing indicators contain information that is valuable to designers, none of these sets were made to guide designers sufficiently in their activities. In that context, the goal of this study was to develop a method to help monitor the implementation level of a circular product (or service) a company is designing. We developed this after noting the need for a method attuned to designers when assessing circular design implementation. We processed the results of our assessment of the efficacy of the method developed into an extensive report, to support strength-weakness analyses and design roadmapping activities. Such reporting can also be used to disseminate results to disciplines outside of design.

Design is considered an important factor in the transition from a linear to a circular economy. The way products are designed determines if, and under what conditions, products can be recovered. For example, design determines whether a product can be taken apart and put together again, maintained, repaired, or remanufactured. All desired events and behaviors a product experiences throughout its entire life cycle, from strategy to recovery, can be facilitated through design [11]. Having industry design professionals adopt circular product design contributes to realizing the economy's potential to become circular. To design products that are durable, reparable, and remanufacturable is a prominent part of the vision for circular product design, complemented by aspects such as having high-quality recycling options at the end-of-life.

The primary aim of circular product design is to maintain the largest part of a product's value for as long as possible [12,13]. Yet, fundamental differences of linear design make circular design hard to implement [14]. Circular products are to be designed for multiple use-cycles, and innovative solutions are to be developed to support that goal, drawing on disciplines across the board [15]. Examples of the fundamental differences for product design are whether designers sell functionality or performance as the core value, rather than the ownership of the product, whether they steer toward customer satisfaction instead of consumerism, and whether they think in terms of end-of-use products having potentially unlimited lifespans, instead of reaching the end-of-life after one use [16]. To make shifts such as these, including the earlier phases of design (i.e., strategic design) can contribute to embedding circular design in existing processes [17].

The content of this paper is structured as follows: The background chapter (2) analyzes existing indicator tools that assess circular product design, followed by the research design chapter (3), which explains the different steps of the approach taken in this study. Chapter 4 then describes the phases of development of the circular product readiness (CPR) method, and Chapter 5 presents the results of the evaluation with companies. Chapters 6 and 7 discuss the results of the study and goes on to draw final conclusions.

7.2 BACKGROUND

This section presents our analysis of a selection of micro-level indicator methods for circular product design. In doing so, it reveals gaps in the field of product-level indicator methods. The selection of methods was found in both grey and academic literature; our decision to include them was based on the extent to which they address design and the extent to which they have been evaluated with companies. The analysis looks into themes relating to circular design that are used by the indicator methods, for instance, life cycle stages or product characteristics, as well as the design indicators set to address these themes.

Five main criteria were identified based on the literature—both that discussing circular product design and that discussing methods' development—to help assess indicator methods.

- The first criterion that was identified concerns the output of the method, which is intended to help differentiate between readiness levels. Readiness can be defined by an "individual's attitude toward a particular change", which is influenced by dimensions—e.g., concerning the content, process, context, and people—that are relevant to the topic at hand [18]. For the method to reflect the readiness, it needs to indicate the level of implementation of a circularity aspect, grading this at one of a set of appropriate predefined levels [18].

- The second criterion is that the method must show the strengths and areas for improvement at a granular level [5,6,19]. This informs designers not only about the current readiness level but also how this can be improved.
- The third criterion is to attune the method to designers. This can be addressed by using product design semantics to evaluate circular design, which means to evaluate design's qualities expressed in product functions and the way it interacts with its (social) environment [20]. To do this, the design terminology of the professional language or jargon of designers can be used.
- The fourth criterion seeks completeness of the method by having it cover a complete range of design factors, from strategy to recovery, in detail. The design process is sequential in nature and the phases build up on the next. They carry important decisions that influence adjacent phases. This underpins the importance of aligning them from front to end and having clearly defined, distinctive phases, such as strategic design, embodiment design, service design, and recovery [15,21,22].
- The fifth criterium requires the method to be easy to apply in any industry, which includes allowing for ease-of-communication within the organization as well as with supply chain partners [23]. But this is also means having a format which fits with the content, and facilitates time-efficient use.

Table 7.1 shows to what extent existing indicator methods meet the method criteria. This section concludes with the take-aways in the light of the research objective of this study.

All methods have their individual strengths and contain valuable elements, like bringing out opportunities for improvement, benchmarking performance or implementation progress, or addressing topics essential to circular design. None of the methods, however, encapsulate the full range of circular product design aspects. Additional research is required to find a comprehensive set of indicators that measures the readiness for the development of circular products and related service offerings.

TABLE 7.1 Evaluation of existing indicator methods measuring circular design implementation.

Method	Purpose	Criteria				
		1. Indicates Levels of Readiness	2. Indicates Company Strengths and Areas for Improvement	3. Uses Product Design Semantics	4. Takes a Full Lifecycle Focus	5. Easy to Apply in Industry
C-Indicators Advisor—Saidani et al. [3]	Offers guidance to practitioners in selecting and applying existing circularity indicator sets		X			X
Circulytics—EMF [24]	Measures the potential of a company to adopt circularity, using a broad set of metrics about the organisation as well products and material flows			X		X
MATChE—Pigosso & McAloone [25]	Helps manufacturing companies assess their readiness for circular economy implementation to enhance the potential of success	X				X
CE Indicator Prototype (CEIP)—Cayzer et al. [5]	Evaluates product performance of producing companies within the circular economy model as defined by the EMF			X	X	
CE transition in product chains (CE-TPC)—Potting et al. [26]	Measures circular policy achievements and their effects on resource flows	X				

In summary, a dedicated method, that focuses on circular product and service design, is needed. A method that can be used by designers to monitor the implementation of circular design in their current offering and that serves as a guidance in the transition to an improved circular offering. The next section outlines the design of the research undertaken to address this gap.

7.3 RESEARCH DESIGN

The content of the method was created based on insights from conducting a literature review, from doing knowledge coproduction sessions with circular design experts, and from company testing. These activities were structured using the Design Science Research approach. Design Science Research operationalizes research that has developing an artefact, like models or methods, as the objective [27]. It provides a frame of six steps that helps design researchers create a rigorous stepwise approach to arrive at the intended artefact (see top row Figure 7.1) [28]. Within these steps, the researcher further details the required activities, attuned to the research objective, using the theory. The research undertaken here, uses all of the six steps, with an additional emphasize on steps 3 and 5.

Method criteria were compiled to guide the development process. The five main criteria were selected based on the analysis of existing methods and literature review in the background section. The method content needs to meet the requirements from Table 7.2.

TABLE 7.2 Content requirements.

Content Requirements	Explanation	References
Reliability	The method outcomes remain consistent for entries by different user within the same company.	[6,30]
Construct validity	The extent to which the indicator method actually measures circular design maturity as opposed to generic design management capabilities or circularity of material flows.	[19,30,31]
Content validity	The indicators fully cover all aspects that influence the maturity of circular design.	[30]
Comprehensibility	The indicators are understandable, meaningful, simple, and are easy to interpret for the representatives of designers and their wider team.	[19,30,31]
Operationability	The extent to which the indicator method is actionable and the outcomes controllable, by the way the format aligns with ongoing design activities and how the outcomes fit the decision structure.	[19]
Transversality	Applicability across different industries.	[3]

A follow-on literature review was conducted to develop the basis for the questions of the Circular Product Readiness method. This informed the development of the themes, indicators, and assessment questions. The method visual was developed to fit the created content. The overall goal of the literature review was to find and select papers that (1) offer information about requirements to successfully apply (strategic) design resources and principles, (2) give an indication of how this can be influenced through (strategic) design decision-making, and (3) contain validated micro-level indicators that measure circularity. The data bases of Web of Science, Google Scholar, and Scopus were searched to find papers by using the search terms: circular, design, product, service, and indicator, within a year range of 2017 to 2021. A total of 110 articles were retrieved of which 50 papers were analyzed in detail to develop a first draft of the themes, indicators, and questions. Snowballing was applied to find additional relevant articles.

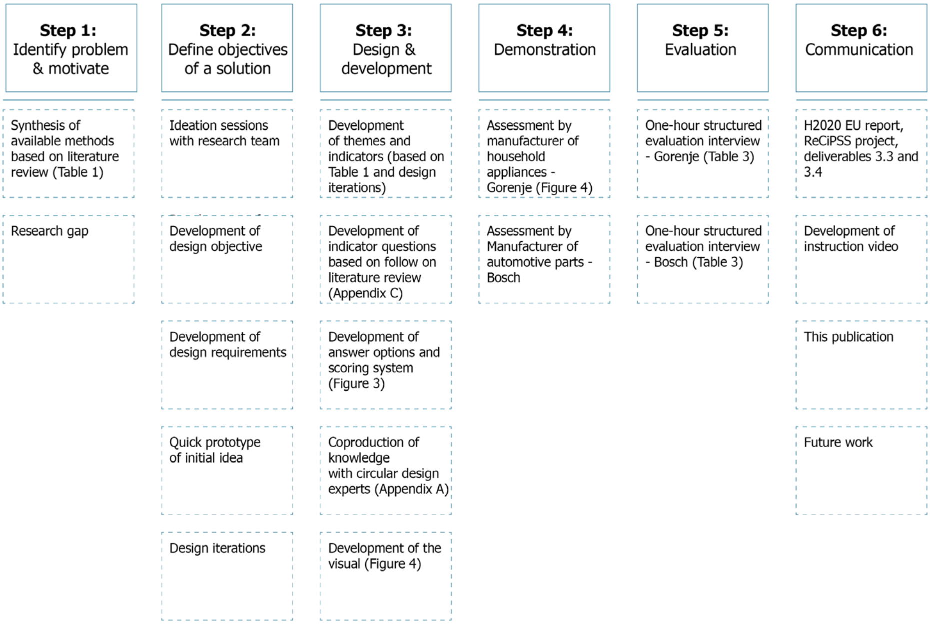

FIGURE 7.1 Method development process based on Design Science Research approach.

To assess the validity of the information found through literature review, knowledge coproduction sessions were organized [29]. Eight of these sessions were organized with researchers specialized in different aspects of circular design, all part of the Design for Sustainability research group of the faculty of Industrial Design Engineering at the Delft University of Technology (Appendix 7-A). A total of 11 experts were consulted during the sessions. 14 out of 20 design topics were evaluated through the knowledge coproduction sessions (Appendix 7-A). The topics that were not covered in the knowledge coproduction sessions were either sufficiently covered by scientific literature, and did not require further input from experts, or were added at a later stage of the design process.

The knowledge coproduction sessions took place in September 2021 and lasted 45 to 75 min (roughly 15 min of introduction, 15 min of discussion, 15 min of brainstorming, and 10 min of evaluation). Prior to the session, the participants received the overview of all themes and indicators as well as the assessment questions for the topic of their expertise. The sessions were structured using an online whiteboard on which the assessment questions could be rated based on significance. The input provided by the experts was collected through note-taking. The notes were analysed after the sessions and served as input to sharpen and clarify the formulation of the questions, and to add or delete questions.

The evaluation of the method was done with two multinational corporations: Gorenje Gospodinjski Aparati D.D., assessing an AKSO washing machine made for pay-per-use application, and Robert Bosch GmbH, assessing a diesel injection system. The company representatives were asked to complete the Circular Product Readiness method independently and provide feedback during a one-hour evaluation interview. This interview addressed the content of the method, the wording and terminology used, and the readability of the method visual. An online whiteboard containing the full list of questions was used to structure the interview. During the interviews, notes were added to the whiteboard to capture the remarks to specific questions. Based on an analysis of the notes, adaptations were made to the assessment questions and recommendations were made for further work. As a final step, the method criteria were evaluated by the researchers. This was done to see to what extent the final design meets these criteria.

7.4 DEVELOPMENT OF THE CIRCULAR PRODUCT READINESS METHOD

This chapter presents the process that led to the final design of the method, which corresponds to step 3 of the Design Science Research approach. The first activity of step 3 is the development of the basic structure of the Circular Product Readiness method. This determined which design topics are to be addressed and how the design topics break down into indicators. This leads to the next activity which determines what questions are to be asked to assess the readiness level. After having this basis, the answer options were developed. The method visual was created by building upon these previous activities.

7.4.1 DEVELOPMENT OF THEMES AND INDICATORS

The final set of themes and indicators was obtained through about 20 rounds of design iterations, the knowledge coproduction sessions, and literature review. The first draft was created prior to literature review. This draft was adjusted according to insights obtained from literature review. The final set of indicators was found through adjustments made based on the knowledge coproduction sessions.

The circular indicator methods selected in the background section were analysed in more detail for their use of design themes and indicators. This was to learn which of their characteristics meet the method criteria and should be taken into consideration for the development of the structure of the Circular Product Readiness method. The following characteristics (partially) met the method criteria. The Circulytics method takes a broad lifecycle focus by including strategic and human-centred design. Having this included is important for linking design to the company strategy, and optimising a product for its context. MATChE also takes a broader focus, by considering take-back services, which are important to ensure return rates. CEIP takes a lifecycle perspective that is rather intuitive to designers, and has a strong orientation towards design aspects. The categorization of indicators would benefit from adopting a practice-oriented structure over a theory-oriented structure like that of the C-Indicator Advisor. As a result of this analysis, the themes could be determined and a more advanced set of indicators was developed.

To further optimise the set of indicators, the circular design experts were asked to evaluate the preliminary selection of indicators in the knowledge coproduction sessions. This helped in determine the priority indicators and through that reach a set that covers all the essential circular design aspects. The final set of themes and indicators can be found in Figure 7.2.

THEMES

Indicators

1. STRATEGY AND PLANNING

1.1 Budget availability for circular product design
1.2 Access to circular design expertise
1.3 Customer research attuned to needs in all use-cycles
1.4 Circular value proposition design

2. HARDWARE AND SOFTWARE DESIGN

2.1 Materials
2.2 Longevity
2.3 Standardization across the product portfolio
2.4 Maintenance & repair
2.5 Hardware supports software updates

3. CUSTOMER EXPERIENCE AND CARE

3.1 User and product on- and offboarding
3.2 Product use-efficiency

4. PRODUCT SUPPORT SERVICE

4.1 Warranty
4.2 Professional support service for maintenance, repair and upgrades
4.3 Spare part supply

5. RECIRCULATION SERVICE

5.1 Product Return Program
5.2 Product Retrieval

6. RECOVERABILITY

6.1 Disassembly
6.2 Refurbishment
6.3 Remanufacturing
6.4 Recycling

FIGURE 7.2 The final set of themes and indicators.

7.4.2. DEVELOPMENT OF THE ASSESSMENT QUESTIONS

Literature review and design iterations formed the basis for the development of the assessment questions and the method visual. A first set of questions was developed based on the structure of themes and indicators, as well as on follow-on literature review. The set was fine-tuned over time through iterations and feedback loops within the research team of the TU Delft. In addition, knowledge coproduction sessions were organized to assess the significance and completeness of the questions. The complete set of questions resulting from these iterations can be found in Appendix 7-B. The table in Appendix 7-C contains the justification of the questions based on literature and the co-creation sessions. The answer options were developed to reflect readiness grades for the implementation of design activities. This was done by considering that design implementation can also be 'planned' or 'initiated', if not yet fully implemented. Most questions have 'not applicable' as an answer option, to let companies tailor this method to their own product type and context, adding to the transversality, as the appropriate strategies to design a product to be circular, vary from product to product.

7.4.3 DEVELOPMENT OF THE SCORING SYSTEM

Scoring takes places at four levels, at that of individual questions, indicators, themes, and at a level that aggregates all scores into a single number (see aggregated score in Figure 7.3 A maximum of 1 point can be scored for each question. All the themes, indicators, and questions have equal weighing. The reason for having equal weighing, is that the importance of the themes, indicators and questions is highly dependent on the type of product that is being assessed. The appropriate weighing can be determined by industry-experts. Adding up the score for a specific unit (theme, indicator, or question) and dividing this by total score for that unit gives the average score (%).

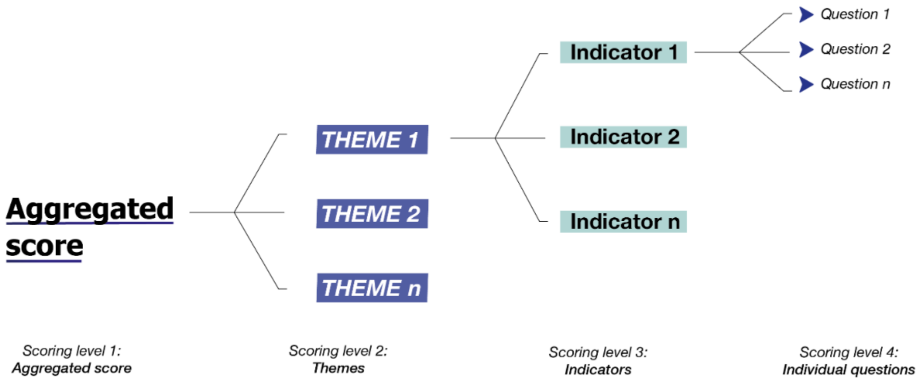

FIGURE 7.3 Scoring system using four levels.

7.4.4 DEVELOPMENT OF THE VISUAL

According to the method criteria, the visual should allow for ease-of-communication of the results, fit the contents, and facilitate time-efficient use. Indicator visuals from literature were used as a reference for the development of the final visual. These indicator visuals tend to use a radial structure to show the scores and show the different axes of evaluation. Scores can be indicated by both lines and numbers. Colours were used to label different indicators.

7

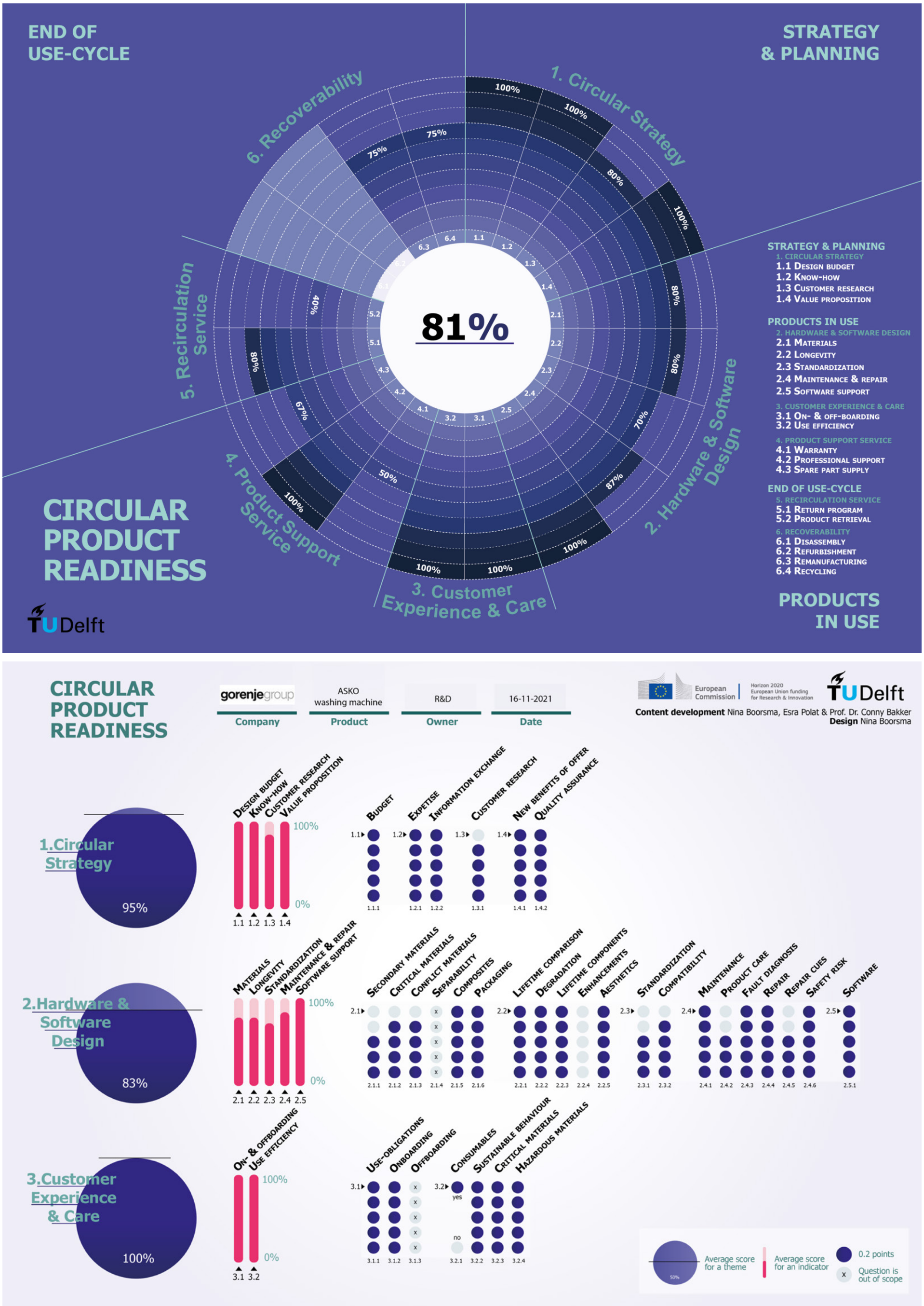

FIGURE 7.4 Final visual for the Circular Product Readiness method—results of Gorenje for themes 1, 2 and 3.

Based on the insights from the indicator visuals from literature and design iterations, the first versions of the visual were created. The visual was updated along with progress in the theme and indicator development. Factors like ease-of-communicated of the results, and having a coherent form language played an important role in the development of the final visual (Figure 7.4). In addition, the visual is developed to show grades of readiness, divided over four levels: scores for the assessment questions, scores for the indicators, scores for the design themes, and an aggregated score. This helps in communicating the specific company strengths as show opportunities for improvement, as it is easy to track which design aspects influence the higher-level scores.

7.4.5 APPLICATION OF THE METHOD

The recommended way of applying the CPR method is by following a four-step process. The first step is to appoint two employees with prior knowledge and understanding of the circular economy and in-depth knowledge of the product under assessment. Appointing at least two employees, helps in accuracy and effectivity the entry. The second step is to process the scores and translate them into percentages. The third step is to evaluate and interpret the scores by reflecting on the company's mission and vision for circular product design. The outcome of this evaluation is finding strengths and opportunities for improvement. The fourth step is to adjust the company design roadmap and (re)allocate design resources to fit the changes.

7.6 EVALUATION

The evaluation was done by providing the companies with the online questionnaire and by providing instructions that explain its use. For both companies the method was completed in pairs. For Bosch, this was done by a Channel Manager and Product Marketing Manager. For Gorenje, this was done by a Lead Engineer for R&D and a Project Manager. The results were translated into the visual by a researcher from the TU Delft (Figure 7.4). The method criteria and content requirements were evaluated with the respondents in a one-hour semi-structured interview.

Several valuable insights were collected during the evaluation and used to make final adjustments to the method. Based upon the evaluation, a question concerning the packaging material selection was added and the wording of several questions was adjusted. In addition, the answer options were evaluated to allow for additional differentiation of implementation levels. The insights from the evaluation are summarized in Table 7.3.

The application of the method at two different companies provided several useful insights. Gorenje scores 75% or higher for most of the design indicators and receives its highest scores for theme 1 'Circular strategy'. Product retrieval (5.2) scores 40%, as it is because of the return rate. Warranty (4.1) receives a score of 50% since the average warranty period of all life-cycles is significantly below that of the first use-cycle. This would only be relevant in the case of selling the product. Disassembly (6.1) and Refurbishment (6.2) are considered out of scope, since remanufacturing is the future aim for Gorenje. The scores indicate in what areas the company excels, but also points out opportunities for improvement of the circularity of their design. The main areas of improvement are the return rate and handling spare part supply. The indicators from the Recoverability theme (6) offer room for improvement once the company starts to adopt asset recovery.

Bosch received high scores on all design indicators that fall within the company's power to influence. Materials (2.1) and Recycling (6.4) are the only indicators that score below 90%. Standardization (2.3) and Software support (2.5) are marked out of scope, since most of the standardization is regulated by law and the product does not make use of software. The Use efficiency (3.2) received a score of 67%, as design of this product relies on other parts/products for the use efficiency of its consumables. The scores reflect the fact that the product suitability for recovery operations from a design point-of-view.

TABLE 7.3 Evaluation of the method criteria and content requirements.

Method Criteria	Evaluation
Indicates levels of readiness	The readiness levels of the circular design aspects are reflected in the answer options. Higher levels of readiness receive more points than the lower levels of readiness. The companies also get points assigned if the implementation is planned or initiated, if not yet fully implemented. Gorenje: For a number of questions, the company was in need of answer options that allows for more differentiation between the answer options, to more accurately reflect their progress. Having the visual use distinct colours to represent 'planned implementation' and 'readily implemented' would add to the usability of the visual. Overall, the results of the assessment helped Gorenje to get insight in their readiness level for circular design. Bosch: This method is expected to be useful as a quick scan for companies which are at the starting stages of implementing circular design.
Indicates company strengths and areas for improvement	The method visual makes it easy to interpret what the areas for improvement are by showing scores on multiple levels. Four levels of dimensionality were distinguished: an aggregated score, scores for the design themes, scores for the indicators, and scores for the assessment questions. Having access to these scores helps in pinpointing strengths and opportunities. Gorenje: From looking at the visual, the company could spot opportunities to evolve further. The company sees the potential of the method to help the company progress over the years. The assessment helped evaluate the company's goals and is expected to be of support in developing design roadmapping activities. Bosch: The challenge for Bosch is dive deeper into circular design and evaluate design decisions on sub-assembly, part and connector level. To monitor progress, the company goes into more detail with respect to experiences and costs.
Uses product design semantics	The accessibility of the method to designers was evaluated in the company tests. All questions that the companies considered in scope, were answered. The link with design was clear. The wording was optimized in a final iteration to further improve the accessibility. Gorenje: For some questions the choice of words could be slightly adjusted to improve readability and make the questions easier to understand. The company representatives indicated that it took 30 to 45 min to complete the assessment. The ideal user is considered to be an employer working with marketing and branding together with a project lead. Bosch: The user needs to be an expert in circular economy to fill in the questionnaire successfully. The parts that brought up most discussion, were those referring to the customer. Who exactly is meant by 'customer' may differ per market (e.g., B2C or B2B). It took 60 min to complete the assessment.
Takes full lifecycle focus	The assessment method takes into consideration themes from the strategic design phase on, until the recoverability phase. Co-creation sessions and evaluation with companies helped assessing the completeness of themes and indicators to cover the full lifecycle. Both companies felt that the method has reached completeness in topics. On some topics, like materials and reverse logistics, the method could go into more depth regarding the expectations of what are favourable conditions. Bosch: One example would be to add a question regarding material use about the level of fatigue strength, as this strongly impacts the reusability of parts. Another example would be to indicate the viability of setting up reverse logistics. Does the product form and size allow for transport through existing logistics channels? Does it require special packaging that protects the product from damage, like scratches? How does the cost-size ratio of a product influence transportability? In the company's experience, smaller sized, high-value products allow for most viable transport options.

TABLE 7.3 Continued.

Method Criteria	Evaluation
Easy to apply in industry	The method visual was designed in a way that allows for ease of communication of the results on the level of an individual answer, as well as more aggregated scores, like that of an indicator, theme or the overall score. The method format was designed for ease-of-use, and for the ease-of-communication of the results. Gorenje: The method format was considered helpful in communicating the results visually to colleagues. Bosch: For the method to guide the design process of the company, it would have to become industry specific.
Reliability	The method was evaluated with two companies, each of which had two company representatives to apply the method, which resulted in a basic level of reliability. To further assess the reliability, the outcomes of several representatives, who independently apply the method on the same product, should be compared for consistency.
Construct validity	The construct of the study is circular product design. Throughout the design process of the method, all questions were continuously evaluated for their relation to circular product design. This was done to make sure the questions referred to actions that can actually be influenced by design, and it helped steer away from questions that are about organisation management, the business model, testing generic circular economy skills, or compliance.
Content validity	The construct validity was tested by asking the companies whether they missed relevant questions or found that certain questions were irrelevant. As a result, one new question was added (regarding the selection of packaging material) and none of the questions were removed. Gorenje: “The themes and indicators are highly relevant.”
Comprehensibility	During the evaluation interviews with the companies, all questions were evaluated one-by-one for their comprehensibility. This resulted in several small adjustments to how the questions were phrased, as well as some adjustments for the questions to fit both professional contexts (i.e., business to consumer and business to business contexts).
Operationability	The operationability was assessed by looking at the time spent on completing the assessment and, again, the clarity of questions and answers.
Transversality	The method was applied by two companies operating in completely different industries: the white goods industry and the automotive industry. Both companies were able to fully complete the method successfully. In both instances, some of the questions turned out to be not relevant to their product. Including the options to answer questions with ‘Not Applicable’ was found to be a useful in making the method widely applicable.

7.7 DISCUSSION

The method content will be discussed in terms of the outcome of the evaluation with companies, the choice for equal weighting, and limitations of the design of the research. The value of the method will be discussed by means of its alleged effectivity to measure design readiness and possible drawbacks of the final design.

7.7.1 METHOD CONTENTS

The CPR method has several contributions to make to the field of circular design assessment in terms of contents. The method contains 63 questions divided over 6 circular design themes, which amply exceeds the number of questions asked in the existing methods (e.g., 15 questions for the CEIP method). The method allows for the possibility to spot strengths and opportunities for improvement, and allows for comparison of several products. Having a report as the outcome of the assessment, with scores on four different levels, creates a detailed overview of the readiness level of companies. Having such functionality is a significant step forwards from existing indicator methods that either use a single score, or lack further reporting. The possibility to mark questions as 'not applicable' to a certain product, allows users to create product-specific profiles, which meets the need for more context specific product-level indicator methods [3].

The assessment questions determine the scope of what is assessed, but the answer options determine how well the readiness level of designers is reflected. Accordingly, Gorenje expressed the need for additional answer options to some questions to reflect their current implementation status. With this improvement, the company expects the method to have the fitting functionality to support their design roadmapping activities on the long run. Since Bosch has been specializing in remanufacturing for years, their breakdown of aspects to assess circular design would preferably go even deeper, aligning to their specific recovery requirements. This was outside of the scope of this study, but may offer an interesting opportunity for further research. The wording of the questions was updated based on the input from both company evaluations, on the one side to improve readability and on the other side to make the questions have a better fit with companies that deal with other professional parties, for example in Business to Business contexts. Concluding from this, to some extent the method evaluation, step 5 of the Design Science Research (DSR) approach (Figure 7.1), led to new design iterations in step 3 of the DSR approach, Design & development, a design route that had been suggested by Peffers et al. [28]. Remaining comments that would require more extensive research are reported on below and can feed into future research venues.

In the current format, all indicators receive equal weighting, independent of the number of questions asked for that indicator. Yet, some indicators may have a stronger, more essential influence on a product's circularity than others. Similarly, all questions that belong to one indicator receive equal weighting. For example, in the 'Strategy and planning' theme 'available budget for circular design' is evaluated together with 'access to circular design expertise'. Yet, one could argue that having budget available but no access to expertise is less favorable than having access to expertise and not having dedicated budget. A weighting system can put additional emphasize to questions, indicators, or themes, that are of higher priority than others. The point of prioritization was earlier raised by Cayzer et al. [5], who in addition highlight the importance of pursuing tighter loops of the circular economy as a first option, where possible. Such aspects could also be considered for weighting. What is important to note, is that the value of having a scoring and weighting system, is in the discussions that they lead up to among designers. Through these discussions the next steps for implementation can be determined, based on which best align with the available resources.

The method was evaluated with two multinationals that produce high-value, durable goods. Once the method is applied to a broader range of companies, in terms of company size, industry, and product type, new insights can be collected concerning the applicability of the method. These insights can also concern content optimization and give an opportunity to further explore the reliability of the method.

7.7.2 VALUE OF THE METHOD

The method has several contributions to make to its users. The method can be used to monitor circular design readiness over time, informing designers about possible actions that support their ambitions of shifting towards a more circular practice. This can support their design strategy and roadmapping activities, using the method to make appropriate actions to keep on track. It meets the need for standardized methods for micro-level measurements, a point for further research brought up by Kristensen et al. [2]. The method can also help inform design leads and design managers about the need for additional training or recruits to strengthen or expand a team's design capabilities. Finally, it can help determine priorities and focal points in the development of new products.

One of the drawbacks for this method may be that it cannot be applied to all industries. The method targets designers developing durable goods. Besides, the method requires prior knowledge and understanding of the circular economy and in-depth knowledge of the product under assessment. A central aim for artefacts developed through a DSR approach is the optimal usefulness of the method, and should therefore be carefully considered [28].

7.8 CONCLUSION

This study has developed and evaluated the Circular Product Readiness (CPR) method that assesses the readiness level of designers to design circular products, by identifying strengths and areas for improvement. It responds to a gap found in the body of literature regarding circular indicators dedicated to assess all aspects of design in depth.

This study delivers the first indicator method which indicates levels of readiness considering all product lifecycle phases, uses product design semantics, and is easy to apply in a broad range of industries. The format of the CPR method not only makes it possible to compare scenarios, but also helps to guide and structure discussions about design. With that, it offers a thinking frame to help develop design strategies and to inform roadmapping activities. The outcomes are accessible to the wider design team as well as to other company divisions; this can help inform the expertise areas, like those of circular supply chains and circular business models, to determine shared priorities and interlinkages.

The CPR method integrates the individual circular design strategies that are most prominently discussed in academic literature today, into one method. This is important, since these strategies connect to one and other and influence each other in a wider circular design approach. As a result, the CPR method can yield a comprehensive overview to help companies move towards circular ways of designing products and services.

A firm basis for the CPR method was developed in this study. Furthermore, it offers opportunities to build upon for future research, which is recommended to look into a number of topics. Besides adapting new research released in the field of circular product design, that may add to the topics to be addressed and further detailing of them, it can look into the prioritization and weighting system of the topics. The latter can be done by having an exercise in which experts prioritize the indicators, which then can lead to a possible alternative weighting system. In addition, further validation with experts from both academia and industry, followed by design iterations, can strengthen its transversality across industries. A database of outcomes may also lead to creating industry reference points, which can help companies interpret their results. Extending the method can also be considered, in several ways. One of which is to have modules deep-diving into specific topics, perhaps industry-specific modules that dive into the details of material fatigue strength, or zoom in to the assessment products that use multiple consumables. Another route would be to link the topics addressed in the CPR method with existing quantified indicators from literature, to allow companies to further quantify opportunities for improvement. As a final recommendation, the visual can be further developed for it to display the phases of implementation: planned, initiated, fully adopted, by, for example, using different colors, to strengthen and detail its guiding function, providing richer information.

AUTHOR CONTRIBUTIONS

Conceptualization, N.B., E.P., and C.B.; methodology, N.B., E.P., and C.B.; software, N.B.; validation, N.B., E.P. and C.B.; formal analysis, N.B. and E.P.; investigation, N.B. and E.P.; resources, N.B. and E.P.; data curation, N.B. and E.P; writing—original draft preparation, N.B.; writing—review and editing, N.B, C.B, R.B. and D.P.; visualization,

N.B.; supervision, C.B., R.B., and D.P.; funding acquisition, C.B. All authors have read and agreed to the published version of the manuscript."

FUNDING

This research was funded by H2020 EU project Resource-efficient Circular Product Service Systems (ReCiPSS) grant number 776577-2 that runs from 2018 to 2022, in which the goal is to establish large-scale demonstrators of circular manufacturing systems. One of the three pillars of this project is product design, with the key objective to develop new circular design methodologies.

INSTITUTIONAL REVIEW BOARD STATEMENT

Ethical review and approval were waived for this study as all activities in the H2020 EU project ReCiPSS project comply to ethical and research integrity principles, stated and undersigned by all participants in the ReCiPSS grant agreement.

INFORMED CONSENT STATEMENT

Informed consent was obtained from all subjects involved in the study.

DATA AVAILABILITY STATEMENT

The data presented in this study are openly available at https://zenodo.org/record/6411939#.YsRQsOxBxhF

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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APPENDIX 7-A

TABLE 7.4 Co-creation expert sessions—participants.

Indicator Number and Topic	Participant(s)
Session 1 1. Design budget (Strategy & Planning) 2. Know-how (Strategy & Planning) 3. Customer research (Strategy & Planning) 4. Value proposition (Strategy & Planning)	Assistent Professor—Scaling up the Circular Economy
Session 2 1. Design budget (Strategy & Planning) 2. Know-how (Strategy & Planning) 3. Customer research (Strategy & Planning) 4. Value proposition (Strategy & Planning)	PhD—Sustainable & Circular Product Development
Session 3 8. Maintenance & repair (Hardware & Software design) 13. Professional support (Product support Service) 17. Disassembly (Recoverability)	PhD Researcher—Design for Reparability and Longevity PhD—Fault Diagnosis for Repair
Session 4 10. On- & Off-boarding (Customer Experience & Care)	PhD—Design for Divestment Professor—Design Methodology for Sustainability and Circular Economy
Session 5 10. On- & off boarding (Customer Experience & Care) 11. Use efficiency (Customer Experience & Care)	PhD Researcher—Consumer Perception of Circular Products
Session 6 5. Materials (Hardware & Software Design) 20. Recycling (Recoverability)	PhD Researcher—Composites in a Circular Economy Professor—Circular Product Design
Session 7 14. Spare part supply (Product Support Service) 18. Refurbishment (Recoverability) 19. Remanufacturing (Recoverability)	Associate Professor—Critical Materials in a Circular Economy
Session 8 General: social aspects of circular product design	PhD Researcher—Circular Medical Devices in Low Resource Settings

APPENDIX 7-B

CIRCULAR PRODUCT READINESS

1. STRATEGY & PLANNING

1.1 BUDGET AVAILABILITY FOR CIRCULAR PRODUCT DESIGN

1.1.1 *Has your company made a budget available for circular design?*

- Yes — 1
- This is initiated — 0.8
- This is planned — 0.4
- This is not considered — 0

1.2 ACCESS TO CIRCULAR DESIGN EXPERTISE

1.2.1 *Does your company have access to circular design expertise?*

This could be circular design expertise internally or from an external party, such as advisors, consultancies, etc.

- Yes, we have access to either internal and/ or external expertise — 1
- We are in the process of acquiring (additional) expertise — 0.8
- We are planning to acquire additional expertise — 0.4
- No, we do not have access to circular design expertise — 0
- N/A — -

1.2.2 *Does your company have channels to exchange product design information with stakeholders, like repair and remanufacturing technicians?*

- Yes, we have access to either internal and/ or external expertise — 1
- We are in the process of acquiring (additional) expertise — 0.8
- We are planning to acquire additional expertise — 0.4
- No, we do not have access to circular design expertise — 0
- N/A — -

1.3 CUSTOMER RESEARCH ATTUNED TO NEEDS IN ALL USE-CYCLES

1.3.1 *To what extent are the needs of customers not only considered in the first use-cycle, but also in the subsequent use-cycles of the product?*

- This is the norm — 1
- This is initiated — 0.8
- This is planned — 0.4
- This is not considered — 0
- N/A — -

1.4 CIRCULAR VALUE PROPOSITION DESIGN

1.4.1 *Does the circular value proposition and its related service and product offer new benefits to customers?*

- Yes, there are new benefits to this circular value proposition — 1
- We are in the process of adding new benefits — 0.4
- No, there are no new benefits to this circular value proposition — 0
- N/A — -

1.4.2 *To what extent does value proposition design support high product quality not only in the first use-cycle but also in subsequent use-cycles for the products?*

- This is the norm — 1
- This is initiated — 0.8
- This is planned — 0.4
- This is not considered — 0

European Commission | Horizon 2020 European Union funding for Research & Innovation — TU Delft

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2. HARDWARE & SOFTWARE DESIGN

2.1 MATERIALS

2.1.1 *What fraction of the material value, by cost price, consists of recycled and/ or reused materials calculated over all use-cycles?*

This can be calculated using the following formula: (cost price of recycled and reused materials / cost price of materials in total) x 100%. For products with multiple use-cycles, the average of this fraction over the use-cycles can be calculated.

- 0% *0*
- 1 - 19% *0.4*
- 20 - 39 % *0.6*
- 40 - 69% *0.8*
- 70 - 100% *1*

2.1.2 *What amount of the material value, by cost price, consists of critical materials?*

Critical materials for product designers are defined by Peck et al. (2015) as "elements from the periodic table of elements (metals/ rare earths) that may be at risk of price volatility and supply restrictions, they are often present in small quantities in technology products, substitution usually changes a product's properties and/ or performance." Examples of common critical materials to the EU are the following: Lithium, Beryllium, Magnesium, Scandium, Chromium, Cobalt, Gallium, and Germanium (Bauer et al. 2010).

- €0 *1*
- €0 - 0,09 *0.8*
- €0,1 - 0,19 *0.6*
- €0,2 - 0,4 *0.4*
- €0,4 *0*

2.1.3 *What amount of the material value, by cost price, consists of conflict materials?*

Conflict minerals refer to raw materials or minerals that come from a particular part of the world where conflict is occurring (i.e. those specifically associated with armed conflict, human rights abuses and corruption) that affect the mining and trading of those materials (Diemer et al. 2021). Examples of common conflict materials include the 3TG: tantalum, tin, tungsten, and gold.

- €0 *1*
- €0 - 0,09 *0.8*
- €0,1 - 0,19 *0.6*
- €0,2 - 0,4 *0.4*
- €0,4 *0*

2.1.4 *Does the product contain easily separable biodegradable or compostable components?*

- The product is fully biodegradable or compostable *1*
- The product contains biodegradable and compostable components that are easy to separate *1*
- The product contains biodegradable and compostable components that are hard to separate *0*
- The product does not contain any biodegradable or compostable components *-*

2.1.5 *Does the product contain composite materials that are designed to last?*

A composite material is a combination of two materials with different physical and chemical properties. Materials commonly used for composites are polymers, metals and ceramics.

- The composite materials used in this product are recyclable *1*
- The product contains composite materials that are easy to separate and designed to last *0.6*
- The product contains composite materials that are easy to separate, but not designed to last *0.2*
- The product contains composite materials that are hard to separate *0*
- No, the product does not contain any composite materials *-*

2.1.6 *Does the product packaging consist of recyclable, biodegradable, or compostable materials?*

- Yes, the packaging is fully recoverable *1*
- The packaging is partly recoverable *0.8*
- This is planned *0.4*
- The packaging is not recoverable *0*
- N/A *-*

2.2 LONGEVITY

2.2.1 *How does the total lifetime of the product compare to the market average?*

Compare the expected total lifetime of your product to the market average.

Higher than average	*1*
Equal to average	*0.8*
Lower than average	*0*

2.2.2 *After what period of time will the user experience noticeable degradation of the product?*

For example degradation due to (cosmetic) wear, battery life, and corrosion.

From 100% of the expected lifetime	*1*
Between 75-100% of the expected lifetime	*0.8*
Between 50-74% of the expected lifetime	*0.4*
Between 0-49% of the expected lifetime	*0*

2.2.3 *Does the product (information) indicate what components are critical to the duration of either the technical lifetime or the economic lifetime (i.e. relevance to the market)?*

Yes, all key parts are indicated	*1*
Only for a selection of key parts	*0.6*
No key parts are indicated	*0*
N/A	-

2.2.4 *Does the product allow for enhancing a product's functionality and/or cosmetic condition throughout its lifetime?*

For example by having a modular or upgradable design.

Yes, for all key parts	*1*
Only for a selection of key parts	*0.8*
This is planned	*0.4*
There are options for enhancement	*0*
N/A	-

2.2.5 *Is the product designed to have a timeless aesthetic?*

This is the norm	*1*
This is initiated	*0.8*
This is planned	*0.4*
This is not considered	*0*
N/A	-

2.3 STANDARDIZATION ACROSS THE PRODUCT PORTFOLIO

2.3.1 *Is Design for Standardization applied throughout the whole product portfolio to support recovery options?*

Design for Standardization aims for standardizing selected parts throughout the product portfolio (e.g. between product generations) over time.

This is the norm	*1*
This is the norm for a sub-set of products	*0.8*
This is initiated	*0.8*
This is planned	*0.4*
This is not considered	*0*
N/A	-

2.3.2 *Is (backward) compatibility applied throughout the whole product portfolio to support recovery options?*

Part compatibility is based on the interoperability between selected parts for multiple product types, and is dependent on, for example, part dimensions, energy uptake, interfaces, and software versions.

This is the norm	*1*
This is the norm for a sub-set of products	*0.8*
This is initiated	*0.8*
This is planned	*0.4*
This is not considered	*0*
N/A	-

2.4 MAINTENANCE & REPAIR

2.4.1 *Is the product designed for ease of maintenance?*

For example, if the product requires regular cleaning, does the design of the product enable this?

This is the norm	*1*
This is the norm for a sub-set of products	*0.8*
This is initiated	*0.8*
This is planned	*0.4*
This is not considered	*0*
N/A	-

2.4.2 *Does the product come with information, like a manual, on how to take care of it?*

Yes, for all parts that require maintenance	*1*
Only for a selection of parts that require maintenance	*0.6*
No information about how to maintain the product quality is provided	*0*
N/A	-

2.4.3 *Does the product come with information, like a manual, on how to diagnose faults in key parts?*

- Yes, for all parts that could require repair — *1*
- Only for a selection of parts that could require repair — *0.6*
- No information on fault diagnosis is provided — *0*
- N/A — *-*

2.4.4 *Does the product come with information, like a manual, on how to repair faults for key components?* .

- Yes, for all parts that could require repair — *1*
- Only for a selection of parts that could require repair — *0.6*
- No information on the repair of faults is provided — *0*
- N/A — *-*

2.4.5 *Does the product have visual or auditory design cues supportive of maintenance and repair?*

- Yes, for all parts that could require maintenance or repair — *1*
- Only for a selection of parts that could require maintenance or repair — *0.6*
- No, the product has no design cues for maintenance or repair — *0*
- N/A — *-*

2.4.6 *Is the safety risk for end-users minimized during self-repair of the product?*

For example by avoiding harmful substances.

- Yes, for all parts that could require repair — *1*
- Only for a selection of parts that could require repair — *0.6*
- No, the product is not safe to repair by customers — *0*
- N/A — *-*

2.5 HARDWARE SUPPORTS SOFTWARE UPDATES

2.5.1 *Does the use of software and software support form a bottleneck for products to live longer than the expected lifetime or for the extension of the product lifetime through re-use or remanufacturing?*

- Software support does not form a bottleneck — *1*
- Extending software support is initiated — *0.8*
- Extending software support is planned — *0.4*
- Software support forms a bottleneck — *0*
- This product does not use any software — *-*

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3. CUSTOMER EXPERIENCE & CARE

3.1 USER AND PRODUCT ON- AND OFFBOARDING

3.1.1 *Are the obligations and responsibilities for access, use, and end-of-life of a product communicated to end-users*?*

*For companies operating in a business to business context, this may not concern the end-user but another party responsible for on- and offboarding.

- Yes — *1*
- No — *0*
- N/A — *-*

3.1.2 *Is the onboarding process tested with end-users* on clarity and convenience?*

*For companies operating in a business to business context, this may not concern the end-user but another party responsible for on- and offboarding.

- Yes, this process is tested and provides clarity and convenience — *1*
- Only a limited amount of clarity and convenience are provided for onboarding — *0.6*
- The development of a clear and convenient onboarding process is in development — *0.4*
- No, clarity and convenience are not maximized for the onboarding process — *0*
  N/A

3.1.3 *Is the end-user* supported in letting go of the product at the end of life, emotionally and/ or practically?*

*For example by supporting them with clearing personal data from the product. *For companies operating in a business to business context, this may not concern the end-user but another party responsible for on- and offboarding.

- Yes, the customer is supported — *1*
- Only a limited amount of support is provided — *0.6*
- No, the customer is not supported — *0*
- N/A — *-*

3.2 PRODUCT USE-EFFICIENCY

3.2.1 *Does the product maximize the use-efficiency of consumables, compared to the market average?*

For example by technologies and innovations that enable energy and water use efficiency. Consumables are goods that are used up while using a product, such as water, energy, ink, paper, and cleaning agents.

- The use-efficiency is higher than the market average — *1*
- The use-efficiency is equal to the market average — *0.6*
- The use-efficiency is lower than the market average — *0*
- This product does not use consumables — *-*

3.2.2 *Does the product activate end-user to opt for sustainable use options?*

For example by a button for energy or water saving modes.

- Yes — *1*
- This is initiated — *0.8*
- This is planned — *0.4*
- This is not considered — *0*
- N/A — *-*

3.2.3 *Does the product require the use of consumables that contain critical or conflict materials?*

For example coffee beans that are obtained from conflict zones.

- No, the customer can select consumables that are free of critical or conflict materials — *1*
- Yes, the customer is restricted to a selection of consumables that contain critical or conflict materials — *0*
- N/A — *-*

3.2.4 *Does the product require the use of consumables that contain contents that can be hazardous to the environment in which they are discarded?*

For example the use of laundry detergents that contain hazardous chemicals

- No, the customer can select consumables that are free of critical or hazardous contents — *1*
- Yes, the customer is restricted to a selection of consumables that contain hazardous contents — *0*
- N/A — *-*

4. PRODUCT SUPPORT SERVICE

4.1 WARRANTY

4.1.1 *Does the product's warranty period last longer than what is legally required?*

Yes	1
This is initiated	0.8
This is planned	0.4
This is not considered	0
N/A	-

4.1.2 *Are products that are returned by the end-user* as part of warranty repaired, refurbished or remanufactured?*

*For companies operating in a business to business context, this may not concern the end-user but another party responsible for returning products.

Yes	1
This is initiated	0.8
This is planned	0.4
This is not considered	0
N/A	-

4.2 PROFESSIONAL SUPPORT SERVICE FOR MAINTENANCE, REPAIR AND UPGRADES

4.2.1 *Does your company, or partnered companies, offer in-warranty maintenance & repair services for the product?*

Yes	1
Only for specific defects	0.8
This is planned	0.4
This is not considered	0
N/A	-

4.2.2 *Does your company, or partnered companies, offer any paid maintenance & repair support service for the product?*

Yes	1
Only for specific defects	0.8
This is planned	0.4
This is not considered	0
N/A	-

4.2.3 *Is the end-user informed about the availability of a professional maintenance and repair service?*

Yes	1
No	0
N/A	-

4.2.4 *Does your company, or partnered companies, offer an upgrade service for your product?*

Examples are upgrading the memory of a laptop and exchanging the armrest of an office chair.

Yes	1
This is initiated	0.8
This is planned	0.4
This is not considered	0
N/A	-

4.2.5 *Is the end-user informed about the possibility to upgrade the product?*

Yes	1
No	0
N/A	-

4.3 SPARE PART SUPPLY

4.3.1 *Are the spare parts to support self-repair by end-users affordable?*

Yes	1
No	0
N/A	-

4.3.2 *Does your company produce extra spare parts for recovery, to enable refurbishment or remanufacturing?*

Yes	1
This is initiated	0.8
This is planned	0.4
This is not considered	0
N/A	-

4.3.3 *Can end-users* return their used parts, that they have replaced, to your company?*

*For companies operating in a business to business context, this may not concern the end-user but another party responsible for returning parts.

Yes	1
This is initiated	0.8
This is planned	0.4
This is not considered	0
N/A	-

4.3.4 *Are parts that are returned by the end-user* repaired, refurbished or remanufactured?*

*For companies operating in a business to business context, this may not concern the end-user but another party responsible for returning parts.

Yes	1
This is initiated	0.8
This is planned	0.4
This is not considered	0
N/A	-

5. RECIRCULATION SERVICE

5.1 RETURN PROGRAM

5.1.1 *Does your company have a program to actively retrieve products from the market?*

- Yes — *1*
- This is initiated — *0.8*
- This is planned — *0.4*
- This is not considered — *0*
- N/A — *-*

5.1.2 *What percentage of the sold products are returned to the company or to partnered companies?*

This includes returned part from buy-back schemes and pay-per service models.

- 0% — *0*
- 1-9% — *0.4*
- 10-19% — *0.6*
- 20-49% — *0.8*
- 50-100% — *1*

5.1.3 *Are end-users* informed about the product return options?*

- Yes — *1*
- No — *0*
- N/A — *-*

5.1.4 *At what point are end-users* informed about the possible return options?*

- During product purchase — *1*
- During use, at end-of-use, or at end-of-life of a product — *0.8*
- N/A — *-*

5.2 PRODUCT RETRIEVAL

5.2.1 *Does the company provide re-usable packaging for return options?*

For example in case the product requires protection during transport.

- Yes — *1*
- A non-reusable replacement packaging is provided — *0.8*
- This is initiated — *0.8*
- This is planned — *0.4*
- This is not considered — *0*
- N/A — *-*

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6. RECOVERABILITY

6.1 DISASSEMBLY

6.1.1 *Does your company list the key parts for disassembly?*

Key parts that should be accessible for repair, upgrades, refurbishment and remanufacturing

Yes, all key parts are listed	*1*
Only a selection of key parts is listed	*0.8*
This is initiated	*0.8*
This is planned	*0.4*
This is not considered	*0*
N/A	*-*

6.1.2 *Is product disassembly optimised for time, cost efficiency, simplicity and tool availability?*

For example, by optimizing the joints and connections, minimizing the risk of damage, minimizing tool and equipment complexity, and reducing the number of product components.

Yes, all key parts are listed	*1*
Only for a selection of key parts	*0.8*
This is initiated	*0.8*
This is planned	*0.4*
This is not considered	*0*
N/A	*-*

6.2 REFURBISHMENT

6.2.1 *Does your company list what parts make the refurbishment operations feasible and viable?*

Yes, all key parts are listed	*1*
Only a selection of key parts is listed	*0.8*
This is initiated	*0.8*
This is planned	*0.4*
This is not considered	*0*
N/A	*-*

6.2.2 *Which fraction of the material value, by cost price, can be refurbished?*

Calculated by dividing the cost price of the materials that can be refurbished by the total cost price of materials

0%	*0*
1-19%	*0.4*
20-49%	*0.6*
50-69%	*0.8*
70-100%	*1*

6.2.3 *Does your company provide refurbishment instructions and protocols to the relevant departments or third parties?*

Yes	*1*
Only informal instructions are provided	*0.8*
This is initiated	*0.8*
This is planned	*0.4*
This is not considered	*0*
N/A	*-*

6.2.4 *Does your company have a clear diagnosis procedure for products returning from the market?*

Yes	*1*
This is initiated	*0.8*
This is planned	*0.4*
This is not considered	*0*
N/A	*-*

6.3 REMANUFACTURING

6.3.1 *Does your company list what parts make the remanufacturing operations feasible and viable?*

Yes, all key parts are listed	*1*
Only a selection of key parts is listed	*0.8*
This is initiated	*0.8*
This is planned	*0.4*
This is not considered	*0*
N/A	*-*

6.3.2 *Which fraction of the material value, by cost price, can be remanufactured?*

Calculated by dividing the cost price of the materials that can be remanufactured by the total cost price of materials

0%	*0*
1-19%	*0.4*
20-49%	*0.6*
50-69%	*0.8*
70-100%	*1*

6.3.3 *Does your company provide refurbishment instructions and protocols to the relevant departments or third parties?*

Yes	*1*
Only informal instructions are provided	*0.8*
This is initiated	*0.8*
This is planned	*0.4*
This is not considered	*0*
N/A	*-*

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6.3.4 *Does your company have a clear diagnosis procedure for products returning from the market?*

Yes	1
This is initiated	0.8
This is planned	0.4
This is not considered	0
N/A	-

6.4 RECYCLING

6.4.1 *Which fraction of the material value, by cost price, can be recycled?*

Calculated by the price of materials that can be recycled divided by the total cost price of materials.

0%	0
1-19%	0.4
20-49%	0.6
50-69%	0.8
70-100%	1

6.4.2 *Does the product fall apart into separate homogeneous or compatible material fragments in the shredding process?*

Yes	1
Only for a selection of parts	0.6
No	0
N/A	-

6.4.3 *Are general recycling processes available for the materials in your product?*

Yes	1
Only for a selection of the recyclable materials	0.6
No	0
N/A	-

6.4.4 *Is there an End-of-Use repurposing plan for the materials that are non-recyclable?*

Yes	1
Only for a selection of the non-recyclable materials	0.6
No	0
N/A	-

APPENDIX 7-C

TABLE 7.5 Justification of assessment questions based on literature review and co-creation.

Assessment Questions	Justification Based on Literature Review and Knowledge Coproduction Sessions
1. CIRCULAR STRATEGY	
1.1 Design budget	
1.1.1 Has your company made a budget available for circular design?	Allocating budget to circular design underpins the strategic value of circular design and their level of commitment to prioritizing the associated design requirements [15].
1.2 Know-how	
1.2.1 Does your company have access to circular design expertise?	The development of, or having access to circular design competencies is seen as a success factor to implement circular design, looking at the financial, operational and structural challenges [33]. The question was added as a result of Co-creation sessions 2, 7 and 8.
1.2.2 Does your company have channels to exchange product design information with stakeholders, like repair and remanufacturing technicians?	The integration of circular design is strongly linked with the frequency and quality of data exchange between technicians who perform recovery operations and design engineers [34].
1.3 Customer research	
1.3.1 To what extent are the needs of customers not only considered in the first use-cycle, but also in the subsequent use-cycles of the product?	Market demand is seen as the strongest incentive for companies to adjust design requirements, collecting data about customer needs with regards to circular design helps in building arguments to implement circular design [15]. The question was rephrased as a result of Co-creation session 1.
1.4 Value proposition	
1.4.1 Does the circular value proposition and its related service and product offer new benefits to customers?	Circular product offers are established in value networks and are effective when all partners gain value from the offer [35]. The fact that circular products are taken back and recovered can offer additional unique value can be offered to customers, like access to use information and access to exclusive features (van Dam et al. 2021). The question was added as a result of Co-creation session 8.
1.4.2 To what extent does value proposition design support high product quality not only in the first use-cycle but also in subsequent use-cycles for the products?	The brand- and product identity help customers build trust in, and accept, products that serve multiple use-cycles [15]. Building this quality perception also helps in getting buy-in from employees [15]. The question was rephrased as a result of Co-creation session 1.
2. HARDWARE AND SOFTWARE DESIGN	
2.1 Materials	
2.1.1 What fraction of the material value, by cost price, consists of recycled and/or reused materials calculated over all use-cycles?	Calculating the ratio of the recoverable share of a product denotes the progress towards the circularity potential of a product [5]. The question was rephrased as a result of Co-creation session 6.
2.1.2 What amount of the material value, by cost price, consists of critical materials?	Critical materials, commonly used by design engineers, tend to have rare material characteristics, yet they are labelled critical, for instance, due to constraints in supply chains, volatile prices, or implications to the environment [37]. Circular design is seen as a promising solution to diminish risks and offer a more sustainable alternative to using these valuable resources [37].

TABLE 7.5 Continued.

Assessment Questions	Justification Based on Literature Review and Knowledge Coproduction Sessions
2. HARDWARE AND SOFTWARE DESIGN	
2.1.3 What amount of the material value, by cost price, consists of conflict materials?	Mineral trade can be involved with inhumane activities, like forced labor, labor under harsh working conditions, or criminal activities [38]. The OECD recommends traceability systems to map upstream supply chain stakeholders in collaboration with industry bodies [39].
2.1.4 Does the product contain easily separable biodegradable or compostable components?	Following the "power of pure circles" principle of the Ellen MacArthur Foundation product circularity increases through separating material streams to their purest possible form, at the core separating the bio- and the techno-cycles [40].
2.1.5 Does the product contain composite materials that are designed to last?	Closing the material loop for composites through recycling remains suboptimal, because of the material use and structure [41]. Therefore, choosing long lasting application through careful designs consideration should be favored [41].
2.1.6 Does the product packaging consist of recyclable, biodegradable, or compostable materials?	Calculating the ratio of the recoverable share of a product denotes the progress towards the circularity potential of a product [5]. The question was added as a result of the company evaluation (Section 5).
2.2 Longevity	
2.2.1 How does the total lifetime of the product compare to the market average?	Comparing a product's lifetime against the market average is considered a valuable indicator to measure utility [10].
2.2.2 After what period of time will the user experience noticeable degradation of the product?	Functional, emotional, and social values play a role in the attachment users experience towards their products [42].
2.2.3 Does the product (information) indicate what key components are critical to the duration of either the technical lifetime or the economic lifetime (i.e., relevance to the market)?	An aspect from circular design is to determining what components are expected to degrade first and, if these components are critical, look for design solutions to prevent this [43]. The question was rephrased as a result of the company evaluation (Section 5).
2.2.4 Does the product allow for enhancing a product's functionality and/or cosmetic condition throughout its lifetime?	Design strategies, like modularity, can allow product's functionality or appearance to be enhanced during its lifetime [44].
2.2.5 Is the product designed to have a timeless aesthetic?	The selection of design style links with timelessness and can influence market acceptance of circular products significantly, which can increase longevity [45]. The question was rephrased as a result of Co-creation session 7.
2.3 Standardization	
2.3.1 Is Design for Standardization applied throughout the whole product portfolio to support recovery options? Design for Standardization aims for standardizing selected parts throughout the product portfolio (e.g., between product generations) over time.	Standardization of sub-assemblies and components across product platforms allow for products to be used over multiple use-cycles as it prevents them from becoming obsolete by replacement [44]. The question was rephrased as a result of the company evaluation (Section 5).
2.3.2 Is (backward) compatibility applied throughout the whole product portfolio to support recovery options? Part compatibility is based on the interoperability between selected parts for multiple product types, and is dependent on, for example, part dimensions, energy uptake, interfaces, and software versions.	(backward) Compatibility of sub-assemblies and components across product platforms allow parts to be exchanged between products generations, lines, and platforms, which increases reusability potential [44]. The question was rephrased as a result of the company evaluation (Section 5).

TABLE 7.5 Continued.

Assessment Questions	Justification Based on Literature Review and Knowledge Coproduction Sessions
2. HARDWARE AND SOFTWARE DESIGN	
2.4 Maintenance & repair	
2.4.1 Is the product designed for ease of maintenance?	If the product requires maintenance to preserve its performance, then it should allow for ease-of-maintenance (Co-creations session 3). In case maintenance cannot be 'designed-out', minimizing the time and effort to maintain a product is recommended to enhance simplicity, reliability, and supportability [46]. The implementation of Design for Maintenance has a positive effect on other recovery activities [47].
2.4.2 Does the product come with information, like a manual, on how to take care of it?	Informing a user about the possibilities for product care, makes the user aware of his or her influence on a product's lifetime [48].
2.4.3 Does the product come with information, like a manual, on how to diagnose faults in key parts?	Providing information about fault diagnosis can help in restoring a product's function in a time-efficient, safe, and cheap way [49].
2.4.4 Does the product come with information, like a manual, on how to repair faults for key components?	Providing information about repairing faults can help in restoring a product's function in a time-efficient, safe, and cheap way [50].
2.4.5 Does the product have visual or auditory design cues supportive of maintenance and repair?	A product's design can help navigate the user in following the simplest and time-efficient route for disassembly in order to maintain or repair a product [49].
2.4.6 Is the safety risk for end-users minimized during self-repair of the product?	A product's design can be built facilitate safe maintenance, disassembly, and repair, not only by providing manuals, like mandated by EU legislation, but also through the physical design features [49]. The question was rephrased as a result of the company evaluation (Section 5).
2.5 Software support	
2.5.1 Does the product make use of any software?	A product that uses software to operate (a part of) its functionality.
2.5.2 Does software support form a bottleneck for products to live longer than the expected lifetime or for the extension of the product lifetime through re-use or remanufacturing?	Products that run software and serve for multiple use-cycles, should have hardware to support continuous software updates and upgrades, as well as availability of new versions of this software [44].
3. CUSTOMER EXPERIENCE AND CARE	
3.1 On- & off boarding	
3.1.1 Are the obligations and responsibilities for access, use, and end-of-life of a product communicated to end-users*? * For companies operating in a business to business context, this may not concern the end-user but another party responsible for on- and offboarding.	A central design intervention in gaining acceptance of users in product-service-systems has to do with communicating a clear and consistent message [51]. The question was rephrased as a result of Co-creation session 4 and the company evaluation (Section 5).
3.1.2 Is the onboarding process tested with end-users* on clarity and convenience? * For companies operating in a business to business context, this may not concern the end-user but another party responsible for on- and offboarding.	Major contributors to rejection of a product-service-system relate to a lack of understanding and lacking service quality, test and design iterations help prevent design flaws [51]. The question was rephrased as a result of Co-creation session 4 and the company evaluation (Section 5).
3.1.3 Is the end-user* supported in letting go of the product at the end of life, either emotionally or practically? * For companies operating in a business to business context, this may not concern the end-user but another party responsible for on- and offboarding.	Design interventions focused on emotional support help increase the readiness level and willingness of end-users to return their product, through reducing uncertainty and confusion [52]. The question was rephrased as a result of Co-creation session 4 and the company evaluation (Section 5).

TABLE 7.5 Continued.

Assessment Questions	Justification Based on Literature Review and Knowledge Coproduction Sessions
3. CUSTOMER EXPERIENCE AND CARE	
3.2 Use efficiency	
3.2.1 Does the product make use of consumables? This includes energy and water use. Consumables are goods that are used up while using a product, such as water, energy, ink, paper, and cleaning agents.	For certain products to fulfil a function, they require consumables which can be either dissipative (e.g., washing detergent) or disposable (e.g., razorblades) [53]. The question was rephrased as a result of Co-creation session 5.
3.2.2 Does the product maximize the use-efficiency of consumables, compared to the market average?	Use efficiency that can be influenced by design relates to facilitating correct use, adjusted to the use context, as well as using appropriate products in the right quantities [53]. The question was rephrased as a result of Co-creation session 5.
3.2.3 Does the product activate end-users to opt for sustainable use options?	Sustainable use can be promoted by complicating the more unsustainable options or simplifying the most sustainable option(s) [54]. The question was rephrased as a result of Co-creation session 5 and the company evaluation (Section 5).
3.2.4 Does the product require the use of consumables that contain critical or conflict materials?	Critical or conflict materials can be avoided or minimized through careful material selection [53]. The question was rephrased as a result of Co-creation session 5.
3.2.5 Does the product require the use of consumables that contain contents that can be hazardous to the environment in which they are discarded?	Hazardous materials can be avoided or minimized through careful material selection [53]. The question was rephrased as a result of Co-creation session 5.
4. PRODUCT SUPPORT SERVICES	
4.1 Warranty	
4.1.1 Does the product's warranty period last longer than what is legally required?	Warranty is provided for longer than the 2- or 5 years than mandatory from a legal perspective to guarantee a product's durability [55].
4.1.2 Are products that are returned by the end-user* as part of warranty repaired, refurbished or remanufactured? *For companies that operate in a business to business context or offer products as a service, this may not concern the end-user but another party responsible for returning products.	Closing the loop for all of a product's material streams adds to the circularity of a product, and is a proven concept for companies to pursue remanufacturing operations [15,56]. The question was rephrased as a result of the company evaluation (Section 5).
4.2 Professional support	
4.2.1 Does your company, or partnered companies, offer in-warranty maintenance & repair services for the product?	In cases where a product stops functioning within the warranty period, the product should be replaced. Turing to repair to restate the function of the product is the preferred action from a circular economy point of view [55].
4.2.2 Does your company, or partnered companies, offer any paid maintenance & repair support service for the product?	The availability of professional repair services as a route to lifetime extension to meet the need for repair in cases where self-repair is impossible or not desired [57].
4.2.3 Is the end-user informed about the availability of a professional maintenance and repair service?	Awareness of the professional support services offered are necessary to close make such services truly operational [57]. The question was rephrased as a result of the company evaluation (Section 5).
4.2.4 Does your company, or partnered companies, offer an upgrade service for your product?	Upgrade services allow customers to update and personalize product performance during a use-cycle [58].

TABLE 7.5 Continued.

Assessment Questions	Justification Based on Literature Review and Knowledge Coproduction Sessions
4. PRODUCT SUPPORT SERVICES	
4.2.5 Is the end-user informed about the possibility to upgrade the product?	The possibility for a customer to upgrade their product should be communicated through the accompanied service [58]. The question was rephrased as a result of the company evaluation (Section 5).
4.3 Spare part supply	
4.3.1 Are the spare parts to support self-repair by end-users affordable?	The availability of spare parts is essential to benefit from a product's reparability [59]. Affordability of such spare parts is a key factor in motivating customers to invest in repair [59]. The question was rephrased as a result of the company evaluation (Section 5).
4.3.2 Does your company produce extra spare parts for recovery, to enable refurbishment or remanufacturing?	The availability of spare parts is essential in performing recovery activities, including the required number of spare parts in the calculations for production is one of the ways to secure availability [15]. The question was rephrased as a result of Co-creation session 7.
4.3.3 Can end-users* return their used parts, that they have replaced, to your company? *For companies that operate in a business to business context or offer products as a service, this may not concern the end-user but another party responsible for returning parts.	Taking back used parts that are released from product through, for example, repair, can be valuable for several reasons: they can help increase circularity though (1) recovery for spare part supply (2) dedicated material recovery [56,61]. The question was rephrased as a result of Co-creation session 7 and the company evaluation (Section 5).
4.3.4 Are parts that are returned by the end-user* repaired, refurbished or remanufactured? *For companies that operate in a business to business context or offer products as a service, this may not concern the end-user but another party responsible for returning parts.	Closing the loop for all of a product's material streams adds to the circularity of a product, and is a proven concept for companies to pursue remanufacturing operations [15,56]. The question was rephrased as a result of Co-creation session 7 and the company evaluation (Section 5).
5. RECIRCULATION SERVICE	
5.1 Return program	
5.1.1 Does your company have a program to actively retrieve products from the market?	Products can be sold in combination with services, or as services, with the benefit of securing the return flow at end-of-use [62]. Having a return program prevents products to turn into waste or move into recycling before the product has reached its technical End-of-Life [63].
5.1.2 What percentage of the sold products are returned to the company or to partnered companies?	The number of products returning from the market has a significant influence on the effectiveness of a closed loop system [64].
5.1.3 Are end-users* informed about the product return options? *For companies operating in a business to business context, this may not concern the end-user but another party responsible for returning products.	Proactively marketing the options for customers to return products helps increase the awareness of the options and the likelihood of customers to engage with the options [65]. The question was rephrased as a result of the company evaluation (Section 5).
5.1.4 At what point are end-users* informed about the possible return options? *For companies operating in a business to business context, this may not concern the end-user but another party responsible for returning products.	Circular design can be used to (emotionally) support customers in returning their products through design interventions at different moments in time to increase product returns [65]. The question was rephrased as a result of the company evaluation (Section 5).

TABLE 7.5 Continued.

Assessment Questions	Justification Based on Literature Review and Knowledge Coproduction Sessions
5. RECIRCULATION SERVICE	
5.2 Product retrieval	
5.2.1 Is the product designed for ease and efficiency of reverse logistics? The product can be designed for to minimized the use of transportation volume, flatbed packaging, or to meet transportation conditions of existing logistical services	The question was rephrased as a result of the company evaluation (Section 5).
5.2.2 Does the company provide re-usable packaging for return options?	Packaging materials typically have a short lifetime and generate a lot of waste, which can be reduced radically by replacing single-use by reusable packaging [66].
6. RECOVERABILITY	
6.1 Disassembly	
6.1.1 Does your company list the key parts for disassembly?	Key components refer to those components in a product that are technically, economically, or environmentally valuable to the recovery activities to reach to enable maintenance, repair, replacement or parts harvesting [43,67]. The question was rephrased as a result of Co-creation session 3.
6.1.2 Is product disassembly and reassembly optimised for time, cost efficiency, simplicity and tool availability?	Design for disassembly helps make the disassembly process of a product feasible, while minimizing damage caused to parts, optimizing part re-use, optimizing the disassembly route to access a key part, and reducing the disassembly complexity in terms of tools, knowledge and skill needed [67]. The question was rephrased as a result of Co-creation session 3.
6.2 Refurbishment	
6.2.1 Does your company list what parts make the refurbishment operations feasible and viable?	The parts or sub-assemblies of a product can contribute to recoverability in different ways, like through increasing viability or feasibility. Understanding their role can help in optimizing their added value through design [15]. The question was rephrased as a result of Co-creation session 7.
6.2.2 Which fraction of the material value, by cost price, can be refurbished?	Calculating the ratio of the recoverable share of a product denotes the progress towards the circularity potential of a product [5].
6.2.3 Does your company provide refurbishment instructions and protocols to the relevant departments or third parties?	Having standardized instructions for recovery operations is the first recommendation towards lean production [68]. The question was rephrased as a result of Co-creation session 7.
6.2.4 Does your company have a clear diagnosis procedure for products returning from the market?	Diagnostics is seen as the critical first, and potentially time-consuming step, of the recovery process [69,70]. Standardization of this process helps avoid deviations and avoid unnecessary time loss [68]. The question was rephrased as a result of Co-creation session 7.
6.3 Remanufacturing	
6.3.1 Does your company list what parts make the remanufacturing operations feasible and viable?	The parts or sub-assemblies of a product can contribute to recoverability in different ways, like through increasing viability or feasibility. Understanding their role can help in optimizing their added value through design [15]. The question was rephrased as a result of Co-creation session 7.

TABLE 7.5 Continued.

Assessment Questions	Justification Based on Literature Review and Knowledge Coproduction Sessions
6. RECOVERABILITY	
6.3.2 Which fraction of the material value, by cost price, can be remanufactured?	Calculating the ratio of the recoverable share of a product denotes the progress towards the circularity potential of a product [5].
6.3.3 Does your company provide remanufacturing instructions and protocols to the relevant departments or third parties?	Having standardized instructions for recovery operations is the first recommendation towards lean production [68]. The question was rephrased as a result of Co-creation session 7.
6.3.4 Does your company have a clear diagnosis procedure for products returning from the market?	Diagnostics is seen as the critical first, and potentially time-consuming step, of the recovery process [69,70]. Standardization of this process helps avoid deviations and avoid unnecessary time loss [68]. The question was rephrased as a result of Co-creation session 7.
6.4 Recycling	
6.4.1 Which fraction of the material value, by cost price, can be recycled?	Calculating the ratio of the recoverable share of a product denotes the progress towards the circularity potential of a product [5]. Expressing this ratio in value provides an inclusive image with respect to, for example, minor metals, that are often used in small quantities (Co-creation session 6; [71]).
6.4.2 Does the product fall apart into separate homogeneous or compatible material fragments in the shredding process?	Separating the materials of a product into uncontaminated material streams is a key factor to high-quality recycling [41,71].
6.4.3 Are general recycling processes available for the materials in your product?	However recyclable a material is, whether a material gets recycled in reality depends on the availability of formal recycling processes, technology, and infrastructure [72]. The more common a material is, in type and mass, the more likely it is that general recycling processes are available. The question was added as a result of Co-creation session 6.
6.4.4 Is there an End-of-Use repurposing plan for the materials that are non-recyclable?	While their use is not uncommon, closing the loop for non-recyclable materials remains a challenge. Until recycling technology progresses, designers should to turn to repurposing scenarios to extend the lifetime of such materials to make continued use of the value of these materials' existing form and characteristics [9,41].

CHAPTER 8

DISCUSSION AND CONCLUSION

The aim of this dissertation was to improve our understanding of and strengthen the role of strategic design in the implementation of Design for Remanufacturing in practice. This builds on the premise that currently, Design for Remanufacturing is predominantly researched from an engineering perspective, largely ignoring the value of strategic design. The main research question is:

> *How can strategic design contribute to the wider implementation of remanufacturing?*

To address this question, six research projects were conducted, as presented in the chapters 2-7 of this dissertation (chapters 2-7), each with its own particular research aim. The first study investigated capabilities needed for remanufacturers to overcome barriers (Chapter 2). The second researched the role of soft barriers at the product development phase of a case company (Chapter 3). The third aimed at formulating design management roles for remanufacturing based on literature and company interviews (Chapter 4). In the fourth opportunities for the strategic integration of Design for Remanufacturing through design management at a case company were explored (Chapter 5). The fifth study focused on developing learning materials for remanufacturers to overcome barriers through workshops (Chapter 6). Finally, the goal of the sixth study was to develop circular design indicators to monitor implementation at companies (Chapter 7).

The results as discussed in the chapters answer the specific chapter sub-research questions (Table 8.1). In this chapter, we zoom out and discuss the results from a more holistic perspective along several different angles. Important terminology is summarized in section 8.1. The main results of this research are discussed in section 8.2, answering all six sub-research questions separately. How remanufacturing can be embedded in practice through strategic design is discussed in section 8.3. The contributions to science are discussed in section 8.3. Finally, the opportunities for future research are discussed in section 8.4.

TABLE 8.1 Sub-research questions and main conclusions.

Chapters	Research questions	Main conclusions
Chapter 2	What capabilities are needed to help remanufacturers overcome barriers to start up or scale up their remanufacturing activities?	Literature and company interviews point out that engineering skills for remanufacturing have been well developed, however, soft capabilities, relating to the way organizations learn and strategize, need to be advanced to help mature the remanufacturing business. These soft skills are currently underdeveloped.
Chapter 3	For remanufacturing, what is the role of soft barriers at the product development stage?	In this case study involving the building industry, the lack of soft capabilities presents a barrier for a wider engagement with remanufacturing. However, the general lack of awareness of remanufacturing seems to be a bigger barrier than the lack of soft capabilities.
Chapter 4	What are the opportunities and barriers to implementing Design for Remanufacturing in early stage product development?	Literature review and company interviews pointed out that opportunities to the implementation of Design for Remanufacturing are to align needs from all involved stakeholders, like those of the marketing department, the remanufacturing department, and supply chain partners; as well as to develop KPIs and roadmaps for applying remanufacturing within a product line or generation. Barriers that need to be tackled are the challenge of determining future market needs, the unpredictability of technological developments, and operating in complex supply chains.
Chapter 5	How can design management support the strategic integration of design for remanufacturing in industry?	The Strategy Map developed based on insights from case study research presents 12 main points through which the case company can proceed with advancing the integration of Design for Remanufacturing in strategic design. Points this map puts central are the importance of having a design vision that advocates designing products for multiple use-cycles, having an integrated business strategy for newly manufactured and remanufactured products, and integrating remanufacturing in customer research.
Chapter 6	How can remanufacturing barriers found in literature and field studies be translated into lifelong learning materials for remanufacturers?	The barriers found in literature review were translated into learning materials for professionals that were used in company workshops. The companies from different sectors, e.g. electrical equipment and logistics, were involved in the workshops. The workshop exercises allowed for in-depth exploration of important strategic circular topics, like ‘describing the offer’, ‘selecting a business model’ and ‘listing the required resources’. Learning materials on the following three topics received the highest rating from participants: ‘assessing product suitability’, ‘selecting a business model’, and ‘planning the reverse logistics’.
Chapter 7	What design indicators from literature are useful for monitoring circular design implementation in industry?	Through literature review and knowledge coproduction sessions with experts, 20 circular design indicators were identified that enable monitoring readiness levels of companies. These indicators cover all product life-cycle, from strategy and planning to recoverability. The method generates an overall score, scores for all themes, indicators, and individual questions.

8.1 TERMINOLOGY USED IN THIS DISSERTATION

Several research terms that are important to this dissertation are briefly summarized in this section. These descriptions will help understand and interpret the conclusions and discussions presented in the following sections. The following terms are addressed: Strategic design, design management, and balanced scorecard and strategy map

STRATEGIC DESIGN

Strategic design helps position a product onto the market in relation to other company offers. It determines the extent to which a product meets market needs, what its functionality should be, and whether it supports the long-term objectives of a company. By doing so, it also dictates a product's potential to re-enter a market after being remanufactured and informs the way design engineers can meet remanufacturing requirements (Atasu et al. 2008; Bulmuş et al. 2014; Wu 2012).

DESIGN MANAGEMENT

Throughout this dissertation, design management theory was used to simultaneously look into the strategic value of design and the value of detailed design engineering. Design management is a field of research that sits at the intersection of the management and design fields. It helps align design and strategy, it prioritizes and organizes design activities, it coordinates resources, and manages stakeholder needs (Erichsen & Christensen 2013).

BALANCED SCORECARD

An important design management framework used in this dissertation is the balanced scorecard for design management (Borja de Mozota 2006). A balanced scorecard is known to incorporate intangible value of business activities, and in the context of this dissertation, that of design management (Kaplan & Norton 2004). It steers away from having a predominant financial-oriented focus, and introduces the customer value perspective, process or performance value perspective, and learning perspective in parallel. This framework, using its four perspectives, was adjusted to fit the context of remanufacturing (Boorsma et al. 2022).

STRATEGY MAP

A strategy map is a framework that puts together the main results of the four perspectives of the Balanced scorecard into one visual (Kaplan & Norton 2004). It visualizes the links and interrelations between the four perspectives and facilitates the discussion and interpretation of these results. In this dissertation, the strategy map helped examine the value creation of remanufacturing design by linking the intangible assets of the four perspectives.

8.2 MAIN RESEARCH RESULTS

Strategic design plays a prominent role in implementing Design for Remanufacturing into the design process. It sets the design direction for individual products in relation to the product line and generations, affecting years, if not decades, of remanufacturing performance. It accounts for preparing products to be remanufacturable in several ways: (1) it links future market needs with potential market segments in relation to a portfolio of products, and (2) it identifies and prepares critical part categories to fit remanufacturing (e.g. high-value parts, software-related parts, and spare parts). These results are unpacked according to the six research projects.

To explore what the research balance between hard and soft capabilities is, as well as defining what soft capabilities entail in the context of remanufacturing, **sub-research question 1** was formulated. *What capabilities are needed to help remanufacturers overcome barriers to start up or scale up their remanufacturing activities?* A literature review and interviews with five third-party remanufacturers, from industries including automotive, industrial robots, and IT, gave insights remanufacturing barriers. Soft capabilities, like sensing and learning, remain less developed than the technical capabilities, and need to be further advanced to help remanufacturers mature their business. The analysis showed that the focus in the literature thus far has predominantly been on the technical capabilities, developing integrating and coordinating capabilities.

The main topics resulting from the literature search and the interviews were highlighted to illustrate what these soft capabilities entail. For the sensing capability these were the difficulty of determining the right price for remanufactured goods and the non-technical barriers to implementing Design for Remanufacturing into the product development process. Additional barriers for the sensing capability noted during the interviews concerned the ability to develop new value propositions for previously owned products, and to anticipate additional consumer needs, by for example developing services. Regarding the learning capability, the literature mentioned the need for market analysis regarding insights in willingness to pay, and the development of educational tools and cross-disciplinary learning. Interviewees discussed the need for educational programs tailored to remanufacturers.

Having established that the soft, strategic factors are insufficiently discussed in remanufacturing literature, a next step was to investigate how these factors influence decision-making for design in practice with **sub-research question 2**: *For remanufacturing, what is the role of soft barriers at the product development stage?* The case company chosen for this study is a manufacturer of high-end window shades. The company supplies products to the contractors who construct buildings.

In their exploration to find circular business opportunities the main focus has been to develop the value proposition in terms of quality offered and attractiveness to the customer compared to new products. This value proposition is based on technical product knowledge, like the use of high-grade materials and its ease of dis- and reassembly, and data from their existing markets. The company lacks information on market acceptance and procedures for product retrieval from End-of-Life buildings. No dedicated market research has yet been performed to gain insights into market needs and requirements. Moreover, the procedure for product retrieval was undefined. An influencing factor is that the concept of circular economy is new to the building industry, and the industry is therefore unexperienced in dismantling buildings for recovery purposes. This also means that the network of professionals involved in constructing buildings, like clients, architects and contractors, are relatively unaware of the concept. In their response to these barriers, the company is investigating how to build long-term relationships with their customers through setting up maintenance services. By doing this, they can create market awareness about the circular economy, and as an additional benefit, monitor the quality of the products over their lifetime. Having an OEM of building products offer services at the moment is not common practice due to the complex legal nature of the building industry, so it will take time to initiate this process.

However important strategic design is in implementing Design for Remanufacturing, this domain is relatively unexplored in the academic literature. To gain insights in strategic design activities, we applied design management theory, leading to **sub-research question 3**: *What are the opportunities and barriers to implementing Design for Remanufacturing in early stage product development?* Interviews were conducted with four companies which produce products with the potential to be remanufactured and three companies with remanufacturing operations in place. The selected companies are active in the sectors for outdoor furniture, vessel and maritime equipment, electro motors, and professional coffee machines.

The most common barriers reported in these interviews are the challenge of determining future market needs and the unpredictability of technological developments, causing reluctance to invest in circular design. Operating in complex supply chains is another important barrier, as it complicates communicating to customers directly (e.g. in the building industry). The transition from drafting conventional product proposals towards circular product proposals is considered complex, as they require new collaborations and need to be evaluated differently from a cost-perspective (i.e., considering longer time-horizons and additional R&D investments). Opportunities identified that support the implementation through design management are, firstly, by making the value of Design for Remanufacturing to the company at large explicit, by initiating product-related information exchange between internal and external stakeholders. Secondly, by embedding Design for Remanufacturing into existing processes by means of KPIs and roadmaps. Overall, a number of design management roles were formulated based on insights gained from the literature review. In addition, the interviews were used to elicit new roles for advancing the implementation of Design for Remanufacturing. Key roles were 'connecting different disciplines within the company to develop relevant, high-quality offers through recovery', 'making recovery roadmaps at an early design stage', and 'identifying the intangible value of remanufacturing to a company'.

Once the role of strategic design for remanufacturing was defined based on design management theory, the next step was to use an in-depth case study to investigate this role in practice and answer **sub-research question 4**. *How can design management support the strategic integration of design for remanufacturing in industry?* The case company selected for this study is a globally operating OEM of professional imaging equipment, with a long history of remanufacturing. The case study included four departments: product development, compliance, remanufacturing, and business development. The results of the case analysis were presented in the form of a Strategy Map.

The Strategy Map presents 12 main points through which the case company can proceed with advancing the integration of Design for Remanufacturing in strategic design (Figure 8.1). These 12 points were found based on four different perspectives. From a process perspective, the company can steer towards appropriate, non-negotiable remanufacturing design guidelines, by identifying critical part (categories) to remanufacturing (e.g., high-value parts, software-related parts, spare parts, etc.). For the customer perspective, the company should consider the inclusion of remanufacturing in customer research and developing a dedicated brand identify and marketing strategy. This fosters the adoption of remanufactured products in the product portfolio. From a value perspective, the company benefits from identifying the intangible strengths of remanufacturing. In addition, and building on this, the advice is to consider a business strategy that integrates both newly manufactured and remanufactured products. Finally, from a learning perspective, it is crucial to use designing for multiple use-cycles as a central design vision. In essence, design management helps reveal the value remanufacturing can have to a company at large. It ensures aligned action from different company disciplines, and commitment to follow through. These structures then contribute to embedding Design for Remanufacturing into the design process.

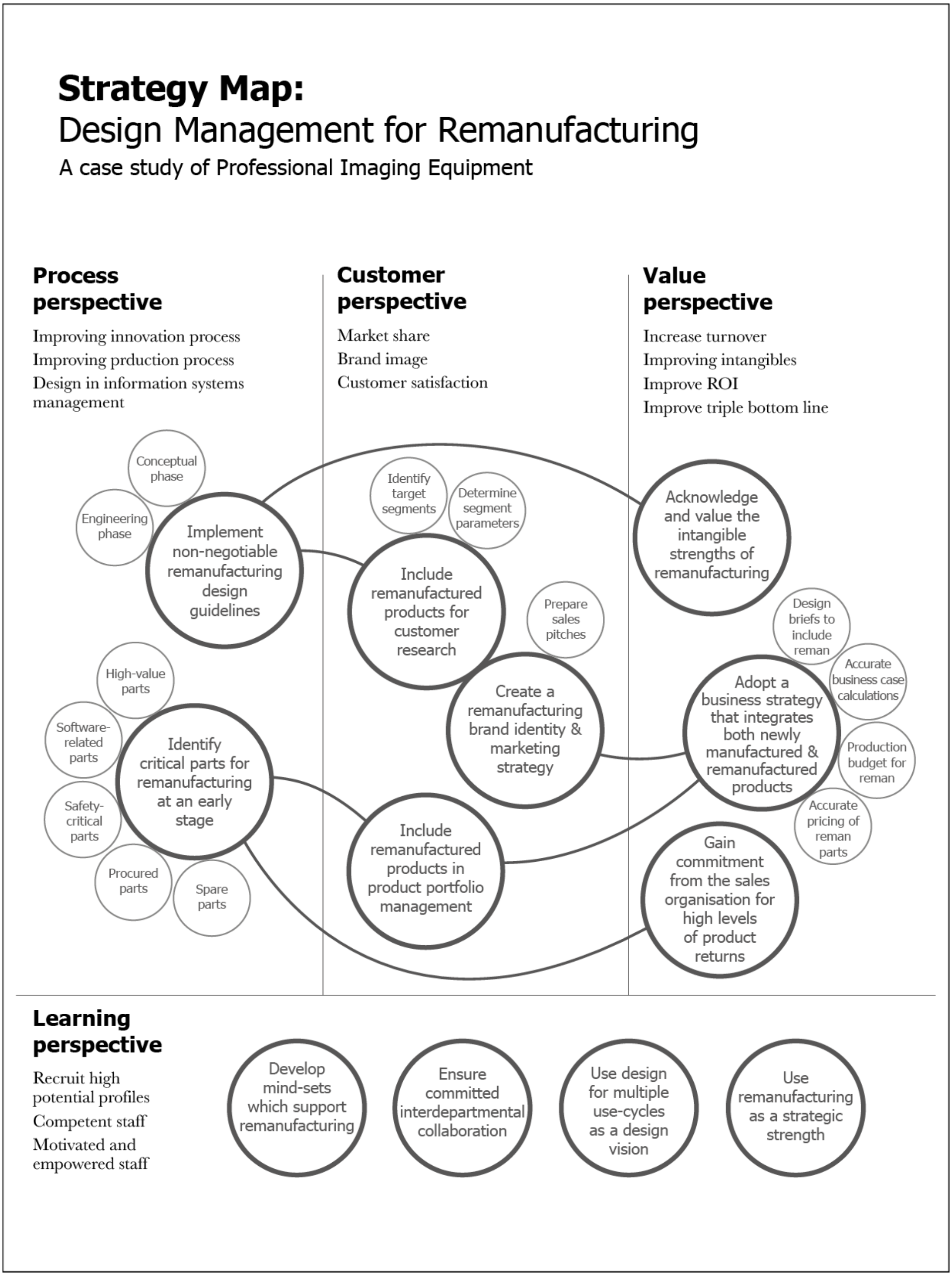

FIGURE 8.1 Strategic elements in Design for Remanufacturing.

The knowledge cross-over from theory to industry plays a crucial role in advancing the implementation of (design for) remanufacturing in practice. This led to **sub-research question 5**. *How can remanufacturing barriers found in literature and field studies be translated into lifelong learning materials for remanufacturers?* The barriers were translated into learning materials for professionals for use in company workshops. Examples of the topics for these barriers are 'definitions, standards, and classification', 'understanding the customer', 'economic benefits and risks', and 'product design'. The companies selected for the workshops are active in the following sectors: construction and real estate, ICT and electronics, electromechanical equipment, electro mechanical products, cooling equipment, transport and logistics, and home appliances. To address the barriers, the workshop exercises were designed to steer towards in-depth exploration of important strategic circular topics. The exercises addressed topics like defining the steps of the recovery process, describing the circular offer, selecting a business model, and assessing product suitability. The learning materials address most of the barriers and can be further developed to include the remaining barriers, like those related to 'product-related data' and 'metrics'. For future learning programs, company representatives are looking for materials that support the implementation of circular concepts. This relates to encouraging internal buy-in, but also to practical advice on designing circular products and understanding customer needs. The representatives pointed out the need for examples of solutions to common (industry) barriers.

The final research question presented in this dissertation was formulated to help monitor the progress of implementing remanufacturing, for which to date, an extensive, design-specific, monitoring method is lacking. This led to **sub-research question 6**. *What design indicators from literature are useful for monitoring circular design implementation in industry?* Existing indicator methods were found to either (1) lack depth with regards to circular design (2) be incomplete, and/ or (3) lack a designer's perspective.

The Circular Product Readiness method developed in this study provides a means to give guidance to and monitor the status of circular design implementation. Through the literature review and knowledge coproduction sessions with experts, 20 circular design indicators were identified that enable monitoring readiness levels of companies (Figure 8.2). These indicators cover all product life-cycle stages in six themes, from strategy and planning to recoverability. It helps companies assess their readiness level to design the different aspects of circular product service systems. The method was evaluated in a one-hour evaluation interview with two multinational corporations active in the white goods industry and the automotive aftermarket, respectively. The method report shows the overall score, and the score for all themes, indicators, and questions separately, as well as opportunities for improvement. In terms of design management, an additional benefit of having an assessment method focused on circular design in a broader sense is that it helps coordinate Design for Remanufacturing in relation to the other circular design strategies a company applies.

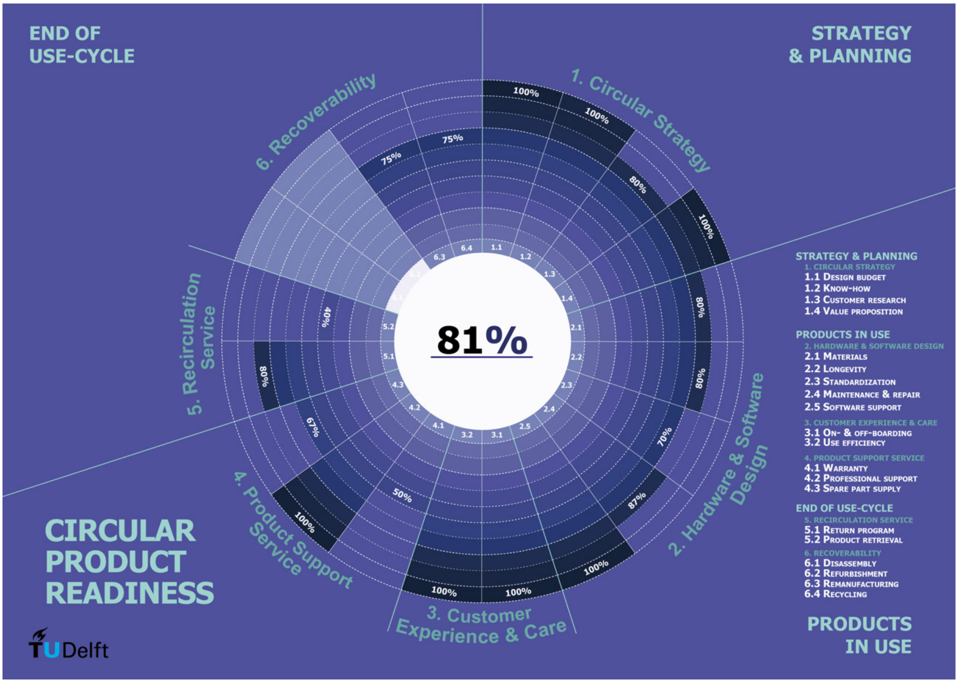

FIGURE 8.2 Visual of the Circular Product Readiness method – results of Gorenje.

8.3 EMBEDDING REMANUFACTURING IN PRACTICE THROUGH STRATEGIC DESIGN

This section answers the main research question of this dissertation. First, it explains how strategic design can integrate remanufacturing and help it shift away from being an isolated company activity. It then explains how remanufacturing, through its strategic integration, can contribute to sustainable innovation. Finally, it discusses the results by addressing its effect on three major barriers to remanufacturing.

8.3.1 END-OF-LIFE STRATEGY TO AN INTEGRATED APPROACH

Remanufacturing is viewed as an End-of-Life strategy by both academia and industry (IRP 2018). The approach is often deployed as company activity which is separate to new production; it has an intrapreneurial character. This dissertation shows, that when introducing remanufacturing into strategic design, companies can adopt an integrated

recovery strategy, which enables more effective use of the remaining value in existing capital and allows for more effective management of market share.
Researchers argue that Design for Remanufacturing, as well as eco-design and sustainable design, need to be considered at the early stages of the design process (Fadeyi et al 2017; Favi et al 2017; Sheldrick & Rahimifard 2013). This allows designers to develop product concepts that inherently consider remanufacturability and avoid making it an 'add-on'.

8.3.2 SUSTAINABLE INNOVATION BY INTEGRATING REMANUFACTURING IN STRATEGIC DESIGN

This dissertation contributes to the notion that remanufacturing should be considered throughout a company's full product portfolio, from introducing sustainable production as a property of an individual product, to becoming a system property. It also allows us to take a step back and see how the full portfolio of products will meet the needs of todays and future customers. One important insight relating to this, is that companies lack insights in the market needs for remanufactured products.

Remanufacturing can further mature when the aim for product development is to generate long-term 'social' sustainable advantage by means of strategic design. Currently, the choice of companies to remanufacture is often driven by filling (unforeseen) gaps in the product portfolio of new products. These gaps arise when market demand lasts longer than a company has planned to produce for. In other words, it arises from a sudden misfit between the type of product functionalities offered and the customer's requirements and needs. The central task of strategic design is to adhere to all market needs with a range of products and optimize a product portfolio to meet these needs. However, the possibility to remanufacture products is overlooked in this process, which means that products' potential to meet needs in secondary markets are not considered. Products are therefore not attuned to the strategic 'social' aspect of remanufacturing, in terms of meeting market needs over the long-term. Integrating remanufacturing into strategic design, and attuning products to market needs over the long-term, can therefore help grow remanufacturing activity and help shift towards more sustainable ways of producing. Adams et al. (2016) state that technically focused sustainable innovation indeed dominates the literature, but only yields incremental environmental gains and that adopting strategic design for remanufacturing would help the shift from 'operational optimization' to 'organizational transformation', embedding sustainability and moving away from purely greening individual products. A requirement for companies to successfully make this transition is to adopt a learning organization culture with respect to circular design to develop the required mind sets and design visions.

A next step in the field of remanufacturing would be to set up collaborations in the wider ecosystem of a company to let remanufacturing innovation evolve into 'systems building', a third term introduced by Adams et al. (2016), an even more radical form of sustainable innovation. Co-designing sustainable solutions within a wider network of stakeholders is also recognized as an effective way forward by Ceschin & Gaziulusoy (2016), as a means to 'stimulate a strategic dialogue'.

8.3.3 TACKLING REMANUFACTURING BARRIERS THROUGH STRATEGIC DESIGN

Strategic design lays the foundation for embedding Design for Remanufacturing in the design process. But can strategic design also overcome the main barriers to remanufacturing? This section discusses the main barriers identified in the literature and in this dissertation (matching supply and demand, cannibalization, and market acceptance) and discusses how, based on the results of this dissertation, strategic design can contribute to addressing some of these barriers.

Matching supply and demand

Remanufacturing requires a used product as an input to its process. Managing the timing of products returning from the market with demand for remanufactured products is considered difficult (Guidat et al. 2015). One way through which strategic design can help address the availability of cores is that it allows companies to develop a remanufacturing roadmap which specifies the products it needs returned and when. The roadmap allows for timely communication of these requirements to a company's the sales organization, which typically have detailed plans of when to approach customers to sell new products. This also means that they know what type of products the customer currently has, and thus means that they know exactly what products are on the markets, in what quantity, and what the approximate timing is for products to become obsolete. This solution is most relevant to companies which remanufacture material-intensive high-value products and are in direct contact with their end-customer.

Cannibalization of new sales

Due to their attractive price and high-quality, remanufactured products can compete with the sales of new products. A possible solution to deal with cannibalization is through more distinct differentiation of products in the product portfolio. By evaluating the remanufacturing potential of products during product portfolio management, companies have more chance of anticipating on possible cannibalization. Knowing which products are likely to compete can inform companies what should be emphasized in the new product for them to remain distinctly differentiated from remanufactured ones.

Market acceptance
Customers still live under the assumption that 'new is better' and they are often unfamiliar with the quality of products the process can produce (Abbey et al. 2015; Guidat et al. 2015). Companies do invest in marketing and branding of remanufactured products, but not to the extent to which they currently market new products, resulting in difference in market visibility between the two product types. New products are 'pushed' onto the market, without properly positioning remanufactured products or giving them an own identify. The market may then interpret this as remanufactured products as being inferior to new products, based on the message (or lack there off) communicated by the company. Correct remanufactured product positioning in the market with respect to other products should take place during the strategic design phase. Visibility can also be improved through the development of standards and certification.

8.4 CONTRIBUTION TO SCIENCE

The understanding of the strategic role of design for remanufacturing is the central motif and contribution to science in this dissertation. This is substantiated in three main themes: remanufacturing forces companies to take a longer time horizon for new product development; Design for Remanufacturing can be attuned to the wider field of circular design through a design monitoring method; and the reframing of remanufacturing in design more generally.

We show that, to achieve a wider implementation of remanufacturing, companies need to look at longer than usual time horizons. The strategic integration of remanufacturing necessitates this long-term perspective. The timeframes for strategic design at companies are, generally, restricted to the duration of a single use-cycle of a product. When adopting remanufacturing activities, in reality this timeframe includes a second if not third use-cycle as well. Existing strategic models found in literature did not meet the need to strategize for products with multiple use-cycles. This could therefore be better expressed in existing strategic models in literature, such as Kaplan & Norton's (2004) Strategy Map (Figure 8.1). In the strategy map, Kaplan & Norton argue that expressing the value of strategy solely in terms of finance is limiting; in this dissertation we argue that the four perspectives themselves are limiting if they are not regarded as dynamically developing over longer time horizons.

Another core contribution is that the implementation of remanufacturing would benefit from being considered in the wider frame of circular design. Circular design strategies, like maintenance, refurbishment and remanufacturing, have design guidelines in common, yet they are also optimized to serve their own specific purposes. It is common for companies to design product which fit a combination of circular applications, like maintenance and remanufacturing, instead of just one. Instead of optimizing one circular design strategy in isolation, it is therefore important to consider all selected strategies simultaneously. The monitoring method for circular design implementation developed in this dissertation evaluates circular design using 20 indicators, and addresses remanufacturing as part of it. It acknowledges that Design for Remanufacturing operates in a wider field of circular design strategies, and that it would benefit from being considered directly from the strategic front-end. Taking a holistic approach brings interlinkages between strategies to the surface the and lowers the chance of encountering design trade-offs.

Remanufacturing is often viewed as a technical, End-of-Life solution, which offers strategic benefits. When viewing it as a strategic approach, remanufacturing can increase its impact on business development and environmental sustainability. Once fully integrating remanufacturing, the recovery potential of existing capital increases. It allows companies to better attune their value propositions for remanufactured products to their customers and, with that, more optimally leverage the remanufacturing potential of products. This allows companies to make more effective use of their resources and minimize wasting end-of-use products that are still functional. This way, remanufacturing can have the potential of being a sustainable innovation strategy. In a similar way, Gehin et al. (2008) propose that remanufacturing can function as a dynamic, innovation strategy to reduce material consumption, costs, and to gain control over secondary markets. This dissertation underpins this statement and moves it forward by detailing the strategic elements that are required to implement this innovation strategy.

8.5 FUTURE RESEARCH

In the dissertation , we explored the contribution of strategic design to the wider implementation of Design for Remanufacturing. Based on this research, we have formulated several interesting directions for future research with regards to Design for Remanufacturing.

REMANUFACTURING CONSUMER PRODUCTS

Remanufacturing mainly takes place in B2B markets for high-value, complex products. Consumer products are seldom remanufactured. To increase the impact of remanufacturing, it would be beneficial to have the option to remanufacture consumer products. An interesting research question would therefore be: Under what conditions and for what product groups is it feasible and viable to set up remanufacturing operations?

A follow up question could be: How can the circumstances be created under which it would be feasible and viable to pursue remanufacturing for consumer products?

PRODUCT RETURNS

At the moment, most companies have no stake in the End-of-life phase of their own products, except for what is regulated by law in terms of recycling. In the scenarios that legal requirements would force companies to take back their own products after use, these stakes could change accordingly. Companies may then find new opportunities to develop circular value propositions, which would have a knock-on effect on product design. A research question could therefore be as follow: How would circular design practices at companies be affected should product returns become mandatory through legislation?

MARKET NEEDS FOR REMANUFACTURED PRODUCTS

An important starting point for new product development is an understanding of market needs. The needs for secondary markets are often less well researched than those of primary markets. Learning more about the differences between these two markets, in terms of needs and characteristics, will not only help in designing products that fit these secondary markets, but also serve these markets better and encourage opportunities for growth of remanufacturing activities. A research question to address this gap could be: Which industry-specific market needs that can be met through remanufactured products? A follow-up research question could then be: How can companies anticipate continually changing market needs to optimize the demand for remanufactured products?

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ABOUT THE AUTHOR

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Nina Boorsma was born on the 29th of March 1989 in Groningen, the Netherlands. She pursued a bachelors' degree in Industrial Design Engineering at the TU Delft with a focus on sustainability, by following a minor in Sustainable Design Engineering and becoming circular economy ambassador for SustainableMotion, a consultancy based in Amsterdam.

During her masters in Strategic Product Design at Delft University of Technology, she further deepened her understanding of sustainable design in her curriculum and her masters' graduation thesis on Design for Remanufacturing of medical equipment at Philips. An article on the results from her masters' graduation was published in the ReMaTec News, a remanufacturing news magazine which is linked to the ReMaTec trade show.

Her professional career started at Spark design & innovation, a product design agency based in Rotterdam, where she worked as a Marketing and Communications Manager. After this, she continued her professional journey at Innoboost, a sustainable strategy consultancy in Amsterdam, combined with a research position at TU Delft in which she worked on two EU projects: 'Key success factors for Re-Use Networks' (RUN) and 'Bridging the raw materials knowledge gap for reuse and remanufacturing professionals' (ReUK). Outcomes of these projects were workshops and idea camps with professionals, and a booklet with best practice examples of remanufacturers.

In the next step of her career, she started working as a PhD researcher on the topic of remanufacturing, to dive deeper into the topics she started looking into during her masters' graduation and research position. As part of her PhD, Nina worked on a workpackage for the development of circular design methodologies for H2020 EU project 'Recourse Efficient Circular Product Service Systems' (ReCiPSS). In this project, she collaborated with 13 partners from 8 different countries to set up two large-scale demonstrators of circular manufacturing systems for the companies Gorenje Gospodinjski Aparati D.D. and Robert Bosch GmbH.