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Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

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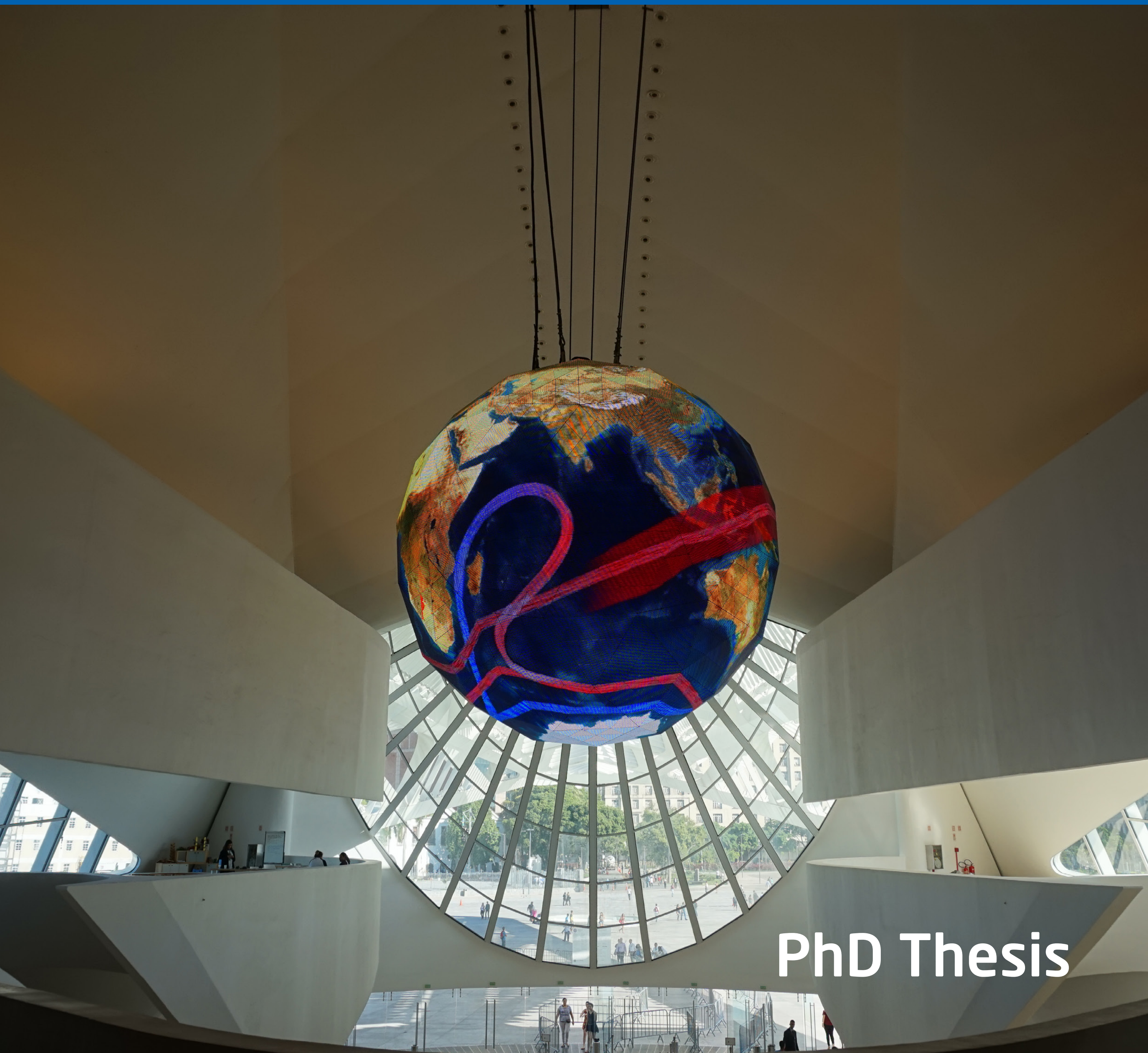
Mariia Kravchenko



PhD Thesis

SUSTAINABILITY SCREENING AS A DECISION SUPPORT FOR EARLY STAGE CIRCULAR ECONOMY DEVELOPMENT: MOVING THE SAILS OF CIRCULAR ECONOMY IN THE DIRECTION OF SUSTAINABILITY

PhD Thesis

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November 2020

Technical University of Denmark (DTU)

Department of Mechanical Engineering

Section of Engineering Design and Product Development

Title: Sustainability screening as a decision support for early stage circular economy development: moving the sails of circular economy in the direction of sustainability

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November 2020

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Funding:

This research received funding under the Nordic research project CIRCit, which was jointly funded by NordForsk, Nordic Energy Research, and Nordic Innovation within the Nordic Green Growth Research and Innovation Programme (grant number: 83144).

Cover image: own photo, 2016, taken in Rio de Janeiro, Brazil. This photo was taken inside of the Museum of Tomorrow, which mixes science and design to focus on opportunities and challenges that tomorrow brings humanity. With creative exhibitions, striking statistics, and future projections, it leaves no one indifferent to the urgency of change - so tomorrow happens.

Abstract

As the urgency of tackling global issues as climate change, resource depletion and biodiversity loss becomes apparent, manufacturing companies are among many other actors in attempting to find new approaches to create economic and societal value, whilst eliminating adverse environmental impact. Circular economy proposes an innovative alternative approach to counter these negative global effects, by offering the opportunity to manufacturing companies to explore how to capitalize on retaining the value embedded in products and operations for longer, thus optimizing the economic and environmental costs and benefits. This notion of 'circularity' has made circular economy attractive for many businesses, who increasingly see circular economy practices as a means towards achieving greater sustainability benefits. While academic studies provide heterogeneous findings, regarding whether and to what extent circular economy brings positive economic and environmental gains, a comparatively underrepresented contribution to social sustainability is widely acknowledged. Considering the rapid uptake of circular economy by the manufacturing industry, it is imperative to support the early stages of circular economy development by integrating economic, environmental and social considerations for a holistic sustainability decision-making process.

Within this context, this research aims at proposing a sustainability screening framework for circular economy. The framework acts as a decision support to enable integration of economic, environmental and social aspects of the triple bottom line perspective into the early stages of circular economy development within the manufacturing industry. The framework constitutes several fundamental elements, such as a leading indicator approach to measuring sustainability performance, a structured procedure to select relevant indicators for sustainability screening of circular economy initiatives and a trade-off navigation framework to support decision making between conflicting sustainability indicators within the screening. The ultimate goal is to support the early development stages by enabling a comparison of circular and non-circular initiatives, integration of improvements and further development of an initiative with the highest sustainability potential.

In this PhD thesis, a *leading performance indicator* approach is used as a theoretical foundation to support measurement of potential economic, environmental and social performance, due to its usefulness in the early development stages. This theory supported the development of an indicator database and a procedure for systematic selection of indicators for corresponding circular economy initiatives. The challenge of making trade-offs, observed during empirical work in manufacturing industry, led to the proposal of the trade-off navigation framework, which aims at supporting sustainability screening by providing a structured approach to navigating conflicting sustainability indicators and facilitating decision analysis of the proposed initiatives and decision objectives.

The research is built on three studies that were conducted to respectively address: i) leading performance indicators as a support for early stage performance measurement for economic, environmental and social aspects, including their applicability for circular economy measurement (Study A); ii) proposal and evaluation of the indicator selection procedure and a user guide for the measurement of circular economy initiatives from the triple bottom line perspective (Study B); iii) proposal and evaluation of the trade-off navigation between conflicting sustainability measures (Study C). This research and corresponding studies were designed following Design Research Methodology (DRM), which provided a framework to carry out design-oriented practical research, combined with a theory-driven approach for the analysis and development of the theory within the field.

The main results from the thesis, documented both in the main body and in the four appended papers, include: i) a database of more than 270 leading performance indicators classified according to economic, environmental and social aspects, business processes and circular economy strategies (Study A); ii) a structured procedure for indicator selection and a user guide to support the measurement of circular economy initiatives from a triple bottom line perspective (Study B); and iii) a structured approach to support decision analysis and trade-off navigation between conflicting sustainability measures (Study C). These results were integrated as key elements in the framework for sustainability screening of circular economy initiatives, which is expected to support a 'hands-on' approach to measuring sustainability performance of the proposed initiatives and integrating sustainability considerations early in business activities alongside other 'traditional' criteria. Overall, the main aim is to support the design and selection of the circular economy initiative that maximizes beneficial outcomes within all dimensions of sustainability.

Sustainability screening for circular economy is a first attempt to support circular economy development using triple bottom line measures, laying the foundation for necessary future work, to further ensure its usability for uptake by industries in both technical and bio-economic sectors.

Keywords: circular economy, sustainability screening, triple bottom line, early development, decision support, manufacturing industry

Dansk resume

Globale udfordringer såsom klimaændringer, udtømning af ressourcer og tab af biodiversitet er blandt de største udfordringer, som i stigende grad påvirker det globale samfund. Fremstillingsvirksomheder, blandt øvrige aktører, har brug for alternative løsninger, der kan skabe værdi for egen forretning og for samfundet, uden at forøge den negative påvirkning på miljøet. Cirkulær økonomi har et kæmpe potentiale som en ny økonomisk model, der har til hensigt at opretholde de værdifulde ressourcer, der indgår i produkter og deres indholdsstoffer, i kontinuerlige kredsløb, hvilket kan hjælpe fremstillingsvirksomheder til at skabe en positiv miljømæssig og samtidig profitabel økonomi. Derfor er cirkulær økonomi for alvor kommet på dagsordenen i mange virksomheder, der sidestiller de cirkulære løsninger med forøget bæredygtighed. Der findes dog delte meninger, især i den akademiske verden, om hvorvidt de cirkulære løsninger fører til positive miljømæssige og økonomiske virkninger, samt i hvilket omfang og under hvilke omstændigheder. Samtidig er der enighed om at der mangler bevis for at cirkulære løsninger kan bidrage til øget social bæredygtighed. For at imødekomme den stigende interesse for cirkulær økonomi i industrien og sikre at cirkulære løsninger bidrager til bæredygtighed, er der behov for at understøtte virksomheder i udvikling af cirkulære løsninger. Dette skal ske i de tidlige udviklingsfaser med inddragelse af et holistisk syn på bæredygtighed, det vil sige med fokus på de sociale, økonomiske og miljømæssige aspekter.

Dette forskningsprojekt har derfor til formål at udvikle et rammeværktøj for bæredygtighedsscreening af cirkulære løsninger. Rammeværktøjet inddrager flere grundlæggende elementer, såsom en metode til vurdering af sociale, økonomiske og miljømæssige aspekter baseret på indikatorer, en procedure til systematisk udvælgelse af relevante indikatorer for de respektive cirkulære løsninger og en teknik for håndtering af bæredygtighedsmæssige trade-offs, der kan opstå mellem modstridende bæredygtighedsaspekter. Hovedmålet er således at understøtte de tidlige udviklingsfaser, hvilket giver mulighed for at sammenligne forskellige cirkulære og non-cirkulære løsninger, introducere forbedringer og videreudvikle de løsninger der har det højeste bæredygtighedspotentiale.

Bæredygtighedsvurderingen tager et teoretisk udgangspunkt i *'leading performance indicators*', der særligt er brugbare til at understøtte vurdering af sociale, økonomiske og miljømæssige aspekter i de tidlige udviklingsfaser. Denne teori har således bidraget til udarbejdelse af proceduren til systematisk anvendelse af relevante indikatorer for de respektive cirkulære løsninger og guiden til bæredygtighedsscreening. Trade-off udfordringen, der blev identificeret under anvendelsen af indikatorer med virksomhederne, har ført til udarbejdelse af teknikken for håndtering af bæredygtighedsmæssige trade-offs. Trade-off teknikken understøtter afvejning mellem modstridende bæredygtighedsaspekter og kan derfor ses som et af de grundlæggende elementer af bæredygtighedsscreeningen.

Projektet indeholder tre studier der blev gennemført for: i) at undersøge anvendeligheden af 'leading performance indicators' som grundlag for at vurdere de sociale, økonomiske og miljømæssige potentielle virkninger af cirkulære løsninger i de tidlige udviklingsfaser (Studie A); ii) at undersøge anvendeligheden af en struktureret bæredygtighedsvurdering af cirkulære løsninger, baseret på de udvalgte 'leading

performance indicators' (Studie B); iii) at udvikle og evaluere en teknik til håndtering af bæredygtighedsmæssige trade-offs (Studie C).

Forskningsprojektet består af tre studier som er bygget op i helhold til de forskellige faser i Design Research Methodology (DRM), der har skabt en ramme for forskningen i forhold til planlægning, metodevalg og evaluering, ved inddragelse af både teoridreven og empirisk undersøgelse.

Disse studier førte til resultater, som blev dokumenteret i artiklerne 1 til 4 og er præsenteret i denne afhandling som følgende: i) en database med mere end 270 'leading performance indicators' der er opstillet efter de sociale, økonomiske og miljømæssige aspekter, forretningsprocesser og strategier inden for cirkulær økonomi (Studie A); ii) en procedure til systematisk udvælgelse af relevante indikatorer for de respektive cirkulære løsninger og en brugerguide til bæredygtighedsscreening (Studie B); iii) en teknik for systematisk håndtering af trade-offs mellem de bæredygtighedsmæssige aspekter (Studie C). Disse resultater indgik i rammeværktøjet for bæredygtighedsscreening af cirkulære løsninger, hvis formål er at understøtte praktisk evaluering af bæredygtighedspotentialet for de cirkulære løsninger. Det overordnede formål er at yde støtte til beslutningstagere under udvikling og gennemførelse af cirkulære løsninger, der leder til forbedret bæredygtighed.

Bæredygtighedsscreening af cirkulære løsninger er et af de første forsøg på at muliggøre evaluering af cirkulære løsninger, i forhold til bæredygtighed, ud fra sociale, økonomiske og miljømæssige aspekter. Ud fra forskningsresultaterne blev der påvist dennes positive potentiale; ikke desto mindre kan fremtidigt arbejde fokusere på at forbedre anvendeligheden, for lettere anvendelse i industrien, både til udvikling af biologiske og teknologiske produkter.

Nøgleord: cirkulær økonomi, bæredygtighedsscreening, den tredobbelte bundlinje, tidlige udviklingsfaser, beslutningsstøtte, fremstillingsindustri.

Preface and acknowledgments

In distant 2005 my journey towards obtaining a Bachelor of Science in Environmental Engineering started. During a course of 4 years, I learned about the issues of air, water and land pollution, solid and liquid waste generation. I and my classmates spent many hours concentrating on the design of treatment and pollution prevention technologies to address these issues. At that time, it seemed as one of the right things to do – dealing with the damage that was unavoidable. But was it unavoidable after all? The answer I found during the Masters' program in Environmental Studies with specialization in Environmental Management and Sustainability Science. It broadened my view on the environmental and social issues – certainly, they could be avoided if business actors were helped with introducing and following environmental and social management practices. Identification of significant environmental and sustainability issues, setting goals and action plans, and monitoring changes to drive continuous improvements could indeed show how businesses acted in environmentally and socially acceptable manner. Yet again, it seemed right, but was it enough? Was the firm-centric approach sufficient to steer the progress towards sustainable development? And there was I, who, in 2017, with this question in mind, applied for a PhD position in Sustainability and Circular Economy at the Section of Engineering Design and Product development at DTU. The beginning of the PhD journey was a real roller coaster: the confusion about circular economy as a concept (what else could it be if not remanufacturing and recycling?), the uncertainty about the difference between sustainability and circular economy (isn't circular economy inherently sustainable?) and the prominent role of business modelling and product development in defining the sustainability potential of a business and product (moving away from a firm-centric view?) were all a part of a steep learning curve. With all the climbs and loops, the dives were full of excitement as I continued discovering new knowledge and gaining experience related to the interplay of sustainability and circular economy. This thesis tries to bring clarity about the questions I asked myself at the beginning of this journey and hopefully will inspire more studies supporting circular economy development towards better sustainability. This could bring advances in both scientific domains: for circular economy - addressing the conceptual uncertainty (what is it?) and related methodological challenges (how to measure it and what for?); for sustainability assessment – improving measurement approaches able to capture the sustainable 'more good' intention along the 'doing less bad' perspective of the triple bottom line approach.

None of the brilliant insights, state of the art knowledge and remarkable experiences I gained throughout this 3-year long PhD journey would be possible without thought-provoking dialogues, invaluable feedback and guidance, and tremendous support from a number of people I am grateful for being surrounded by. Therefore, I would like to express my very great appreciation to:

… my supervisors from DTU Tim McAloone and Daniela Pigosso for providing continuous professional and personal support throughout the whole journey. Your profound knowledge of eco-design and sustainable product and service development has strengthened my understanding of the importance of integrating sustainability as early in the decision process as possible. I feel lucky about having had time with you for scientific discussions, but also for informal chats during the lunch breaks. I truly admire your balance of professional and personal approach, which shows appreciation for a PhD researcher as a colleague and as an individual.

Tim McAloone, I am grateful for your considerate and genuine guidance, which always helped me to a see a bigger picture – it helped me to turn many challenges into opportunities and become sharper about my research direction and contribution. Daniela Pigosso, a sincere thank you for being supportive and always encouraging me to move forward. You have this extraordinary ability to explain complex phenomena using simple terminology and visualization. Your passion for research and teaching, sustainability and circular economy is unique and has inspired me in so many ways.

… my colleagues from CIRCit project for the lively discussions we had together shedding the light into the dark corners of circular economy. A mix of backgrounds, cultures, ages, genders and experiences – that is what made the CIRCit experience truly exceptional. I had a pleasure to meet many of you in person and experience the dynamics and diversity of your thoughts and suggestions. I thank all and each of you - Fenna Blomsma, Marina Pieroni, Sasha Shahbazi, Eivind Kristoffersen, Jutta Hildenbrand, Jingyue Li, Carina Wiik, Anna Rùna Kristinsdottir, Anna-Karin Jönbrink, Kjartan Due Nielsen, Helena Soimakallio, Johan Dahlstrom, Sandra Jungner, Lone Groes Hede, Lena Kristina Carlberg and many others - for your enthusiasm and valuable contribution to CIRCit project and to my PhD. I am grateful for the financial support from NordForsk, Nordic Energy Research, and Nordic Innovation for jointly funding CIRCit project, and a part of my PhD project, under the Nordic Green Growth Research and Innovation Programme.

Likewise, a great appreciation goes to the industrial partners of CIRCit project. Without your time and effort, I would not obtain the valuable insights and results for my research. Thank you for showing your interest in sustainability screening for circular economy and letting me in to observe your work, and appreciate your intentions and ambitions for making the world a better place.

… the scientific community I had a pleasure to be engaged with: Design Society, CIRP, ERSCP. Valuable dialogues, useful critiques and curiosity from the community helped me to position my research within a wider spectrum of research areas and approaches. This made me confident in disseminating my research to larger audiences within and outside the research community.

… my colleagues from K&P and other institutions, with special thanks to Herle, Nicklas F., Sania, Lorenzo, Gianmarco, Marina, Mikhail, Ugo, Maria S., Camilla, for the wonderful time in the office, and in the online environment.

… my former colleagues from E&M team at UCN in Aalborg. All of you made me feel respected, competent and welcomed at my first workplace in Denmark. I extend my appreciation to John Midtgaard, who, as a team leader, has always shown a great trust in my abilities, valued my personal and professional skills and believed in my potential. All of this made it harder to leave E&M to pursue this PhD – one of the conflicting decisions I had to make.

On this note, my gratitude goes to Andrew Cass, who has always been supporting me as a colleague and friend at UCN and after my leave. Andrew, you have this amazing personality, which is reflected in everything you do – from the unique ideas you get, to their distinctive execution to bringing talented people in, among whom I had a pleasure to be. Thank you for believing in me, following me along the journey and showing proudness in my achievements.

… my wonderful family and friends. To my parents, grandparents, relatives and friends, and my Dmitri, thank you for being by my side and continuously supporting my endeavours. I love you with all my heart and I am proud and lucky to share this experience with you!

Research framing within the Nordic project, CIRCit

This PhD project was conducted within a larger Nordic research project CIRCit, which influenced the PhD research context, focus and the boundaries. “CIRCit: Circular Economy Integration in the Nordic Industry for Enhanced Sustainability and Competitiveness”, was a part of the Nordic Green Growth Research and Innovation Programme funded by NordForsk, Nordic Energy Research, and Nordic Innovation (CIRCit, 2020). The CIRCit research consortium consisted of a joint collaboration between the project lead Technical University of Denmark (DTU), Research Institutes of Sweden (RISE), Norwegian University of Science and Technology (NTNU), Innovation Center Iceland (ICI), and the Technology Industries of Finland (TiF). Bringing together academic and consultancy actors allowed securing a transdisciplinary research approach. Additionally, the project ensured engagement of partners from SMEs and large organizations from the Nordic region to assist research co-creation and evaluation, thus ensuring the practical validity of the outputs.

The main objective of the CIRCit project was to conceptualize, develop and implement a set of tools and approaches to enable the Nordic Industry to accelerate the transition towards a sustainable society by means of a circular economy. The project comprised six research focus areas, which aimed at contributing to the overall research objective. The focus areas represented the knowledge fields required to support the transition to a circular economy, such as business model innovation, product design and development, digital technology, end-of-life operations, value chain collaboration, and the topic of this thesis – sustainability screening. While all the other areas focused on developing support for the exploration of new ideas fit for circular economy, proposing concepts (e.g. product design for repair and maintenance) and analysing their feasibility (e.g. technological, financial, legal, etc.), the sustainability screening was designed to support assessment of the conceptualized solutions. The objective is to support the early development stages by enabling comparison of circular and non-circular initiatives based on their sustainability performance, allowing identifying improvement opportunities and adjusting the solution to improve its sustainability potential before developing it further. On these premises, the sustainability screening did not focus on supporting creation of the CE solution alternatives, but on assessing these in their early development stages, to guide decisions for their improvement and potential implementation.

Influenced by the focus areas, the sustainability screening took into account a business process perspective, considering business model development, product development, production and operations, after-sales service and end of life operations, as key processes to be assisted with performance indicators. Additionally, the collaboration of the researchers across the six focus areas in CIRCit helped to develop ‘CE strategies framework’, which was needed to support circular economy innovation process, when targeting the manufacturing industry. A series of workshops between CIRCit research actors were held to conceptualize and develop a framework, which was subsequently applied and evaluated with stakeholders from the Nordic industry. Consequently, the framework was improved and the results were published in a journal article (listed as Paper B). The CE strategies framework aimed at supporting a circular economy innovation processes through: 1) creating a comprehensive understanding of circular strategies; 2) mapping strategies currently applied; and 3) finding opportunities for improved circularity across a range of business processes (Blomsma *et al.*, 2019). As a result, the CIRCit CE framework accommodated a number of strategies spanning from dematerialized and multifunctional offers to sharing schemes to remanufacturing, recycling and recovery strategies. Therefore, it was chosen as one of the backbones for the development of the sustainability screening for circular economy initiatives to address several methodological challenges, as highlighted in the upcoming chapters.

Due to the geographical scope of CIRCit project being concentrated in the Nordic region, the PhD research was conducted and tested with Nordic manufacturing companies, which expressed their interest in applying sustainability screening to the CE initiatives already proposed, either as an outcome of work with other CIRCit focus areas or through own development activities. Consequently, CIRCit project has influenced this PhD research in terms of the conceptual approach to circular economy, focus on operational business processes, and empirical investigations limited to the Nordic region context.

List of appended papers

Paper 1 **Kravchenko, M.,** Pigosso, D. C. A., & McAloone, T. C. (2019). Towards the ex-ante sustainability screening of circular economy initiatives in manufacturing companies: Consolidation of leading sustainability-related performance indicators. *Journal of Cleaner Production*. Vol. 241, 118318 https://doi.org/10.1016/j.jclepro.2019.118318

Author contribution

This paper presented results of a systematic literature review aimed at consolidating leading performance indicators for triple bottom line dimensions of sustainability. Main author carried out a systematic literature review, analysed results and composed the manuscript for the initial review and final publication.

Paper 2 **Kravchenko, M.,** Pigosso, D. C. A., & McAloone, T. C. (2020). A Procedure to Support Systematic Selection of Leading Indicators for Sustainability Performance Measurement of Circular Economy Initiatives. *Sustainability*. *12*(3), 951 https://doi.org/10.3390/su12030951

Author contribution

This paper presented an indicator selection procedure and results of its application in case studies. Main author carried out the development of the procedure, conducted case studies and analysed results, and composed the initial and final manuscript.

Paper 3 **Kravchenko, M.,** Pigosso, D. C. A., & McAloone, T. C. (2020). DEVELOPING A TOOL TO SUPPORT DECISIONS IN SUSTAINABILITY-RELATED TRADE-OFF SITUATIONS: UNDERSTANDING NEEDS AND CRITERIA. *Proceedings of the Design Society: DESIGN Conference*, 1, 265-274. https://doi.org/10.1017/dsd.2020.137

Author contribution

This paper described the results of literature review aimed at investigating criteria to support development of a trade-off analysis. Main author conducted the review, analysed results and composed the final publication, which was ranked as one of the top best papers.

Paper 4 Kravchenko, M., Pigosso, D. C. A., & McAloone, T. C. (In Review). A trade-off navigation framework as a decision support for conflicting sustainability indicators within circular economy implementation in the manufacturing industry

Author contribution

This paper focused on the presentation, application and evaluation of the trade-off navigation framework. Main author conceptualized the framework, evaluated it with industrial and academic experts and prepared a full manuscript.

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Publication-based research outputs, not included in the thesis

Paper A **Kravchenko, M.**, McAloone, T. C., & Pigosso, D. C. A. (2019). Implications of developing a tool for sustainability screening of circular economy initiatives. *Procedia CIRP*, 26th CIRP Life Cycle Engineering Conference (LCE2019), *80*, pp. 625-630 https://doi.org/10.1016/j.procir.2019.01.044

Author contribution

This paper aimed at introducing the idea behind collection and classification of leading indicators as a foundation for sustainability screening of circular economy initiatives. Main author carried out the data collection and contributed to the proposal of the conceptual framework. Carried out the writing and integrated improvements after the peer-review process.

Paper B Blomsma, F., Pieroni, M., **Kravchenko, M.,** Pigosso, D., Hildenbrand, J., Kristinsdottir, A. R., Kristoffersen, E., Shahbazi, S., Nielsen, K. D., Jönbrink, A-K., Li, J., Wiik, C., McAloone, T. C. (2019). Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation. *Journal of Cleaner Production*, Vol. 241, 118271 https://doi.org/10.1016/j.jclepro.2019.118271

Author contribution

The paper is a joint contribution of all partners in CIRCit project. As a third author, the contribution related to the development of the conceptual framework described in the paper. Third author supported writing of the paper parts focused on sustainability and business process. Contributed to the review of the paper in draft and final forms.

Paper C **Kravchenko, M**., Hjort Jensen, T., Pigosso, D.C.A., McAloone, T.C. (2020). Circular Economy Sustainability Screening: CIRCit Workbook 1, ISBN: 978-87-7475-600-2, Technical University of Denmark, 44 p. https://orbit.dtu.dk/files/210454846/WB1_CIRCit_double.pdf

Author contribution

This workbook is one of the outcomes of CIRCit project. Main author carried out the writing utilizing own conceptual framework and results of empirical investigation with manufacturing companies. The workbook was used during dissemination activities in CIRCit webinars and workshops.

Paper D **Kravchenko M**., McAloone, T. C., & Pigosso, D. C. A. (2019). Stay in the loop: the role of indicators in supporting decisions for circular economy strategies aiming at extending products life. In *Proceedings of the 19th European Roundtable for Sustainable Consumption and Production: Circular Europe for Sustainability: Design, Production and Consumption* (Vol. I, pp. 406-422). Institute for Sustainability Science and Technology, Universitat Politècnica de Catalunya - BarcelonaTech (ISST-UPC). https://orbit.dtu.dk/en/publications/stay-in-the-loop-the-role-of-indicators-in-supporting-decisions-f

Author contribution

This paper focused on the exemplification of indicators suitable for the development of circular economy strategies aiming at extending products life. Main author carried out all the writing and elaboration of the case example.

Paper E **Kravchenko M.,** McAloone, T. C., & Pigosso, D. C. A. (2020). To what extent do circular economy indicators capture sustainability? *Procedia CIRP*, 27th CIRP Life Cycle Engineering Conference (LCE2020), 90, 31-36 https://doi.org/10.1016/j.procir.2020.02.118

Author contribution

This paper addressed the review of indicators for circular economy and the extent to which they address triple bottom line aspects. Main author performed a literature review and conceptualized the paper.

Paper F **Kravchenko, M**., Pigosso, D.C.A., McAloone, T.C. (2020). Circular economy enabled by additive manufacturing: potential opportunities and key sustainability aspects. Proceedings of the Design Society: NordDesign Conference, Technical University of Denmark, 14 p. https://doi.org/10.35199/NORDDESIGN2020.4

Author contribution

This paper explored key sustainability aspects important to take into account for developing circular economy enabled by additive manufacturing. Main author was responsible for data collection and conceptualization of the paper.

Paper G Laurent, A., Owsianiak, M., Dong, Y., **Kravchenko, M.**, Molin, C., Hauschild, M. Z. (2020). Assessing the sustainability implications of research projects against the 17 UN sustainable development goals. *Procedia CIRP*, 27th CIRP Life Cycle Engineering Conference (LCE2020), 90, 148-153 https://doi.org/10.1016/j.procir.2020.01.077

Author contribution

This paper presented results of the course about SDGs assessment of the student's research projects. Main author's project was selected as a case example. Main author analysed own project on its contribution using an exemplary case, the results of which were documented in this publication. Author assisted manuscript revision.

Thesis overview

Overall, the thesis consists of five chapters, as shown in Figure 1, aiming at presenting the research in details. This thesis is paper-based, with four key papers embedded as parts of Chapter 3: Results and reflections. Additionally, the research contributed to other publications, listed as supplementary.

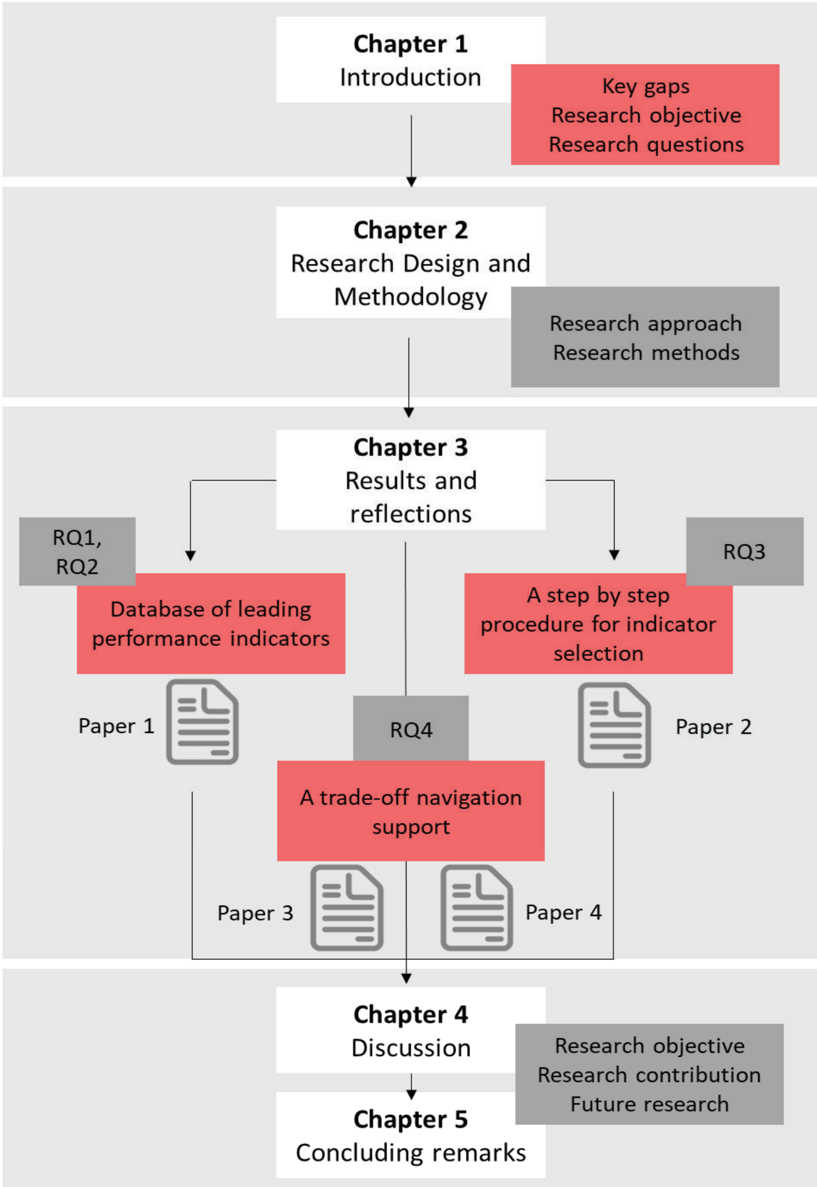

Figure 1. Paper-based PhD thesis outline

“The real act of discovery consists not in finding new lands, but in seeing with new eyes.”

~ Attributed to Marcel Proust ~

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List of abbreviations

BP	Business Process
BM	Business Model
CE	Circular Economy
DRM	Design Research Methodology
LCA	Life Cycle Assessment
PD	Product Development
PSS	Product Service System
SME	Small and Medium-sized Enterprise
TBL	Triple Bottom Line
TONF	Trade-off navigation framework

1. Introduction

This introductory chapter presents the overall context and theoretical background supporting the development of this PhD thesis, highlighting research gaps and presenting motivation for the research. The chapter then presents the research aim, objectives and research questions employed throughout the research, as well research delimitations and target audience.

1.1. Context and motivation

Resource scarcity, climate change and rapidly changing demographics have been since 2010 the top three megatrends reported to shape global society in the upcoming decades (Retief *et al.*, 2016), influencing all major areas of human activities from economics and education to agriculture and tourism. Understanding megatrends allows introducing adaptation and innovation plans and strategies to steer the development of these major areas. For a growing population, the strategies should focus on ensuring the provision of food and water, healthcare, housing and education, for resource scarcity – via ensured resource efficiency, preservation and recirculation (OECD, 2016). The approach to these actions requires a systems perspective, focusing on intermediate and long-term economic, social and environmental benefits delivered at local and global levels, thus contributing to 'sustainable development' (EEA, 2019).

The manufacturing industry plays a key role in the world's economy, contributing to one-third of the gross economic output in Europe alone by providing jobs and ready goods for society and other industries, including transportation and service (EEA, 2013). At the same time, the industry directly contributes to one-third of total greenhouse gas emissions locally in Europe and is responsible for emissions, resource and labour exploitation and waste generation associated with upstream and downstream activities, globally (Parrique *et al.*, 2019). Industrial actors can create value for sustainable development by addressing these and other sustainability issues in several way: firstly, by maintaining own sustainability, i.e. introducing and improving corporate strategies and practices, such as minimization of energy and material use, increasing work safety and satisfaction, reducing pay inequality; secondly, by contributing to the 'world's' sustainability, i.e. engineering and introducing new technologies for sustainability, such as renewable energy, medical aid devices, or by a combination of these (Massa and Tucci, 2013). Notably, which practices are considered for implementation by every single company is determined (constrained or aided) by particular organizational contexts, constructed by internal (organizational) capabilities and external (legal, political, natural, cultural) circumstances and resources, forming a natural-resource-based view of the firm (Hart, 1995).

1.1.1. Industrial approaches to sustainability challenges and the role of a Circular Economy

Following the natural-resource-based view, four types of corporate approaches to address environmental and sustainability challenges can be distinguished: (i) end of pipe treatment; (ii) pollution prevention; (iii) product stewardship; and (iv) sustainable development (Hart, 1995).

Since the early 1970's, the introduction of environmental regulation, facilitated largely by the EU environmental policy, has forced the manufacturing industry to control its pollution output, in order to retain a 'licence to operate' (Lukman *et al.*, 2016). This led to the adoption of (i) 'reactive', end of pipe, and later in mid-80's (ii) 'preventive', pollution prevention, strategies to reduce and treat emissions and waste at the source to comply with environmental regulations (Buysse and Verbeke, 2003). While pollution control and treatment (the 'end-of-pipe' approach (i)) requires additional equipment, hence necessitates costs, the pollution prevention (ii) approach could lead to cost savings and drive profits, due to efficient resource use, hence providing competitive advantage (Hart, 1995). The pollution prevention strategy goes beyond legislation and introduces cleaner production for better utilization of by-products and waste, minimization or elimination of toxic substances, and continuous improvements to drive eco-efficiency from the production process (Lukman *et al.*, 2016). Eco-efficiency contributes to relative resource decoupling, i.e. decline of emissions and waste per unit of economic output, however it does not lead to absolute decoupling, which results in an increased total resource consumption and emissions, due to the increased total production output (Parrique *et al.*, 2019). Despite the rise of preventive environmental management initiatives in the early 90' with more focus on both production and non-production activities, none of the strategies took into account upstream and downstream activities, thus risking exacerbating issues outside the firm (Kørnøv *et al.*, 2007). Consequently, the awareness of the problems outside the firm advanced the shift towards product-oriented environmental (late 90's) and social (early 00's) initiatives, referred to as (iii) product stewardship (ibid.). As a proactive strategy it broadened the scope to include 'life cycle thinking', which considers all the upstream and downstream activities associated with a product (Finkbeiner *et al.*, 2010), thus providing a holistic understanding of not only environmental, but also social impacts and economic contribution. Product stewardship does not only allow improving products and processes from an environmental and social point of view (Bhander, Hauschild and McAloone, 2003), it can also assist development of products with lower life cycle costs (Buysse and Verbeke, 2003). Due to the 'beyond compliance' logic, the strategy can drive competitive advantage through product differentiation and collaboration with stakeholders (Hart, 1995). Eco-design, cradle-to-cradle, design for sustainable behaviour, design for the base of the pyramid (Ceschin and Gaziulusoy, 2016) are a few of the approaches to a proactive product development that integrate environmental (eco-design focus) and sustainability-related considerations early in the process with the aim to improve the performance of products and related processes (Hallstedt, 2017; McAloone and Pigosso, 2018). A desire to increase customer satisfaction and potential to reduce environmental impact (Tukker, 2004) led to an increased number of product service solutions since the early 00's (Haase, Pigosso and McAloone, 2017). The key principle of a product service system is to build business on the value of utility of the product and services rather than on the value of the transfer of product ownership (Bey and McAloone, 2006). The ability to collaborate with stakeholders and identify relevant sustainability issues allows to introduce combinations of practices along the life cycle, seeking to promote user and employee health and safety, decent work conditions, eco-efficiency, waste minimization, remanufacturing, recycling at the end of life and more (Azapagic, 2003). Finally, the (iv) sustainable development strategy aims to minimize the burden of firm growth and increase sustainability of the systems (Hart, 1995; Loorbach et al., 2010), which requires a long-term commitment to develop and implement changes with actors and across levels (Bocken et al., 2014). This requires special capabilities to plan how the company does business, with whom and what sustainability benefits would be achieved on the systems level (ibid.).

The sustainable development approach includes strategies for sustainable value creation (Bocken, Rana and Short, 2015), sustainable supply chain management (Stindt, 2017), design of products, technologies and services for sustainable innovation and transition (Ceschin and Gaziulusoy, 2016). Importantly, high awareness of sustainability issues and collaborations across stakeholders facilitates innovation for sustainability, thus advancing the evolution from one strategy to another (Bocken *et al.*, 2014), although a company can pursue several strategies concurrently to minimize risks, manage tensions and build capabilities needed for the advancement (Loorbach *et al.*, 2010). This typology of the corporate approach to sustainability is often used to assess the level of sustainability maturity in companies, i.e. what principles and at what scale does the business integrate sustainability into business activities (Gouvinhas *et al.*, 2016).

The overview of the approaches provides an insight into how corporate actors respond to basic needs and bring a better quality of life by managing social, economic and environmental dimensions in a holistic way so not to jeopardize the needs of further generations, which complies with the core aim of sustainable development (Lukman *et al.*, 2016). Different from a non-corporate perspective, corporate sustainability is about managing business to comply not only with the TBL responsibilities, but also benefit from competitive advantage in short and long term (Bocken *et al.*, 2014), which requires industrial actors to continuously work towards finding new approaches to collaborate and co-create with suppliers, customers and other stakeholders (Elkington, 1998).

1.1.2. The emergence of Circular Economy as a means to sustainability

A Circular Economy (CE) in this sense could be seen as a new approach to foster such collaboration to create economic value while aiming at reducing environmental burden (Lieder and Rashid, 2016). CE is often referred to as a new economic model that envisions waste minimization and resource value preservation for a more resource effective and efficient production and consumption system (Murray, Skene and Haynes, 2017). Although there are various definitions of CE (Kirchherr, Reike and Hekkert, 2017), the way it combines knowledge from different fields such as industrial ecology, eco-efficiency, cradle-to-cradle design, the performance economy, natural capitalism and more (Korhonen, Honkasalo and Seppälä, 2018), offers a promising potential to engage business actors in transforming linear systems to circular ones (Berndtsson, Drake and Hellstrand, 2017).

CE solutions require redesign of business models, products and supportive networks (e.g. supply chains) to allow businesses to be a part of the CE system (Geissdoerfer *et al.*, 2018). Dematerializing products, offering shared, access or performance-based product service solutions (PSS), providing upgrade and repair service, facilitating remanufacturing and recycling are a few examples of CE strategies relevant for the manufacturing industry (Blomsma *et al.*, 2019). CE strategies are denoted as “principles” of CE (Nußholz, 2017), and can be viewed as “how to” for CE by proposing a range of activities with an objective of enhancing eco-effectiveness (Kalmykova, Sadagopan and Rosado, 2017), seeking to maximize the ecological and economic benefits for the system rather than relying on reducing resource use and pollution to sustain production output, as in the narrower eco-efficiency view (Niero *et al.*, 2017). As a CE model envisions a shift towards more resource effective production and consumption systems (Lieder and Rashid, 2016), manufacturing industries are required to go beyond firm-centric operational logic and create new ways to generate value (Pieroni, McAloone and Pigosso, 2019). The CE emphasises practices for extension of resource life through product, component and material reuse, remanufacturing, refurbishment, repair and recycling combined with principles of cleaner production, eco-efficiency and performance economy (Korhonen, Honkasalo and Seppälä, 2018), enabled by business model innovation, circular product design and digital technologies (Blomsma *et al.*, 2019). The opportunity to capitalize on retaining the value embedded in the products or operations for longer, as well as to optimize the economic and environmental costs and benefits, has made CE attractive for many businesses (Velenturf *et al.*, 2019).

Due to the large focus of a CE model on reducing environmental pressure and creating economic benefits, it is considered as one of the key strategies to enhance sustainability performance of businesses (including their products and operations) (Bakker *et al.*, 2014; Ghisellini, Cialani and Ulgiati, 2016). It has been shown that some CE strategies can help companies to minimize use of resources and optimize cost-effectiveness of their solutions (Velenturf *et al.*, 2019): Agrawal *et al.* (2012) report about economic benefit and lower environmental impact of a leasing model for printers compared to a sale model; Sundin and Lee (2012) report reduction of a total carbon footprint by one third as a result of a remanufacturing activity for inkjet cartridges. A decreased consumption of chemicals of 30%, reduced costs and improved working conditions in the food processing sector are reported by Schwager, Decker and Altenegger (2016) as a result of purchasing a Chemical Leasing service. Chemical Leasing business model relies on generating profits based on chemicals' functionality rather than on the volume of chemicals sold (ibid.). Unsurprisingly, a generation of new revenue streams, improved social relations between industrial actors and local societies, increase in efficiency and productivity of processes, improved public environmental awareness and image of a company are a few of the anticipated benefits of CE implementation (Rizos *et al.*, 2016; Kumar *et al.*, 2019).

Despite the reported benefits, not all CE strategies (and not in all circumstances) can bring the anticipated economic and environmental gains (Tukker and Tischner, 2006; Allwood, 2014), yet alone simultaneously contribute to the TBL dimensions of sustainability (Kirchherr, Reike and Hekkert, 2017; Murray, Skene and Haynes, 2017). Accordingly, Agrawal *et al.* (2012) conclude that leasing for carpets is economically beneficial, however environmentally worse (as opposed to the findings for printers); Lonca *et al.* (2018) report that use of re-treaded tyres increases fuel consumption of the vehicle due to a higher rolling resistance. A reuse strategy for electronic and electric goods might not always be beneficial from energy consumption point of view, due to the fact that older equipment might not be as energy-efficient as new one (Cooper and Gutowski, 2017); furthermore, reuse might not always lead to the replacement of a new product and does not offset the demand for production, as found by Makov and Font Vivanco, (2018) for the case of smartphone reuse. Replacing virgin material sources with recycled materials offers a great opportunity within CE to minimize the overall environmental impact (O'Connor *et al.*, 2016), however the issues of resource intensity of the recycling processes, the quality of a recycled material (Allwood, 2014) and the social responsibility of recycling practices (e.g. e-waste recycling practices in developing countries) (Giurco *et al.*, 2014) highlight the importance of a 'case-by-case' assessment (Schaubroeck, 2020).

Although the existing literature offers an antagonist view of whether the inherent objective of a CE is economic or environmental prosperity (see Ghisellini, Cialani and Ulgiati, 2016 and Kirchherr, Reike and

Hekkert, 2017 for opposite findings), the missing link to the social dimension is widely acknowledged (Murray, Skene and Haynes, 2017), thus questioning the CE benefits for the holistic triple bottom line perspective of sustainability (ibid.). Even with a narrower economic and environmental perspective, more publications argue that not all CE practices (and not in all circumstances) contribute to boosting economic prosperity and minimizing environmental impact (Agrawal *et al.*, 2012; Allwood, 2014; Kjaer *et al.*, 2018).

These examples emphasise the need to raise the question, whether CE inherently fosters sustainable development without delivering a positive contribution on the TBL dimensions (Kalmykova, Sadagopan and Rosado, 2017; Murray, Skene and Haynes, 2017). Notwithstanding, any strategy or initiative is unlikely to deliver a positive contribution to sustainability unless it considers a TBL perspective as a decision-making strategy and not only as an add-on element in reporting and communication (Waas *et al.*, 2014). Integrating sustainability into decision-making involves identifying sustainability issues, defining sustainability objectives and assessing sustainability potential of current or proposed initiatives (ibid.).

The importance of measuring CE benefits before, during and after implementation has been highlighted by various authors (Elia, Gnoni and Tornese, 2017; Potting *et al.*, 2017). Importantly, the benefits of any other sustainability-oriented initiative should also be supported by performance measurements and assessments for an informed decision-making process for sustainability (Waas *et al.*, 2014). While assessment methods such as life cycle assessment (LCA) (for measuring environmental impact) or performance metrics (used for corporate reporting) have become some of the dominant approaches to measuring environmental contribution of proposed initiatives (Lozano, 2019; Beemsterboer, Baumann and Wallbaum, 2020), there seems to be no unified approach to measuring CE environmental and economic benefits, nor the performance from the TBL perspective (Kristensen and Mosgaard, 2020). Moreover, a number of theoretical and practical questions about suitability of the 'conventional' methods (e.g. LCA) for CE measurements still remain (Elia, Gnoni and Tornese, 2017), requiring attention to their ability to address various CE practices (ibid.), applicability to support early development stages (Sassanelli *et al.*, 2019), and include social and economic evaluations (Kristensen and Mosgaard, 2020).

1.1.3. Metrics, indicators and assessment techniques in a Circular Economy context

In addition to overall CE frameworks and CE strategies, metrics, indicators and assessment techniques are a strong focus of a CE research (Elia, Gnoni and Tornese, 2017; Linder, Sarasini and van Loon, 2017). Metrics, indicators and assessment techniques are proposed to guide the planning of affirmative action, monitoring of the transition to CE and measuring its effects (Potting *et al.*, 2017). Focused on the manufacturing industry (micro level of a CE transition), a number of approaches have been proposed. The Material Circularity Indicator (MCI) proposed by the Ellen McArthur Foundation measures a product level circularity by accounting for the percentage mass of a product that is reused and recycled, complemented by the factors for recycling efficiency and product lifetime (EMF - Ellen MacArthur Foundation, 2015). MCI is seen as a decision support tool for product designers (ibid.). Linder, Sarasini and van Loon (2017) developed a cost-based approach for measuring product circularity by accounting for products' composition in terms of virgin and recirculated materials and the activities required to recirculate materials. The indicator can be used by procurement managers to inform their procurement choices, as well as to benchmark companies (ibid.). The Circular Economy Toolkit (CET) proposed by Evans and Bocken

(2017) aims to guide CE design and development by offering a qualitative assessment of business opportunities of certain CE practices (e.g. maintain/repair, remanufacture), thus combining business and product development choices. Azevedo, Godina and Matias (2017) developed the Sustainable Circular Index (SCI) to support corporate managers in assessing their company level of sustainability and circularity. SCI is based on the aggregation of operation-centric economic, social and environmental indicators pre-selected from the Global Reporting Initiative and ISO 14031 (ibid.).

Despite the growing field of research on metrics and assessment techniques for CE, the literature reports a lack of an overall assessment framework, able to support the early stages of CE development, whilst simultaneously considering the holistic sustainability perspective (Kalmykova, Sadagopan and Rosado, 2017). Furthermore, concerns are raised about whether the proposed measures and tools are adequately capturing all the important aspects within the narrower environmental or economic perspectives and how to combine them to enable an integrated assessment (Saidani *et al.*, 2017). The challenges of the proposed metrics and assessment techniques are manifold:

#1. Firstly, the diversity of approaches and the level of metric aggregation complicate comparison between products or companies (Pauliuk, 2018). The challenge might be related to the construct of a CE, which is still an emerging field with no standardized set of corresponding strategies or harmonized terminology (Kirchherr, Reike and Hekkert, 2017).

#2. Secondly, material flows are the dominating parameters of measurements in CE models, with non-material flows being underexposed (Blomsma and Brennan, 2017). This narrow scope of the measurement flows is often linked to the historical focus on recycling, which was seen as a way to close the resource loop in a CE system (Potting et al., 2017). However, more attention should be given to quantifying non-material flows of separate and of combined CE strategies (Blomsma and Brennan, 2017).

#3. Thirdly, design, development and implementation of CE initiatives often requires synchronizing decisions across business processes (Bocken et al., 2016), which means that decisions about identifying, implementing and leveraging key design and implementation criteria need to be made concurrently to operationalize CE strategies. This requires the support tools and measurements to reflect on the specifics of those decisions and provide decision support without increasing the complexity of the tools and the results of their application (Blomsma and Brennan, 2017).

Additionally, the applicability of existing sustainability assessment techniques and methods poses another challenge for the measurement and decision support of CE from a TBL perspective (Azevedo, Godina and Matias, 2017; Elia, Gnoni and Tornese, 2017). Several gaps can be highlighted, including:

#4. Existing impact assessment methodologies (e.g. LCA, MFA) do not allow measuring CE strategies focused on dematerialization and service provision (Elia, Gnoni and Tornese, 2017); furthermore, their focus on quantity and quality of non-material flows (e.g. land use, water, toxicity) is limited (ibid.).

#5. Life cycle assessment (LCA) is a widely adopted methodology to measure an environmental impact (Beemsterboer, Baumann and Wallbaum, 2020). While being widely adopted, it only focuses on the environmental dimension; furthermore, the results are presented as impact category indicators (e.g. climate change, acidification), which are not easily interpreted by industrial practitioners, thus hinder their inclusion into early stages of decision-making (Bengtsson, 2001; McAloone and Pigosso, 2018).

#6. Among all the performance indicators proposed for the manufacturing context, indicators for the social dimension of sustainability are often under-prioritized (von Geibler *et al.*, 2006); this results in sustainability assessments being condensed into the environmental dimension only (Gagnon, Leduc and Savard, 2012).

#7. Indicator-based and other performance measurement frameworks (e.g. OECD indicator framework (OECD, 2003)) provide simple lists of indicators with little or no guidance on how to select relevant indicators (Arena *et al.*, 2009; Issa *et al.*, 2015), thus failing to incorporate the user perspective (Matschewsky, Lindahl and Sakao, 2015) and support cross functional teams (Dekoninck *et al.*, 2016).

#8. Many measurement and assessment frameworks do not support the interpretation of results and provide no guidance about how to navigate complex decisions in sustainability trade-off situations, which are inherent in evaluations involving multiple sustainability criteria (Gibson *et al.*, 2005; Byggeth and Hochschorner, 2006; Buchert, Halstenberg and Stark, 2017; Salari and Bhuiyan, 2018).

Therefore, many of the abovementioned challenges and gaps need to be addressed in order to support sustainability-informed CE initiative development, the lack of which can lead to unintended consequences of CE implementation, later on (Matschewsky, 2019). With a view to addressing several of these challenges, a particular approach to early stage sustainability assessment, called 'a leading performance indicator approach', was chosen as the fundamental theoretical foundation. The potential of this approach in supporting early stages of assessment as well its contribution to a trade-off challenge is discussed next.

1.2. Theoretical underpinnings for the early stage sustainability assessment

Early stage, or ex-ante, sustainability performance assessment is a technique with the overall aim of integrating sustainability issues into early decision-making, by identifying and assessing sustainability performance of solutions and initiatives and providing better insights to enable more balanced and informed decision-making (Waas *et al.*, 2014). In light of the abovementioned challenges related to sustainability assessment and performance measurement, methods and techniques that produce complex results or are characterized as time-consuming and costly, hindering the integration of sustainability into early decision-making (Hallstedt, 2017; Brambila-Macias, Sakao and Lindahl, 2018). Yet, decisions made early in the development process (e.g. especially in the early stages of product development) determine the (sustainability) consequences of proposed solutions (Ulrich and Eppinger, 2012; Sihvonen and Partanen, 2017).

To ensure the sustainability assessment can be performed by practitioners and the results are employed for decision-making, it should rely on simple metrics (McAloone and Pigosso, 2018) and support a structured and contextually-based assessment (Keeble, Topiol and Berkeley, 2003). Therefore, *a leading indicator approach* for sustainability performance assessment can be considered as a powerful approach that allows measuring sustainability performance using information available in the early development stages (Epstein and Roy, 2001). Leading performance indicators are an *input type* of indicator, because they can be used early (i.e. lead) in the design and development stage and are often measuring information used by planners and designers routinely (Pojasek, 2009; McAloone and Pigosso, 2018).

Leading indicators serve as preventive signs due to their ability to provide information about causes of the performance in an understandable for the decision-maker manner ex-ante, thus allowing to introduce improvements to the (design) solution as early in the process as possible (Pojasek, 2009). In contrast, whenever lagging indicators are employed, the assessment provides information about impacts or past performance of actions, and often in a compounded manner, which may not offer useful information about the exact causes of such performance, thus may not be effective for decision-making early in the design process (McAloone and Pigosso, 2018).

Accordingly, this PhD research uses a leading performance indicator approach as a theoretical foundation for the measurement of potential economic, environmental and social performance to support decision-making in the early stages of CE development.

Essentially, any design and development activity is a decision-making activity involving prioritization of (design) solutions that satisfy key (design) decision criteria (Hansen and Andreasen, 2004). While indicators enable assessment and comparison of circular and non-circular initiatives based on their performance within economic, environmental and social dimension, this type of assessment leads to an increased complexity of the decision-making process (Hannouf and Assefa, 2018). This is associated with the number and diversity of indicators (or criteria) to be considered during decision-making (Gibson *et al.*, 2005; Ulrich and Eppinger, 2012). Aside from the 'traditional' criteria, the challenge is related to the uncertainty in selecting and balancing relevant indicators for measuring economic, environmental and social performance simultaneously (Dekoninck *et al.*, 2016) as well as assessing the social dimension, often characterized by its qualitative nature (Bhamra, Lilley and Tang, 2011). The holistic integration of indicators from the triple bottom line perspective often results in trade-offs, which are common in decision-making (Gibson *et al.*, 2005). Trade-offs are situations characterized by conflicts between the desired performance indicators (Byggeth and Hochschorner, 2006), where it is impossible to satisfy all performances simultaneously (Dutta *et al.*, 2016). Subsequently, decision-making for sustainability should not only take into account the performance evaluation, but also analysis of decisions between conflicting performance indicators (Byggeth and Hochschorner, 2006; Held *et al.*, 2018). A trade-off decision support is needed to help structuring the decision process by making trade-off explicit and by supporting and tracing justifications behind designers' choices (Buchert, Halstenberg and Stark, 2017; Held *et al.*, 2018). Therefore, sustainability trade-off theory is another theoretical pillar this PhD research relied on in the proposal of decision-making support in the early stages of CE development.

1.3. Research aim and objectives

In view of the abovementioned challenges and gaps, and supported by the theoretical underpinnings, this PhD research intended to investigate solutions to support decision-making for the early stages of CE initiative development from a holistic TBL perspective with the ***overall aim*** to:

- support the design and selection of the circular economy initiative that maximizes beneficial outcomes on all dimensions of sustainability

To contribute to the aim, the research objective was to conceptualize, develop and evaluate a framework for sustainability screening in the context of a circular economy development within the manufacturing industry. To achieve the objective, this research consisted of three studies, Study A, B and

C, each aiming at addressing major research gaps presented earlier. Following the theoretical lens of leading performance indicators, Study A focused on understanding what environmental, social and economic indicators exist and how they can be used to support CE measurement. Study B was geared towards understanding how to support a systematic selection of indicators for corresponding CE initiatives. Study C focused on investigating how to support decisions between conflicting sustainability indicators. Each study contributed with the results, which supported the proposal of the sustainability screening framework. Overall, the framework constitutes several fundamental elements such as an approach to measuring sustainability performance that relies on leading performance indicators and a procedure for a systematic indicator selection for corresponding circular economy initiatives. Additionally, it encompasses a trade-off navigation framework to support decision-making between conflicting sustainability indicators in a transparent and structured manner. The purpose of the framework is to advance the discussion on the need to support manufacturing companies in measuring the sustainability performance of alternative CE initiatives in their early development stages, thus allowing for the adjustment of a candidate initiative to improve its performance, before detailing and implementation (Figure 1).

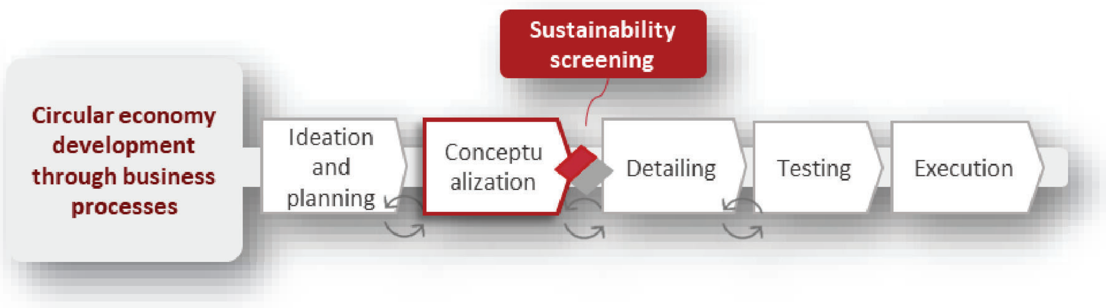

Figure 2. Sustainability screening as an early stage decision support

The research questions were formulated to reach the research objective and guide the Studies that contributed to the development and execution of the research.

1.4. Research questions

The research was driven by the main research question (MRQ) and supporting sub-questions (RQ) as presented:

<table>
<tr><th colspan="2">MRQ: How to provide decision-making support for manufacturing companies' in sustainability screening of circular economy initiatives in the early stages of development?</th></tr>
<tr><td rowspan="2">Study A</td><td>RQ.1: What leading performance indicators exist, to measure economic, environmental and social aspects of sustainability?

RQ.1 was formulated to help systematically investigate the existing leading performance indicators for manufacturing industry that are proposed for ex-ante measurement of economic, environmental and social performance. This, firstly, addresses challenge #5 by proposing measures useful for early stages of decision-making; secondly, it deals with challenge #6 of prevailing focus on environmental indicators by collecting indicators for environmental, economic and social dimension to enable an integrated TBL screening.</td></tr>
<tr><td>RQ.2: How to categorize indicators to enable meaningful selection of indicators for early development stages of CE initiatives?

RQ.2 was tailored to challenges #2 and #4 of too narrow coverage of CE strategies by considering a number of strategies spanning from dematerialized and multifunctional offers to sharing schemes to remanufacturing and recycling strategies. Additionally, it was necessary to address the specifics of the decisions across a number of business processes to support synchronized design and implementation of CE initiates (challenge #3). Subsequently, RQ.2 guided the indicator categorization process, needed to ensure its consistency and allow replication by other studies.</td></tr>
<tr><td>Study B</td><td>RQ.3: How to support a systematic selection of relevant sustainability performance indicators for early stage sustainability screening of CE initiatives?

RQ.3 was driven by gap #7 related to the indicator selection process. There was a need to develop a procedure to assist selection of relevant indicators, with the aim to apply it with manufacturing companies to identify the strengths and weaknesses and improve its usefulness and usability. This highlighted the importance of formulating the guidelines to ensure the procedure and the database can be systematically applied by practitioners to perform sustainability screening of their CE initiatives, allowing to introduce improvements and set benchmarks (challenge #1).</td></tr>
<tr><td>Study C</td><td>RQ.4: How to support decision-making when trade-offs arise between sustainability performance indicators?

Since sustainability screening aims at supporting selection of the circular economy initiative that maximizes beneficial outcomes on all dimensions of sustainability, it was necessary to ensure that the decision process is supported after relevant indicators are selected and applied. Therefore, RQ.4 was formulated with the aim to support decisions between conflicting sustainability indicators, so to encourage analysis of and reflection on the decision (challenge #8). Firstly, RQ.4 assisted investigation of the criteria to be considered for the development of a trade-off support, and secondly, guided its development and evaluation.</td></tr>
</table>

1.5. Research delimitations

This chapter presents the delimitations of this research in light of the aforementioned research objectives and overall research framing within CIRCit project. First, this research focuses on sustainability screening as an approach to support early stage CE initiative development – for that, a CE initiative needs to be detailed at a conceptual level. Therefore, the scope of the present research does not support a CE initiative development in terms of the analysis *whether and which areas* of the business to engage in CE, neither *which CE initiatives* are technologically feasible and financially viable to develop. Major focus is placed on offering an approach to understanding the potential sustainability performance of CE initiatives conceptualized during five operational business processes, in line with the focus areas of CIRCit project. Additionally, this research supports the development of the concepts through the TBL lens rather than the management of the processes, for which another approaches exist (Rodrigues, Pigosso and McAloone, 2016). This further condenses the focus of this research on the level of products and processes rather than on organizational or systems' level. Furthermore, the sole focus of this research is on the triple bottom line indicators and not on indicators and metrics that were specifically developed for a CE context.

In terms of the approach to CE, a framework of CE strategies developed by the CIRCit research team was used to frame CE and locate thirteen CE strategies to support classification of leading performance indicators. The strength of selecting a framework with a broad spectrum of CE strategies lies in addressing CE strategies beyond recycling. This research, although contributing to the methodological facet of CE, does not engage in the analysis of the 'circularity degree' or circular economy performance of proposed CE initiatives (examples of which are discussed by e.g. Saidani *et al.*, 2019). Following the geographical scope of CIRCit, the empirical investigations in this PhD research were limited to the Nordic region context, which is known for its high awareness of environmental issues and proactive approach to corporate sustainability (Short *et al.*, 2012; Salo, Suikkanen and Nissinen, 2019). Therefore, the validity of this research should be supported by testing it in the context outside of the Nordic region with different or lower level of sustainability maturity.

1.6. Target audience

This research and its findings are of value to a variety of actors. First, it is of interest to the research community exploring approaches to support CE initiative development using sustainability lens. With the point of departure in the manufacturing industry, this work may be relevant to scholars focusing on this industry or other economic sectors (e.g. construction, service), to investigate how a similar research approach might apply there. Similarly, this work might inspire studies investigating sustainability indicators for CE at meso (industry level) or macro (systems and regions) levels. Second, it is of interest to practitioners seeking support for developing CE initiatives using the sustainability lens. This work is, therefore, relevant for practitioners working with business modelling, product development, production planning, and service support as well as environmental and sustainability managers. Additionally, consultancy agencies may benefit by learning how to perform the sustainability screening for CE initiatives and consult industries regarding potential improvements based on the results of the screening.

2. Research Design and Methodology

This chapter expands on the research design and methodology followed to assist the development and evaluation of this research. Firstly, a philosophical view to research is introduced, which influenced the research framing and the choice of research approaches employed in this study. Secondly, a design research methodology is presented, which provided a suitable framework for structuring this research with its transdisciplinary orientation. Additionally, research methods and approaches for Study A, B and C are described in detail.

2.1. Philosophical framing

Philosophical view has a profound impact on research influencing the way the research is conducted, how and what kind of methods are chosen and how results are articulated (Creswell, 2014). In turn, understanding what science the research is trying to contribute to, makes the researcher aware of how a particular philosophical orientation influences research practices and interpretations within that science. To give a better insight into the philosophical view in this research, it is important to introduce sustainability not as a concept of sustainable development, but as a separate science. Despite the term 'sustainable development' has existed for more than three decades, sustainability science is still regarded as an emerging field (Brandt et al., 2013). One of the definitions of sustainability science is that it "embodies the scientific possibility of transcending the reductionist analyses of the traditional sciences by means of a holistic approach to problem-solving, based on a systemic design and mapping of contemporary long-range phenomena, in both the economic and social domains and in environmental, political, and ecological areas" (Sala, Ciuffo and Nijkamp, 2015; p. 315). Essentially, sustainability science requires linking multiple disciplines to identify and analyse sustainability problems and guide the development of solutions to overcome them (Brandt *et al.*, 2013), which in turn requires a transdisciplinary approach to sustainability research. Transdisciplinary research, therefore, is distinguished by two features. Firstly, it strives to contribute to developing a new knowledge beyond the concerned disciplines, and secondly, it needs to establish interaction flows between researchers and non-academic actors, linking the science to real world actions and reinforcing mutual learning (Sakao and Brambila-Macias, 2018). For sustainability solutions to work, sustainability research should not only produce coherent theoretical frameworks and integrated methods and tools, but 'generate impact' by engaging practitioners in knowledge co-creation and empowering them with 'practitioner-friendly' methods (ibid.).

On this line, the philosophical orientation posited by the author is pragmatism. According to Creswell, 2014, "pragmatism as a worldview arises out of actions, situations, and consequences rather than antecedent conditions" (p. 10). Following this orientation, researchers are concerned with problems and solutions, often employing a mix of approaches and methods to understand what solutions are needed, how solutions work or don't, and why (Creswell, 2014). Pragmatism sees "problem solving as a human activity" (Morgan, 2014; p. 1046), which always occurs within a specific application and decision context. In this way, the fundamental principles of pragmatism are well suited for transdisciplinary research helping to explore and understand the connections between knowledge and action in a given context (Kelly, 2020). This is particularly helpful to deal with the complexity attributed to conducting transdisciplinary research in sustainability, which is anchored in knowledge production and application in a practical context. For the application perspective, pragmatism helps the researcher to deal with dynamic organizational (real world) context in which decisions are taken, because "the actual decision-making process involving values among the decision makers as well as the level of needed knowledge involved in decision-making" (Thollander, Palm and Hedbrant, 2019, p. 1) are main reasons why organizations engage (or do not) in sustainability in the first place and why certain sustainability solutions become possible or less possible (Tregidga, Kearins and Milne, 2013). Therefore, for the sustainability screening framework and corresponding tools to be effective in supporting decisions, the research draws on the use of multiple research methods, which support an in-depth understanding of the research phenomenon from different perspectives (Cohen, Manion and Morrison, 2007). The research is qualitative in nature, relying on a set of research approaches and methods, strategically chosen for each research question as described in details in the following chapter. A qualitative approach was followed because it allows employing multiple strategies for data collection to explore how and why a phenomenon occurs (Yin, 2011).

2.2. Design Research Methodology as a methodological framework

While the philosophical orientation held by the researcher provides an insight into the approach to knowledge acquisition and production, and scientific reflection, a research design framework provides a concrete procedure to support operationalization of the research questions (Creswell, 2014). This includes selection and deployment of the procedures to articulate how the findings were realized and how they connect to the overall research purpose (Cohen, Manion and Morrison, 2007). By connecting means to ends, the research reliability and validity can be tested by the research community (ibid.). The research design for this PhD project was based on the Design Research Methodology (DRM), developed by Blessing and Chakrabarti (2009). DRM is specifically designed for the conduction of research in design science, offering methods, tools and procedures to support a more rigorous design research (Blessing and Chakrabarti, 2009). Design science is dedicated to the study of man-made artefacts and of the process of designing these artefacts aiming at improving existing systems or solving societal or organizational problems (Dresch, Lacerda and Valle Antunes Jr., 2015). Research conducted under the design science, therefore, seeks not only to produce knowledge about the artefacts, but also to develop or improve the process of design by proposing design support (ibid.). The [design] support can include workbooks, guidelines, software, models, techniques, procedures and similar … essentially any output that prescribes means to conducting a design activity to attain the desired design objectives (Blessing and Chakrabarti, 2009).

An interactive database with leading performance indicators, an indicator selection procedure, a user guide and a trade-off navigation framework were developed as a support for early stage sustainability screening of circular economy initiative development. The research process was characterized by three attributes inherent in design science research (Denyer, Tranfield and Van Aken, 2008):

- research questions being driven by a need to solve problems from a practical world;
- large focus on generating prescriptive knowledge aimed at solving or improving the practical problem, yet strongly connected with the descriptive knowledge about the foundations of support design and development;

- evaluation of research results through field testing, allowing to revise and refine the results to strengthen the practical validity of the research and improve the theory.

For that reason, design research as a method was followed to assist creation and evaluation of support, providing an understanding of its validity and utility from both a practical and a theoretical perspective (Dresch, Lacerda and Valle Antunes Jr., 2015). Due to the pragmatist approach to the research, namely that not only the science orientation, but also the researcher's beliefs, previous research experiences and actual interventions influence the research assumptions and interpretation (Creswell, 2014), the DRM has ensured the criteria for study evaluation were defined and followed to comply with internal and external research validity (Morgan, 2014).

The generic DRM framework proposes four main stages (Figure 2) (Blessing and Chakrabarti, 2009), which were followed during this PhD research:

- **Research clarification (RC)** stage, which assists the overall *research design* as it supports identification of research gaps and needs to scope the study and to formulate the research aim, objectives and research questions, as well as plan methods for data collection and interpretation.
- **Descriptive Study I (DS-I)**, which assists an in-depth *understanding of the research phenomenon* and provides a logic of identifying key characteristics to be addressed for the process of support development.
- **Prescriptive Study (PS),** which assists the *development of the support*, intended to address all the identified characteristics and fill in the research gaps. Prescriptive knowledge from the researcher is considered as one of the foundations in design science research as it ensures the proposed support generates the desired outcomes (Dresch, Lacerda and Valle Antunes Jr., 2015).
- **Descriptive Study II (DS-II),** which assists implementation and *evaluation of the support*, allowing to test its practical utility and advance theoretical contribution.

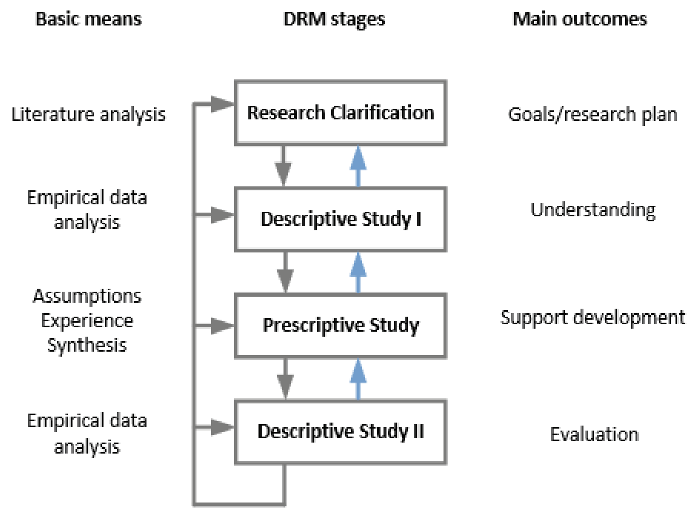

Figure 3. The DRM framework, adopted from Blessing and Chakrabarti (2009)

Despite of what may seem as a sequential process, the DRM stages are not linear, which allows building knowledge in an iterative way and returning to any stage to understand or fill in newly discovered gaps and propose improvements (Blessing and Chakrabarti, 2009).

Following the transdisciplinary nature and pragmatic orientation in this research, a combination of methods was employed to help answering the research questions within Study A, B and C correspondingly, as depicted in Figure 3. The DRM stages guided the research process taking into account the nature of the research questions (*why, what and how*), helping to attain specific research results.

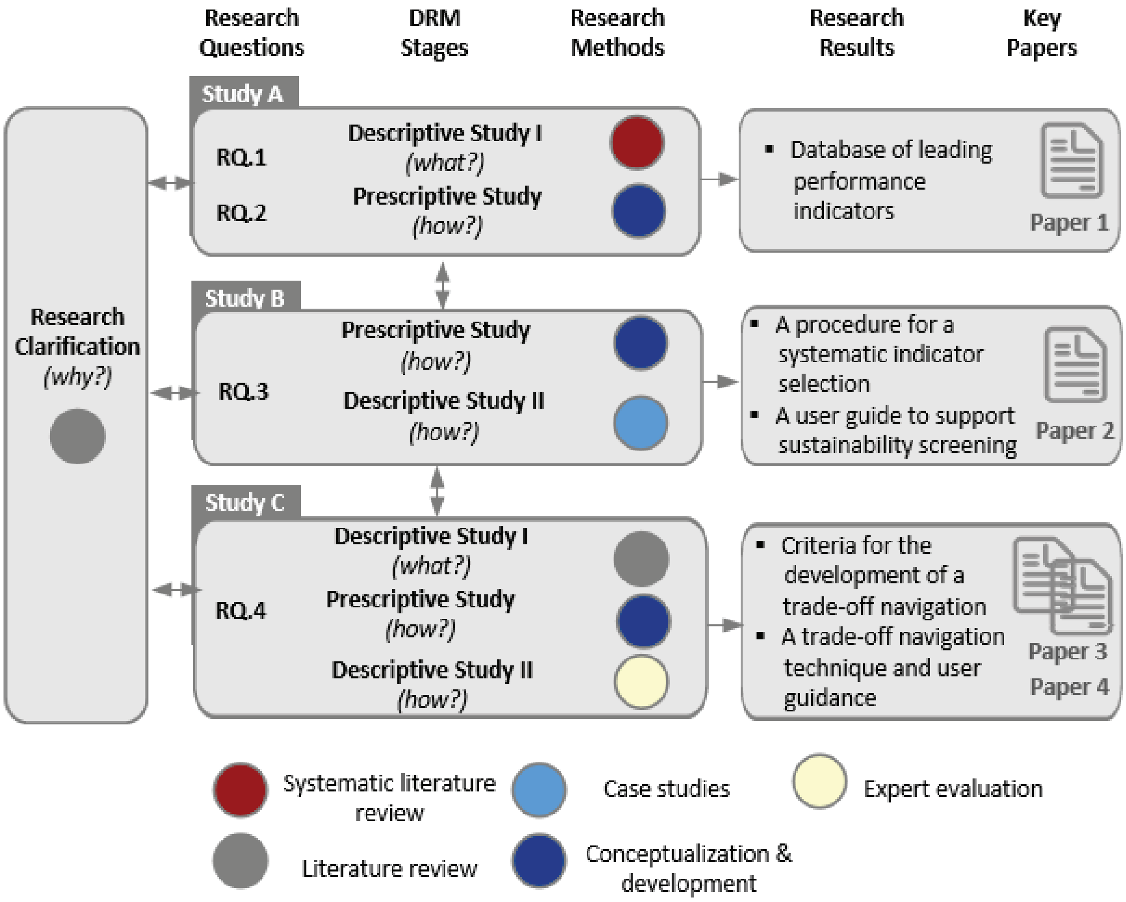

Figure 4. Research design according to DRM: research questions and methods employed and results and publications achieved for Study A, B and C correspondingly

2.2.1. Research Clarification

A *literature review* was employed at various points throughout the research as one of the methods allowing to frame research problem and synthetize relevant concepts (Nightingale, 2009). Grounded in RC aims, the research commenced by following an exploratory approach, seeking to answer the questions of *why*, e.g. 'why this needs to be investigated' and 'why this research is relevant'. Literature review, or a selective review (Yin, 2011), as opposed to a systematic literature review method, allowed to cast a broader perspective on the areas of interests to demonstrate a need for the research (hence questions *why*), clarify research assumptions (pragmatic view), as well as establish a relationship to previous studies (Rocco and Plakhotnik, 2009).

Therefore, literature review #1 for RC stage, driven by the objective of gap exploration and research scoping, targeted the key works in the areas of:

- **Performance measurements for sustainability in the context of manufacturing industry**

(Joung *et al.*, 2013)	Categorization of indicators for sustainable manufacturing
(Waas *et al.*, 2014)	Sustainability assessment and indicators: Tools in a decision-making strategy for sustainable development
(Pojasek, 2009)	Using Leading Indicators to Drive Sustainability Performance
(Badurdeen *et al.*, 2015)	Sustainable Value Creation in Manufacturing at Product and Process Levels: Metrics-Based Evaluation

- **Frameworks and tools supporting design and development of CE initiatives**

(Elia, Gnoni and Tornese, 2017)	Measuring circular economy strategies through index methods: A critical analysis
(Potting *et al.*, 2017)	Circular Economy: Measuring innovation in the product chain
(Bocken *et al.*, 2016)	Product design and business model strategies for a circular economy

- **Integration of sustainability criteria in the early development stages**

(Gagnon, Leduc and Savard, 2012)	From a conventional to a sustainable engineering design process: Different shades of sustainability
(Stindt, 2017)	Implementation Potential of Sustainability-oriented Decision Support in Product Development
(Byggeth and Hochschorner, 2006)	Handling trade-offs in Ecodesign tools for sustainable product development and procurement
(Azapagic and Perdan, 2005)	An integrated sustainability decision-support framework Part I: Problem structuring

The review process focused on a set of papers identified through a snowball sampling from the key publications in the above-mentioned areas (Denyer, Tranfield and Van Aken, 2008). Driven by the *why* questions, the review allowed to concentrate on exploring the following: why supporting the development of CE initiatives, why concentrating on leading indicators approach for performance measurement of TBL dimensions, what the specifics of integrating sustainability criteria into decision making are and why there is a need to address a trade-off challenge.

The exploration allowed obtaining a clear understanding of the research problematics and gaps (as presented in Chapter 1), framing the research questions and planning research outcomes (Figure 3) in a way to ensure the research is academically and practically valuable and feasible to solve within the research timeframe and context (Blessing and Chakrabarti, 2009). The findings of the exploratory review allowed scoping the research phenomenon to be investigated, formulate research assumptions and hypotheses, as summarized in Table 1. Formulating a hypothesis allows testing validity of the proposed design support for the scoped phenomenon, and avoid generalizations outside (Denyer, Tranfield and Van Aken, 2008).

Table 1. Research phenomena, hypotheses and assumption

Research phenomena	Hypotheses
a) 'use of leading performance indicators for sustainability screening in early stages of circular economy development'	• the classification of sustainability-related leading performance indicators according to CE strategies, business processes and TBL aspects and the corresponding procedure *can support* manufacturing companies in the selection of *relevant sustainability indicators* for the screening of their proposed CE initiative
b) 'use of trade-off navigation as a decision support between conflicting sustainability indicators'	• the trade-off navigation can support manufacturing companies in making trade-offs transparent and supporting argumentations for trade-off justification and acceptability
Research assumption	
If companies can use sustainability screening in the early stages of CE initiative development, they will be able to measure and select a more sustainably beneficial initiative	

Additionally, the review allowed identifying areas of interests and contribution (research phenomenon), which unfold the transdisciplinary nature of the research, covering aspects of multiple disciplines such as engineering, decision-making, social sciences and business and management, thus helping to position the potential contributions of the research outcomes (Figure 4).

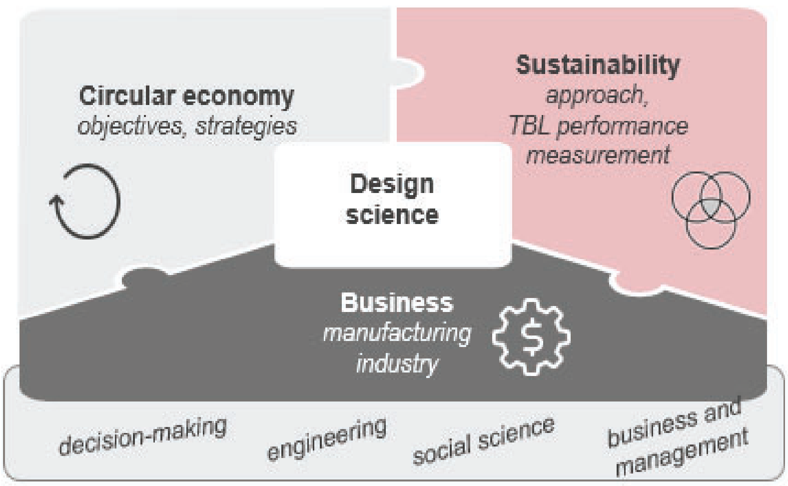

Figure 5. Transdisciplinary lens of the PhD research

Additionally, the key works allowed focusing on some of the core concepts that guided the development of the sustainability screening in the prescriptive stages. For instance, the key works for performance measurement in the context of sustainability for manufacturing industry were used to establish the aspects under each dimension of the TBL for indicator classification (RQ.2 in Study A). Additionally, they helped to distillate key recommendations to support the development of the indicator selection procedure with focus on contextual selection and the recommended number of indicators (RQ.3 in Study B). The works focused on the integration of sustainability criteria in the early stages of decision-making in business processes provided an understanding of key decisions taken during business processes, which guided the indicator classification process (RQ.2 in Study A). Also, these works allowed to identify the gap related to a trade-off decision support: despite a large number of frameworks and tools to support sustainability considerations in early stages of business processes, few provide support in result interpretation and none supports navigation of decisions in trade-off situations (Byggeth and Hochschorner, 2006; Haffar and Searcy, 2017; Stindt, 2017). These findings has led to a new literature review, *literature review #2*, aimed at investigating the criteria to be considered for the development of a trade-off support (RQ.4, descriptive stage in Study C). Initially, only one publication by Byggeth and Hochschorner (2006) (in the research area of sustainability integration into early development stages) addressed the incompleteness of the product design support tools to address trade-offs. This led to the investigation of publications addressing trade-off issues related to the integration of sustainability criteria into product design process (e.g. eco-design literature), and as well in procurement, logistics and production (e.g. sustainable supply chain management literature). Following recommendations from the selected works, several criteria were consolidated with the aim to guide the prescriptive stages in the development of a trade-off support and advancing knowledge in the area (RQ.4 in Study C).

2.3. Research methods for Study A: towards the development of a database of leading performance indicators

2.3.1. Descriptive Study I-A (RQ.1)

To advance the research and support a more detailed investigation of the research phenomenon - 'use of leading performance indicators for sustainability screening in a circular economy context', *a systematic literature review (SLR)* was conducted, driven by RQ.1: "What leading performance indicators exist, to measure economic, environmental and social aspects of sustainability?"

The main goal of the SLR was to identify and consolidate information on leading performance indicators proposed to measure aspects from a triple bottom line perspective relevant for a micro-level application, i.e. related to the manufacturing industry (products, services, and operations). Grounded in the aims of the Descriptive Stage I (DS-I) of DRM, the investigation aimed at describing the prevalence of leading performance indicators for each dimension of the TBL and provide a basis for developing a support for sustainability screening based on the indicators (Blessing and Chakrabarti, 2009). SLR, as opposed to a literature review, follows a specific procedure that is rigorously planned, conducted and documented to minimize the researcher bias (Biolchini *et al.*, 2005). The SLR in this study followed the procedure proposed by Biolchini et al. (2005) consisting of three steps: (1) review planning; (2) review execution; and (3) results analysis. In review planning (1), a review protocol was prepared to document the objectives of the investigation, inclusion and exclusion criteria and sources of publications. During the review (2), the review criteria were followed to retrieve relevant studies, followed by their analysis and consolidation of relevant information (3). The SLR procedure with key considerations is presented in Table 2.

Table 2. Excerpt of the protocol for a systematic literature review for Study A

Review planning	Review execution	Review Analysis
Objective	*Selection process*	*Information extraction*
to identify leading performance indicators proposed to measure aspects from a triple bottom line perspective	i) run search strings at the selected sources ii) gradual screening of publications according to the inclusion criteria: 1. Reading title, abstract, key-words 2. Reading introduction and conclusion 3. Reading full paper	Indicator attributes: i. Name of the indicator; ii. A detailed description; iii. Formula; iv. Unit; v. Desired trend and vi. Recurrence
Sources selection logic		
Search string with key words: •Performance indicator: metric, index, indices, measure • Sustainability: sustainable, triple bottom line, environment and economy and society • Business processes: BM, product development, end of life, value chain		
Inclusion criteria		
1) proposition, application or review of a leading indicator for sustainability assessment; 2) focus on manufacturing companies or micro-level (product, process, service)		
Sources of publications		
Scopus, ISI Web of Knowledge in English		

665 articles were originally identified after the search by the key words applied in Scopus and Web of Science. By applying the inclusion criteria, all the papers had their title, abstract and key words analysed, resulting in the selection of 159 papers, which had their introduction and conclusion read, resulting in 60 papers chosen. After having fully read the papers, 17 works were used to retrieve the indicators and used to locate additional 70 works through a snowballing, or cross-referencing, technique. In total, 52 papers were selected, coming from a total of 25 different journals, 3 handbooks and 8 scientific conference proceedings in the period 1994 – 2018 with larger dominance of publications from 2012 – 2018. The papers addressed various topics, including cleaner production and sustainable production and engineering, sustainable supply chain, eco-design, sustainable transformation and business innovation, among others. A detailed summary of the literature review contributed to the results described in Chapter 3.1. and documented in Paper 1. The results of the SLR served as a theoretical foundation for developing a prescriptive method for the selection of key performance indicators and a user guide for sustainability screening of CE initiatives.

2.3.2. Prescriptive Study A (RQ.2)

Development of a design support was carried out through a prescriptive study in line with DRM (Figure 4). A prescriptive study entails the development of a prescriptive support to employ during design processes based on the insights obtained from the background theory and knowledge gaps (RC and DS-I stages) and supported by empirical investigations (DS-II). Creation of a support in this research was characterized by theory building through conceptual modelling, which was distinguished by a consolidation and organization of the key concepts to create a new perspective for the studied phenomenon (Denyer, Tranfield and Van Aken, 2008). Following the design science research attributes, the objective of the prescriptive approach is to propose a conceptual model that offers a general template for the creation of solutions for a particular class of field problems, the effectiveness of which should be tested in real world settings (ibid.).

To achieve that, the task was to model the key concepts found in the literature reviews using the CE as a lens. Guided by RQ.2: How to categorize indicators to enable meaningful selection of indicators for early development stages of CE initiatives?, a series of workshops between CIRCit researchers helped to prioritize key criteria for indicator classification, such as a number of CE strategies, business process and a number of aspects under TBL dimensions. The workshops helped clarifying the relationships between the concepts and establish a logic for indicator classification, which then could enable a meaningful selection of indicators. More specifically, indicator classification was done independently for each classification criteria using the conceptual framing depicted in Figure 5.

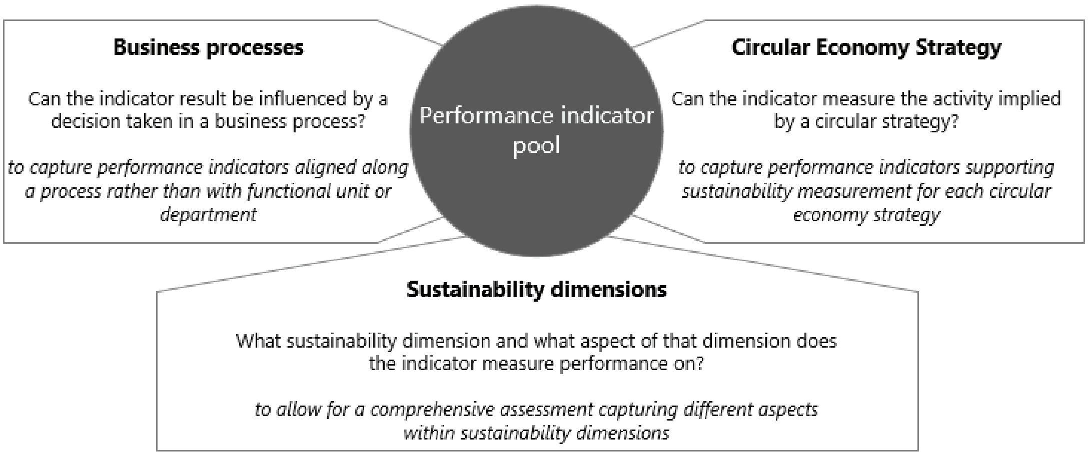

Figure 6. Key questions that guided indicators classification

For the TBL aspects, indicators were classified by matching the activity or state measured by an indicator with a corresponding (or several) aspect under a TBL dimension, following the literature. Economic, social and environmental dimensions were selected as three dimensions to represent the TBL perspective, often used to measure the progress of actions towards sustainability (Elkington, 1998). Accordingly, each dimension was represented by a number of TBL or sustainability aspects, defined as elements of an organization's activities, products, or services that has or may have an impact on the environment, stakeholders within and outside value chain and economic performance (ISO, 2014; Fontes, 2016). Environmental dimension concerns the identification and management of organization's aspects to ensure long-term positive impact on living and non-living natural systems (ISO, 2014). Aspects that belong under environmental dimension capture resource consumption (material, energy, water, land), emissions to water, soil, air, and chemicals and are listed in Table 3. Economic dimension represents positive value creation and distribution by a company supported by long-term relationships with customers, partners and suppliers (OECD, 2003; Global reporting Guidelines, 2011). It concerns the way assets and resources are managed to optimize cost-efficiency, ensure revenue streams and customer satisfaction related to the quality of the product or service offered. Social dimension is defined as the dimension that addresses identification, accounting and management of values and needs of different stakeholders a company interacts with (Fontes, 2016). The stakeholders can be identified as internal and external groups of people that interact with and directly or indirectly affected by the company and its activities. Consequently, twelve aspects were established under environmental dimension, five under economic and eight under social (Table 3).

Table 3. TBL aspects for indicators classification. Alphabetic order. Extracted from Azapagic, 2003; Global reporting Guidelines, 2011; Fontes, 2016.

Environmental aspects of sustainability	Economic aspects of sustainability	Social aspects of sustainability
· Air pollution · Energy consumption · Gaseous emissions · Land use · Liquid waste generation · Material consumption · Material safety · Product architecture · Soil pollution · Solid waste generation · Water consumption · Water pollution	· Operational costs · Product quality · Revenue · Tactical costs · User costs	· Community relationships · Employee empowerment · Employee health and safety · Employee training & education · Employment conditions · Equality · Supplier relationships · User relationships

For business processes, the classification was based on the extent to which an indicator can be influenced by a decision taken during a particular business process. A list of decisions taken during each business process was compiled based on the literature (consolidated in Appendix I). In summary, the decisions normally concern 'traditional' criteria (requirements) that are necessary to establish and prioritize to support (design) activities to proceed with the (design) alternative that satisfies the established criteria. Traditional criteria could be legal aspects, customer requirements, functionality of a product, technical efficiency, costs, etc. (Bovea and Pérez-Belis, 2012). It has been posited that integration of sustainability criteria along the 'traditional' criteria early in the process facilitates understanding of potential sustainability implications of the proposed alternatives, allows reviewing any alternative by introducing improvements before proceeding to the later stage (Gagnon, Leduc and Savard, 2012; Morioka, Evans and Carvalho, 2016; McAloone and Pigosso, 2018). Therefore, classification of leading performance indicators measuring sustainability aspects according to business processes would enable identification of key indicators to consider TBL criteria along the traditional criteria.

For CE strategies, the classification was based on the correlation between the activity implied by a CE strategy (supported by its description) and the focus of indicator measurement. A description of each CE strategy was derived in several workshops between CIRCit project researchers, resulting a CE Strategies Framework published in Paper B and as shown in Figure 6 (Blomsma et al., 2019). As a result, inclusion of thirteen CE strategies ranging from dematerialization strategies and product service offerings to strategies of recycling and recovery ensured going beyond materials perspective to address business, product, and operations. This wide perspective reflected the challenge reported earlier in the literature overview about too 'narrow' focus of measurement techniques on recycling (Blomsma and Brennan, 2017; Elia, Gnoni and Tornese, 2017).

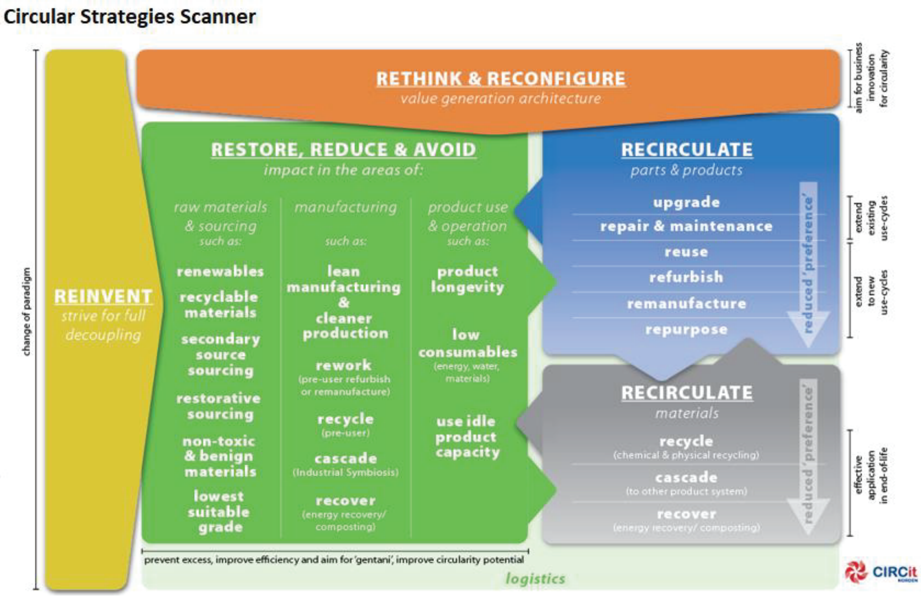

Figure 7. CE strategies used for indicators classification according to the Circular Strategies Scanner framework developed in CIRCit (nb: cascade strategy was merged with recycling for classification) (Blomsma et al., 2019)

The classification was done in the indicator database complied in an Excel-based worksheet, allowing to connect the indicators and classification criteria. The results of this process are described in details in Chapter 3.1 and published in Paper 1.

2.4. Research methods for Study B: towards the development of a step-by-step procedure for indicator selection and user guidance for sustainability screening

2.4.1. Prescriptive Study B (RQ.3)

Grounded in the iterative nature of DRM, a first version of the procedure was prescribed. The need for an indicator selection procedure was identified from the literature review in RC stage, which highlighted the importance of supporting a user in a systematic selection of relevant indicators based on the contextual settings (Arena *et al.*, 2009; Dekoninck *et al.*, 2016). The procedure development was aligned with RQ.3: How to support a systematic selection of relevant sustainability performance indicators for early stage sustainability screening of CE initiatives?, which steered the development of both, the indicator selection procedure and a user guide which incorporated the proposed procedural steps and relied on the indicator database. Therefore, RQ.3 aimed at proposing support to assist a structured process of sustainability screening of CE initiatives in manufacturing industries. The activities during the development process were divided as follows: i) establishing the criteria for development; ii) developing the first version; iii) developing a plan for evaluation; iv) introducing improvements after evaluation rounds. Grounded in PS aims, the criteria to guide the development of the support were established as presented in Table 4. They were consolidated from the literature review in the RC stage (criteria #9-#14 and #15-#18), recommendations from the DRM framework (criteria #3-#6) and the content of the indicator database developed in Study A (criteria #1-#2 and #7-#8).

Table 4. Conceptual criteria for the support development. (nb: 'Own' as a source concerns own suggestion to cover the gaps identified in RC and according to the results of Study A).

Criteria #	Elaboration on criteria	Attribute	Source
#1	The support should be useful in early design stages	Use context	Own
#2	The support should be useful for a secondary manufacturing company	Use context	Own
#3	The support should indicate potential application of it	Use context	(Blessing and Chakrabarti, 2009)
#4	The support should indicate who the user is	Use context	(Blessing and Chakrabarti, 2009)
#5	The support should indicate the required inputs to operate with the support	Use context	(Blessing and Chakrabarti, 2009)
#6	The support should indicate the expected outputs	Use context	(Blessing and Chakrabarti, 2009)
#7	The support should enable and guide how to identify relevant business processes and CE strategies based on the description of a CE initiative	Content	Own
#8	The support should assist understanding of an indicator and the results of its measurement	Content	Own
#9	The support should encourage the iterative process for indicator selection to ensure only high priority (relevant) indicators are selected	Content	(Keeble, Topiol and Berkeley, 2003)
#10	The support should guide customization or creation of indicators to match the contextual settings	Content	(Issa *et al.*, 2015)
#11	The support should encourage selection of indicators that cover a holistic triple bottom line perspective	Content	(Gibson *et al.*, 2005)(Gibson, 2010)
#12	The support should indicate how many indicators to select for the screening process	Content	(Rahdari and Anvary Rostamy, 2015)
#13	The support should provide guidance, formulas and units to help quantify indicators after selection	Content	(Rahdari and Anvary Rostamy, 2015)
#14	The support should indicate activities after indicator calculation (e.g. result interpretation and decision making)	Content	(Rahdari and Anvary Rostamy, 2015)
#15	The support should be easy to learn	Application	(Brambila-Macias, Sakao and Lindahl, 2018)
#16	The support should be easy to use (logical simplicity)	Application	(Brambila-Macias, Sakao and Lindahl, 2018)
#17	The support should not require a special software (technical simplicity)	Application	(Brambila-Macias, Sakao and Lindahl, 2018)
#18	The support should ensure a structured and transparent decision process	Application	(Gibson, 2010)

Following the 'content' criteria #7-#14, a first prototype of the support was proposed. For the selection procedure, 'own' criteria were fulfilled by 'mirroring' the indicator classification logic, i.e. a set of questions about what decisions are needed and what activities are envisaged were formulated in order to help locating key business processes and CE strategies involved in a CE initiative under consideration. Additional steps were proposed to guide the contextual selection of indicators (e.g. help prioritizing relevant indicators after they are located in the database), their customization and creation, the recommended number of indicators for the screening, as well as their calculation and result interpretation. These steps were driven by the criteria (#9-#14) consolidated from literature review #1 (as referenced in Table 4). Consequently, few steps with specific guidance were accommodated in the procedure as a first prototype, which was reviewed by the CIRCit researchers, improved and incorporated in the user guide by describing each step of the procedure, accompanied by practical examples intended to visualize the activities under each step. Additionally, the guide incorporated description of the target audience, expected time to complete each step, inputs and expected outputs for each step, as directed by DRM and reflected in criteria #1-#6. The proposed procedure, the user guide and the corresponding indicator database were evaluated in descriptive study II (DS-II B), which led to their refinement to their final versions, as described in Chapter 3.2.

2.4.2. Descriptive Study II-B (RQ.3)

The process of developing and evaluating the proposed support for the selection of key performance indicators followed a hypothetical-deductive approach (Shareef, 2007), which is used to construct an inquiry based on existing theories and knowledge (results of the SLR, deductive approach), proceeding by formulating a hypothesis that is then tested to explore the consequences of the generated inquiry (Yin, 2011). Therefore, a case study approach was selected to test the following *hypothesis*: “the classification of sustainability-related leading performance indicators according to CE strategies, business processes and TBL aspects and the corresponding procedure *can support* manufacturing companies in the selection of *relevant sustainability indicators* for the screening of their proposed CE initiative”.

Case study as a research is considered especially useful for providing in-depth descriptions of the studied phenomena, because they are conducted in real-time world settings influenced by geographical, organizational and other contexts (Yin, 2006). While case studies can be used to provide description and generate theory (Eisenhardt, 1989), “case studies have a distinctive place in evaluation research” (Yin, 2006; p. 15). Case studies offer a unique opportunity of close collaboration between the researcher and the participant, which enables gathering experiences and learnings to improve the studied phenomenon or an aspect of it (Teegavarapu, Summers and Mocko, 2008).

The hypothesis guided selection of cases with different sectorial requirements, adhering to the format of a multiple case study research. A multiple case study approach helps understanding the differences and similarities between the cases (i.e. different contexts), which enables providing compelling arguments whether the hypothesis was supported or challenged (Yin, 2011). To demonstrate credibility and confirmability of the research, case studies should be designed to specify the objectives, approaches to data collection and to data analysis (Yin, 2006). Therefore, a case study protocol was developed following the strategy outlined by (Yin, 2006) and using the checklist from (Runeson and Höst, 2009) to address key case study design elements.

Guided by the initial hypothesis, the case study objective was to:

- evaluate the usefulness and usability of the proposed support by measuring:

- to what extent does the selection procedure and the indicator database enable selection of relevant indicators for sustainability screening of CE initiatives
- how time-efficient and easy is to understand and apply the procedure and the database

Subsequently, the evaluation focused on success evaluation – evaluation of usefulness of the proposed procedure and the database, and application evaluation – evaluation of its usability. Therefore, the initial type of evaluation (DS-II stage) was followed, which, as opposed to the comprehensive evaluation, does not aim at evaluating the impacts of the support, which would also include evaluation of support use (i.e. whether the support is actually used) (Blessing and Chakrabarti, 2009). Led by the hypothesis, the measurement criteria were defined in the evaluation form following the recommendations for research evaluation provided by DRM for DS-II (Blessing and Chakrabarti, 2009). These criteria ensured adherence to the narrow scope, i.e. testing and measuring specific sources of evidence instead of 'all information' (Baxter and Jack, 2008). Particularly, the evaluation focused on three main attributes: 'generic' – related to language, terminology, clarity of the input and output data, navigation tabs and symbols; 'selection procedure' – related to the coherence of the procedural steps and ease of application; and 'indicator database' – related to understanding of indicators, their background information and usefulness for the proposed CE initiative. Consolidated feedback and evaluation of the main attributes is presented in Appendix II.

To set up a case study, the criteria for case selection were developed as following: i) the companies should belong to a manufacturing category, i.e. engaging with development and manufacture of capital- and/or consumer goods; and ii) the companies should have a proposal of a CE initiative and express interest in understanding its sustainability potential. The case selection followed a purposive sampling seeking to obtain information from a wide range of sources (Yin, 2011), therefore, included SMEs and large companies as well as companies from different sectors.

To achieve the case study objective, a combination of different data collection methods was selected. After establishing a contact with selected companies, *semi-structured interviews* with duration of 1 hour were conducted with the aim of clarifying the focus, i.e. a proposed CE initiative and its details, consequently allowing making a list of participants for the engagement in a fieldwork (i.e. face-to-face participatory workshops). Before the fieldwork, a method of *desk research* was employed to retrieve secondary data about the selected companies, their product and service portfolio, engagement in any sustainability-related initiative. Secondary data included the contents of companies' websites, reports and other publicly available information. The *fieldwork* included a series of three workshops designed to: i) *demonstrate* the database and the selection procedure, ii) *observe* and assist the participants in applying them, and iii) *evaluate* the fieldwork and the support. To register evidence in a structured way, notes and observations were registered in a pre-developed observation guide, which was afterwards used in the data analysis. The observation guide and the evaluation form with the measurement criteria were used to develop minutes from the workshops, which were approved by the participants (known as respondent validation by Yin, 2011), thus ensuring the accuracy of findings, as a way of warranting interpretive validity of the research (Creswell, 2014).

The case study was conducted in several cycles in the period from September 2018 to August 2019. In total, five companies engaged in the fieldwork (Cycle 1 and 2) and two companies (Cycle 3) provided evaluation through a questionnaire, allowing to refine procedure and the database after each cycle. Cycle 3 was used to evaluate the support without facilitation by the researcher. A *questionnaire* was operationalized in Google forms following the evaluation form used in the fieldwork. Summary of the cases, their sectorial representation, number of participants and their roles is provided in Table 5.

Table 5. Case studies for empirical investigation in Study B

Evaluation cycle	Company	Size	Sector	Number of participants and their roles
Cycle 1	C1	Micro enterprise (SME)	Furniture solutions for public and private spaces	2: 2 co-founders with expertise in product design
	C2	Large enterprise	Manufacture and service of heavy industrial equipment	3: CSR and HSE specialist; head of corporate sustainability department; environmental specialist
	C3	Large enterprise	Textile for various applications for public, private and commercial segments	4: sustainability manager; product developer; head of a design management; director of a subsidiary company
Cycle 2	C4	Large enterprise	Ergonomic mobility aids	8: sustainability manager; quality management; product manager; product developer; head of product management; supply chain manager; head of product management; production leader;
	C5	Medium-sized enterprise (SME)	Beverages	7: director of innovation; 2 innovation project managers; CEO assistant; director quality and sustainability; HR-specialist; production leader;
Cycle 3	C6	Medium-sized enterprise (SME)	Food processing	1: technical business development
	C7	Large enterprise	Outdoor and transportation products	1: sustainability analyst

As in any other qualitative study, the data collection and analysis occurred concurrently (Baxter and Jack, 2008). This strategy allowed converging the within-case and cross-case data and findings, to test the hypothesis and guide the improvement of the support in an iterative way. Suggestions of improvements were consolidated in a table and categorized according to the measured criteria, the attribute of the evaluation and a company suggesting it (Yin, 2011). Consequently, the notes from the observation guide, the desk research and pre-fieldwork interviews were analysed together with the results from the evaluation form, which guided the improvements of the selection procedure, the corresponding indicators database, and assisted development of the user guide, helping to answer RQ.3. Suggestions of improvements and their integration into support are presented in a consolidated form in Appendix II.

2.5. Research methods for Study C: towards the development of a trade-off navigation framework

2.5.1. Descriptive Study I-C (RQ.4)

Initially, the gap related to the support required to assist decision processes between sustainability-related trade-offs was observed during the case study research. This led to the investigation of the gap in the literature (RC stage) to confirm whether it has been reported previously and what solutions are proposed to address the gap. The findings revealed that despite a large number of frameworks and tools to support sustainability considerations in early stages of business processes, few provide support in result interpretation and none supports navigation of decisions in trade-off situations (Byggeth and Hochschorner, 2006; Haffar and Searcy, 2017; Stindt, 2017). Analysis of trade-offs does not only support a structured process of providing justifications for which alternative to favour, but it also reinforces understanding of the sustainability performance of the alternatives in light of a broader corporate context (Waas *et al.*, 2014). Therefore, a descriptive study was initiated aiming at investigating what criteria are essential to provide a trade-off support, which consequently could guide the prescriptive stage for the development of a trade-off navigation support, contributing to RQ.4: How to support decision-making when trade-offs arise between sustainability indicators?

A *literature review* was selected as the main method for DS-I aiming at describing the challenge of operating with multiple sustainability criteria during development process. Given the focus of this research on several business processes, the review focused on works from the domains of product development, supply chain and logistics, and business model development. The representative works (e.g. Abbasi and Nilsson, 2012; Driessen and Hillebrand, 2013; Zetterlund, Hallstedt and Broman, 2016) were selected using a snowballing technique from the literature from RC stage from the area of 'integration of sustainability criteria in the early stages of decision-making in business processes'. The review focused on: i) the identification of examples of typical trade-offs occurring either within or between various sustainability-related criteria, and ii) the extraction of recommendations how to support development of a trade-off analysis for sustainability-related trade-off situations. The selective nature of a literature review allowed to select few criteria to guide the prescriptive stage rather than aim for an exhaustive list of criteria (Yin, 2011). As a result, four criteria were collected providing a theoretical foundation for the development of a trade-off navigation framework. The results of DS-I are presented in Chapter 3.3. and were documented in Paper 3.

2.5.2. Prescriptive Study C (RQ.4)

The development of a trade-off navigation support focused on the trade-off navigation framework and a user guide to perform decision analysis in trade-off situations. The development was carried out in an iterative manner by: i) establishing the criteria for development, supported by criteria #1-#6 for the use context and criteria #15-#18 for the application established earlier in Study B (Table 4); ii) developing the first version based on the theoretical findings from DS-I-C; iii) developing a plan for support evaluation; iv) introducing improvements after the evaluation. Firstly, four criteria from DS-I C were translated into navigation framework as summarized in Table 6. Own criteria, #5, was formulated to provide a flexible support relevant for different business processes, following the research context involving a number of business processes.

Table 6. Criteria for the development of a trade-off navigation framework based on key findings from literature

Criteria #	Elaboration	Criteria embedded in the TONF
Pre-condition		
#1 – Reveal trade-offs between and within sustainability dimensions (Gibson *et al.*, 2005); (Byggeth and Hochschorner, 2006); (Abbasi and Nilsson, 2016); (Watz and Hallstedt, 2020)	- To reveal trade-offs, a sustainability assessment or performance measurement should be employed, providing results about performance from a three-dimensional perspective	**Input data:** - indicators (or criteria) to cover a holistic TBL perspective (cross and within dimensions) - information about corporate and initiative-specific objectives and targets - multifunctional team of decision-makers
Decision analysis		
#2 – Provide several prioritization techniques to encourage open dialogue (Driessen and Hillebrand, 2013); (Morrison-Saunders and Pope, 2013); (Stindt, 2017)	- Prioritization techniques should encourage open dialogue about negotiable and non-negotiable criteria and facilitate ranking of alternatives - Prioritization techniques should encourage result interpretation and allow for deliberations of potential risks and opportunities of the proposed alternative initiatives	**A step-by-step guidance:** - guidance for setting acceptability ranges - guidance for setting non-negotiable and negotiable criteria - guidance for prioritization and dialogue on trade-off acceptability - guidance for a pairwise comparison and ranking
#3 – Provide rules to evaluate trade-off acceptability (Gibson *et al.*, 2005)	- Rules should encourage evaluation of trade-off acceptability	
#4 – Easy to use (Matschewsky, Lindahl and Sakao, 2015); (Zetterlund, Hallstedt and Broman, 2016); (Buchert, Halstenberg and Stark, 2017)	- Should be easily integrated in the decision process and applied directly by an industrial practitioner in daily routines (i.e. without support of a third party expert)	N/A - the TONF does not require utilizing programming techniques and requires direct involvement of a practitioners/decision-makers - practical examples to support each step of the guidance
#5 – Flexible for different business processes (own criteria based on the summary of challenges in Table 2)	- Should be rather flexible to accommodate needs of decision-makers in different business processes	N/A - practical examples to support each step of the guidance

As a result, navigation support was operationalized by proposing a trade-off navigation framework accompanied by a corresponding guidance and decision matrices in Excel workbook, which intends to visualize the trade-off analysis and support traceability of decisions. The trade-off navigation and guidance were developed with the following considerations: a set of sustainability-oriented alternatives and their performance on the key sustainability criteria should be provided; 'acceptability ranges' should be elicited, which intend to reveal where trade-offs are and provide the boundary conditions for the trade-off analysis and decision-making. The guidance provided examples of how to define the acceptability ranges, taking into account the contextual settings of a company (related to the four types of corporate sustainability approaches as presented in the Introduction Chapter 1). Additionally, the guidance is provided about how to use acceptability ranges to support prioritization and weighting of criteria. The guidance and the accompanying Excel workbook served as inputs for the development of a user guide, which aimed at supporting the deployment of the trade-off navigation by industrial practitioners. Following the 'use context' and 'application' criteria from Table 4, the guide incorporated description of the target audience, inputs and expected outputs of the navigation.

2.5.3. Descriptive Study II-C (RQ.4)

Similar to DS-II-B, a hypothetical-deductive approach was followed to evaluate and improve a trade-off navigation support, focusing on RQ.4: How to support decision-making when trade-offs arise between sustainability indicators?

A combination of *interviews* and a *questionnaire* was used to evaluate the usefulness and usability of the proposed trade-off navigation framework. Questionnaire and interviews are considered a common resource for gathering data about the outcomes of a support application (Blessing and Chakrabarti, 2009). The following hypothesis was formulated to guide the evaluation: 'the trade-off navigation can support manufacturing companies in making trade-offs transparent and providing argumentations for a trade-off analysis and acceptability'.

Guided by the hypothesis, the objective of the evaluation was to understand:

• to what extent does the trade-off navigation support a structured and transparent decision-making process by: i) helping to make trade-offs explicit; ii) providing support for building argumentations for trade-off acceptability; iii) providing prioritization and ranking techniques to reinforce a dialogue about priority areas;

• how time-efficient and easy is to understand and apply the trade-off navigation support

Two types of experts were selected for the evaluation: first type, industrial practitioners, who were engaged in sustainability-related projects in industry; and second type, academic experts from the field of sustainability evaluation and eco-design. Industrial practitioners were involved in the following way: firstly, interviews were conducted with the selected participants individually. The interviews lasted for 1 hour and followed the corresponding steps: i) presentation of the objective of the trade-off navigation support; ii) presentation of the expert and their work with sustainability; iii) demonstration of the trade-off navigation support with guidance using an exemplary case; iv) a semi-structured interview focused on the trade-off support attributes and general feedback. After the interview, the participants had to individually apply the trade-off support and fill in the evaluation form. The evaluation form consisted of 20 questions and was distributed to the participants as a questionnaire using Google forms. Being an instrument in this qualitative study, a questionnaire was not intended to provide a statistical correlation between the evaluation criteria and answers, but rather lead to the improvement of the proposed support

(Blessing and Chakrabarti, 2009). The questionnaire focused on collecting the information about respondent's knowledge area, familiarity with any sustainability-related decision support technique including for a trade-off support, followed by questions focused on various attributes of the trade-off navigation support. The questions were varied, so as to both include closed-ended evaluation, relying on a three- and four-point Likert scales such as "to a larger extent", "to some extent", "no support" and "not satisfactory", "needs improvement", "satisfactory" and "very satisfactory", and an open-ended evaluation, in order to gather improvement suggestions. The same evaluation questionnaire was used for the evaluation with academic experts. For the academic experts, a workshop with the same exemplary case was held with the following objective: to observe, gather and compare feedback for two situations: first required the experts to navigate a decision for the presented case without a structured support; second was facilitated by the proposed trade-off navigation guidance and the matrices in Excel. The feedback was consolidated in the evaluation form and combined with the results from the questionnaire, which was answered by the experts at the end of the workshop. The questionnaire was identical to the questionnaire received by the industrial experts except for the part focusing on the experts' background information. The results of the evaluation are presented in Chapter 3.3., while all the feedback, improvement suggestions for each attribute of the support and their integration were summarized and presented in Appendix III.

3. Results and reflections

This chapter addresses the key findings of the research. In line with the research questions for the respective Studies, the chapter begins with an overview of findings for Study A – a database of leading performance indicators. After a short reflection on the contribution, Paper 1 is embedded. Subsequently, the results for Study B are presented, followed by the reflection on the contribution and supported by Paper 2. Finally, the results for Study C are put forward, followed by Paper 3 and Paper 4. The relationships between the results and main research objective are then discussed in Chapter 4 - Discussion.

3.1. Results for Study A: A database of leading performance indicators for TBL dimensions

A database of leading performance indicators for TBL dimensions is the first research finding corresponding to the exploration of RQ.1: What leading performance indicators exist, to measure economic, environmental and social aspects of sustainability? and RQ.2: How to categorize indicators to enable meaningful selection of indicators for early development stages of CE initiatives? Key findings regarding consolidation (RQ.1) and classification (RQ.2) of the leading performance indicators are presented below.

3.1.1. Consolidated database of leading performance indicators

Initially, approximately 400 leading performance indicators for TBL dimensions were collected in an indicator pool retrieved as a result of a SLR. SLR was conducted with the objective to identify and consolidate information on leading performance indicators proposed in the literature to measure performance from a triple bottom line perspective. The indicator pool was reviewed to remove duplicates and was registered in the database developed in an Excel spreadsheet with a total number of 279 indicators. The consolidation process included registration of each performance indicator in a database with the corresponding attributes, such as name of the indicator, a detailed description, formula, unit of measurement, and a desired trend. In case of the missing description, it was formulated and added to ensure completeness of the information. Being cognizant of the fact that industrial practitioners might need support in understanding each indicator and its relevancy, a 'purpose and significance of indicator value' was added to the key indicator attributes, as shown in Figure 7.

Indicator information				
Name of the indicator	Detailed Description	Purpose and significance of indicator value	How to measure the indicator	Unit of measure
Specific Energy Consumption in the process	This indicator measures the total energy consumption of the (manufacturing) process per production output. Production output can be a product or product parts, materials, etc	Measuring this indicator gives a good understanding of the efficiency of the manufacturing process. Higher value indicates the inefficiency of production process. This indicator should always be used together with "material consumption" indicator	Total energy consumed/Production Output	kWh/UP (Unit of Production, e.g. mass in t or kg, volume in m³, number, monetary value in EUR, etc.)

Figure 8. Excerpt from the indicator database constructed in Excel

Results of the literature review in RC stage, deliberations within CIRCit project and insights from the SLR analysis helped to establish the criteria for indicator classification, thus answering RQ.2. Accordingly, the key classification criteria were sustainability aspects under triple bottom line dimensions, business processes and CE strategies. These criteria were considered important to guide the research in developing an indicator selection procedure to ensure the selection of only relevant indicators is supported. Using the performance indicators from the database, conceptualization of a leading performance indicator database relied on a systematic indicator classification according to the logic established in the PS-A as following:

- For sustainability aspects, the classification was guided by the indicator description and a unit of measurement the indicator had assigned to it: e.g. 'water consumption' indicator measured by m^3 was assigned to environmental category, while indicator 'cost of water use' measured by EUR was assigned to economic category.
- For business process, the classification was based on the extent to which an indicator can be influenced by a decision taken during a particular business process. For example, the number of modules in a product is decided upon during a product development process; therefore, the indicator 'number of modules in a product' was assigned under 'product development' process.
- For CE strategies, the classification was based on the correlation between the activity implied by a CE strategy (supported by its description) and the focus of indicator measurement. For instance, 'remanufacture' was defined as "an activity aiming at extending to new use cycles by returning a product (discarded/not in use) to at least Original Equipment Manufacturer (OEM) performance specification and quality" (Blomsma *et al.*, 2019; p. 11). This process is usually more rigorous, laborious and costly than refurbishment and involves total disassembly and reassembly. Following this definition, the indicators 'Cost of remanufacturing, 'Labour cost per unit of product (or production output)' and 'Total Solid Waste Mass' were, as few examples, assigned to the CE strategy 'Remanufacture'.

Based on the gaps presented in Chapter 1.1.3., the classification aimed at ensuring measurement of separate or combined1 CE strategies (Blomsma and Brennan, 2017), across business processes engaged in CE development (Bocken et al., 2016), and for the aspects under TBL dimensions. This was operationalized by positioning key classification criteria as headings in the columns and then marking the relevancy of each indicator for the corresponding criteria. This way ensured that the 'filter' feature could enable a flexible selection of relevant indicators depending on the combinations of CE strategies, business process and TBL dimensions in focus. Integration of the 'filter' feature guided the development of indicator selection procedure in Study B.

Based on the classification logic presented, the following indicator distribution was achieved:

For the triple bottom line dimensions and related aspects:

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[1] Combined CE strategies, or CE configurations, are situations where two or more CE strategies are present (Blomsma *et al.*, 2019)

- 61% of all indicators covered the *environmental* dimension with the highest number of performance indicators measuring performance on such aspects as material consumption, energy consumption, product architecture and solid waste generation.
- 23% of all indicators were classified under the *economic* dimension with the aspect 'operational costs' being the richest on indicators.
- 16% of all indicators were classified under the *social* dimension, most of which relate to employee-related aspects (working conditions, health and safety, training and education).

These findings corroborated the literature, reporting the prevalence of environmental indicators over economic and social (Ahi and Searcy, 2015). Furthermore, the coverage of aspects within the TBL dimensions highlights larger focus on 'internal', i.e. firm-centric, aspects, such as production related environmental indicators (e.g. waste generation or energy consumption) and social indicators to measure employee-related aspects.

For business process coverage:

- 'production and operations' was represented by the largest number (76%) of performance indicators, followed by 'product development', with environmental indicators dominating for both processes.
- all business processes, except for 'business model' and 'product development' were covered by indicators from all triple bottom line dimensions; however,
    - 'product development' was dominated by the environmental indicators and had a lack of social indicators;
    - 'business model' was the most poorly represented by performance indicators, with environmental indicators missing altogether.

Notably, certain indicators would be relevant for several business processes due to the overlapping boundaries between various business processes where decisions need to be taken across (Bititci *et al.*, 2011). Showing the lack of indicators for certain dimensions, the findings confirm the reductionist approach in TBL measurements (Gagnon, Leduc and Savard, 2012). Additionally, the findings indicate a gap of TBL indicators suitable for business model development and of social indicators relevant for a product development, thus confirming the literature (Bhamra, Lilley and Tang, 2011; Evans *et al.*, 2017).

For CE strategy coverage:

- CE strategies 'reduce, restore and avoid impact in manufacturing', 'refurbishment', 'remanufacture' and 'recycling' were represented by the largest number of indicators of all strategies. This can be explained by the activities implied by these strategies, which demand large inputs of labour, materials and energy.
- CE strategies with focus on radical transformations, such as 'reinvent the paradigm' and 'rethink business model' have the least number of indicators, however the available indicators cover a range of aspects under all TBL dimensions.
- Each CE strategy considered in the study was covered by indicators from a TBL perspective

These findings indicate that leading performance indicators cover all CE strategies and business processes considered in the review, thus paving the way towards their applicability to support sustainability screening in a CE context.

Reflection on the contribution

In summary, the findings of this study address several research gaps in the following ways: firstly, this study provides a repository of more than 270 leading performance indicators, which are useful to support decisions in the early stages. As opposed to lagging indicators often employed by many sustainability assessment techniques, leading indicators rely on data available in the early stages of development processes, thus can be directly used to indicate areas of worsened performance and guide (design) improvements (Pojasek, 2009). Secondly, the scope of leading performance indicators in this study does not only entail the environmental dimension, but also social and economic, thus providing a basis for a holistic measurement from a TBL perspective, which is often reduced to environmental dimension in many sustainability assessment approaches (Gagnon, Leduc and Savard, 2012; Morioka and Carvalho, 2016). Thirdly, the collected indicators go beyond the production-centric scope (i.e. production and operations process), which is frequently addressed in various indicator frameworks (Azapagic, 2004), and cover a range of other processes, including business model development, for which the lack of measurements was previously reported (Morioka and Carvalho, 2016; Ludeke-Freund *et al.*, 2017); product development, for which the lack of measurements for social and economic dimension was reported (Bhamra, Lilley and Tang, 2011); and for value chain related processes of after sales service and end of life operations, for which a general lack of sustainability metrics was reported in contrast with 'traditional' metrics of cost, time and quality (Atlee and Kirchain, 2006; Björklund, Martinsen and Abrahamsson, 2012; Varsei *et al.*, 2014). Furthermore, this study offers a first attempt to classify leading performance indicators according to thirteen CE strategies ranging from dematerialization and service provision to recycling and recovery of energy and nutrients. The indicators, therefore, can be used to measure CE strategies beyond recycling and beyond material parameters, which are predominantly measured by the proposed CE measurement techniques and indicators (Elia, Gnoni and Tornese, 2017). Additionally, the indicators cover various aspects under TBL dimensions, such as water use, land use, wastewater, cost of transportation, joint type and number of modules, contribution to local initiatives, as few examples, thus providing an opportunity to measure and support development of CE strategies from the holistic TBL perspective. Despite the high number of indicators, few gaps were identified: social dimension is still underrepresented by indicators; especially, indicators for stakeholder inclusiveness, i.e. user/customer and supplier perspective, are scarce. This finding corroborates the literature on performance measurements for sustainability (Ahi and Searcy, 2015) as well as in the context of CE, which emphasizes the importance of developing measurements for social dimension to capture the shift of customer and supplier relationships from short to long term agreements (Xing, Wang and Qian, 2013). Additionally, most indicators are suitable for the technological products and not for the biological products, such as food and chemicals.

Consequently, the *first research outcome was the database of leading performance indicators* that constituted one of the building blocks of a sustainability screening for CE. The underlying logic of focusing on leading performance indicators, elaboration on the SLR and its results, with an in-depth presentation of the indicators and discussion on their classification were documented in a journal publication – Paper

1, which is embedded next. This publication also provides a hyperlink to the developed indicator database. Additionally, the paper summarizes identified gaps and calls for future research in developing leading performance indicators with focus on: i) environmental aspects of land use and soil pollution; ii) social dimension for the product development process; iii) environmental dimension for business model development; as few examples.

Paper 1: *Kravchenko, M., Pigosso, D. C. A., & McAloone, T. C. (2019)*

Towards the ex-ante sustainability screening of circular economy initiatives in manufacturing companies: Consolidation of leading sustainability-related performance indicators.

Journal of Cleaner Production. Vol. 241, 118318
https://doi.org/10.1016/j.jclepro.2019.118318

Journal of Cleaner Production 241 (2019) 118318

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Towards the ex-ante sustainability screening of circular economy initiatives in manufacturing companies: Consolidation of leading sustainability-related performance indicators

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ARTICLE INFO

Article history:
Received 26 April 2019
Received in revised form
2 September 2019
Accepted 5 September 2019
Available online 7 September 2019

Handling editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Circular economy
Leading indicators
Sustainability screening
Performance indicators
Manufacturing

ABSTRACT

The concept of Circular Economy proposes an innovative alternative model to counter the failed support of society's current 'linear' mode of operating, with the goal of achieving increased sustainability. A wide range of approaches have been proposed to help businesses plan for and implement circular strategies. Despite positive claims about the potential of circular economy implementation to simultaneously reduce environmental burden whilst enhancing business benefits, not all circular solutions (or circumstances) bring the desired positive effects, especially in the broader context of sustainability. For this reason, any decision to adopt a circular economy strategy ought to be carefully assessed with regards to its potential sustainability performance, prior to its implementation. While several attempts to measure or estimate the sustainability effects of circular economy strategies have been made, they often deploy methodologies that rely on multifaceted input information. Furthermore, such efforts provide results by means of employing lagging indicators, which are complex and may not be easily understood by decision-makers in a manufacturing company context. This paper provides a review of leading sustainability-related performance indicators, identified through a systematic literature review. As a result, more than 270 leading performance indicators have been retrieved and consolidated in a database. Subsequently, these indicators have been classified according to three categories: sustainability dimensions; business processes; and circular economy strategies. The key findings show that leading sustainability-related performance indicators are available for a wide range of Circular Economy strategies, thus making it possible to measure the potential sustainability performance of circular strategies prior their implementation. Furthermore, the specificities of leading indicators available for each classification category are presented, several gaps are identified and direction for future research is established.

Contents

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https://doi.org/10.1016/j.jclepro.2019.118318
0959-6526/

1. Introduction

Circular Economy (CE) is rapidly gathering momentum as the world's leading advocacy associations and governmental bodies recognize the approach as a way of boosting economies, without exploiting the resources at the rate that exceeds the Earth's capacity (European Commission, 2015; WBCSD, 2010). CE is seen as a new business strategy that can be adopted to operate at the global, regional and municipal level (macro level), industrial park level (meso level) and company and product level (micro and nano levels) (Kirchherr et al., 2017). Proposed CE definitions are ample, coming from a wide range of sources, such as scientific literature (see, for example Kirchherr et al. (2017) for the analysis of 114 definitions) to the grey literature, including publications and governmental reports (EMF, 2013; European Commission, 2015). CE as a concept is "...loosely based on a fragmented collection of ideas" (Korhonen et al., 2018, p.39), which rest on practices like cleaner production, reliance on renewable energy and materials, elimination of toxic chemicals and waste, increased producers' and consumers' responsibility, and more (Ellen MacArthur Foundation, 2015; Ghisellini et al., 2016). Despite the heterogeneity of definitions and interpretations, CE is seen as a model to support decoupling of environmental pressure from economic growth (European Commission, 2015; Zhang et al., 2016).

In a manufacturing context, circular solutions require redesign of business models, products and supportive networks (e.g. supply chains) to allow businesses to be part of the circular economy system (Geissdoerfer et al., 2018). Examples of CE implementation by manufacturing companies are available and includes strategies such as the provision of product-service systems to intensify the product use and support its operation; circular sourcing and manufacturing with focus on usage of secondary raw materials and internal waste recycling; repair and remanufacturing activities to extend the life of products and components. All these strategies seem to be geared by a combination of environmental and business drivers to reduce resource consumption, minimize waste, and boost profitability.

Unsurprisingly, CE is often linked to sustainability, where the adoption of CE practices is expected to facilitate sustainable development, as both concepts rely on promoting economic and environmental prosperity. Notwithstanding these similarities, the relationship between the concepts is thus far not explicit in literature and the positive link between the adoption of CE and sustainability may be seen as 'assumptive'. For example, product leasing is not automatically 'greener' (Agrawal et al., 2012), but might in contrast inspire more frequent product replacement, which will in turn lead to an increase of production. At the same time, result-oriented business models may be more environmentally beneficial than leasing or than conventional product sale schemes (Agrawal et al., 2012; Tukker and Tischner, 2006). Our synthesis of similar literature shows that the relationship between the CE implementation and achieved environmental and financial benefits is ambivalent (see more in Bartolomeo et al. (2003); Moreau et al. (2017); Rizos et al. (2016); and Zink and Geyer (2017)), leading to the conclusion that not all CE initiatives (and not in all contexts) are intrinsically contributing positively to sustainability. Furthermore, several studies indicate social wellbeing as the least prominent objective of CE (Murray et al., 2017; Sauvé et al., 2016), thus contrasting the essence of sustainable development, which rests on the balanced three-dimensional paradigm (i.e. balance between social, environmental and economic dimensions).

In combination to the myriad of CE definitions, the existence of diverging approaches to CE and the ambivalence of statements on potential sustainability benefits of CE implementation risk hampering the uptake of CE in industrial context. Furthermore, in order to ensure a multi-dimensional benefit for sustainability, a holistic thinking approach is needed, where the potential benefits and trade-offs arising from CE implementation can be evaluated. Korhonen et al. (2018) state that no CE initiative or action is successful unless it contributes positively to sustainability, while several other authors (Kalmykova et al., 2017; Potting et al., 2017) highlight the lack of assessment tools that can measure sustainability impact of implemented CE strategies or assess the potential impact of CE strategies before their implementation. The initial attempts to measure environmental effect of CE strategies have been undertaken, frequently executed by employing existing methodologies, such as material flow analysis and life cycle assessment (Elia et al., 2017; Niero and Hauschild, 2017). While these methodologies are extremely useful, their applicability in the context of ex-ante assessment and support for early decision-making is often limited, as they require multifaceted input information and expertise (Arena et al., 2013). Furthermore, the results of these assessments, presented with help of lagging indicators, e.g. eutrophication potential as an impact dimension in a life cycle assessment, are complex and may not be easily understood in strategic and tactical decisions. More discussions stipulate the need for ex-ante assessment approaches to explore whether proposed CE strategies have potential to bring the desired social, economic and environmental effects, in order to support early CE development decisions (Elia et al., 2017). For a meaningful ex-ante sustainability assessment, leading indicators are preferred over lagging, as they can be used to plan and monitor the effectiveness of proposed actions by focusing on critical areas or resolving any uncertainty early in the planning and development process (Pavlov and Bourne, 2011). A deeper discussion about leading and lagging indicators is provided in Section 2.2.

In the light of the status regarding CE and its doubtful link to sustainability, and the importance of evaluating sustainability potential in early stages of CE development, this research aims to cover the identified gap by developing a consolidated database of leading performance indicators to be used for ex-ante sustainability screening of CE strategies in manufacturing context. The main assumption in this research is that leading performance indicators can be used to analyse the potential economic, social and environmental performance of circular solutions in the early stages of the decision-making process.

The study involves the development of a database in which leading sustainability-related performance indicators are identified and classified according to a number of criteria to support the selection of the most relevant indicators to be employed to support a given decision. This classification allows the configuration of different combinations of circular solutions to be exploited in various business processes, thus displaying a suitable set of sustainability performance indicators to be measured early in the decision-making stage. Performance indicators provide a better insight into strengths and weaknesses of the circular solution, thus enable more informed and balanced decision-making for sustainability. The database of performance indicators is a first building block of a foundation for the development of a sustainability screening framework, which will also comprise a procedure for a systematic indicator selection and guidelines for decision-making for sustainability in a CE context.

The structure of the present paper is in the following order. A relevant review of literature on sustainability assessment and performance indicator is presented in Section 2. Research methodology is elucidated in Section 3, encompassing the methodology and theoretical frameworks adopted in the present study. Thereafter, results of the systematic literature review are presented in Section 4. A discussion of the research findings and identified gaps are provided in Section 5. Finally, conclusions are drawn, based on the goal of the research and the achievements presented in the paper, with suggestions for further work.

2. Literature background

This section introduces sustainability assessment and measurement approaches and the role of leading performance indicators in sustainability measurements.

2.1. Sustainability assessment and measurement

Numerous definitions of corporate sustainability can be found in the literature (Searcy, 2012), most of which are closely related to the definition of sustainable development, coined by the Brundtland Commission and released in the report “Our Common Future” in 1987 (WCED, 1987). Dyllick and Hockerts, for example, defines corporate sustainability as: “meeting the needs of the firm's direct and indirect stakeholders (such as shareholders, employees, clients, pressure groups, communities, etc.), without compromising its ability to meet future stakeholder needs as well” (Dyllick and Hockerts, 2002). The central focus is the recognition and fulfilment of stakeholder requirements and long-term thinking, which is recognized in other scientific definitions as well.

Despite the widely accepted definition of sustainable development, manufacturing companies are still facing a number of challenges to transform and operationalize the concept at a practical level (Joung et al., 2013; Pavlovskaia, 2014). The main interpretation of the concept of ‘sustainable development’ has been primarily aligned with the ‘Triple Bottom Line’ (TBL) approach, based on the management of and contribution to environmental integrity, social well-being, and economic resilience (Elkington, 1998). Therefore, companies develop and implement practices that focus on gaining and maintaining economic advantages while minimizing environmental burden and maximizing social prosperity. Sustainability performance measures can be applied to trace how ‘much’ and how ‘well’ implemented practices helped the company to move towards sustainability by advancing in the TBL domains. Internationally recognized standards and guidelines like ISO 14031; the Global Reporting Initiative (GRI); and the UN Global Compact, have been voluntary used by corporations to measure and track performance in sustainability dimensions.

When it comes to measuring sustainability performance of improvement initiatives, sustainability assessment is often used to evaluate how well the chosen sustainability requirements were fulfilled. Sustainability requirements can be understood as criteria that must be fulfilled for a specific element or activity (i.e. manufacturing process, product or service), in order to be considered sustainable (at least in relation to the element or activity that have not fulfilled the same requirements) (Krajnc and Glavic, 2003; Pavlovskaia, 2014). For that reason, the identification, integration and fulfilment of sustainability requirements for products and operational activities can be considered as interpretation and operationalization of the theoretical concept of sustainability by practitioners. Depending on the implementation level, different sustainability criteria exist. For manufacturing processes, for example, such criteria are (but not excluded to) efficient use of energy and materials for reduced operational costs, minimization of pollution and safe work environment (Amrina and Yusof, 2011; Joung et al., 2013; Krajnc and Glavic, 2003).

Sustainability assessment, therefore, is a procedure that aims at evaluating whether the improvement initiative has the potential to contribute to sustainability in a short and long-term perspective (Ness et al., 2007; Pope et al., 2004). Referring to the works of Pope et al. (2004) and Waas et al. (2014), the purpose of any sustainability assessment is to:

- Contribute to a better understanding of the meaning of sustainability and its contextual interpretation;
- Integrate sustainability into decision-making by identifying and assessing (past and/or future) impacts;
- Foster sustainability objectives.

Literature distinguishes between different forms of sustainability assessment: ex-ante assessment, i.e. the assessment of future actions, durante (during), and post evaluation, the assessment of past actions and their outcomes (Pope et al., 2017); and different types of assessment, based on a number of approaches, for example, monetary, biophysical, indicator-based (Gasparatos and Scolobig, 2012). Of the three sustainability assessment approaches, the indicator-based approach seems to offer the best possibility to plan, monitor, control and quantify sustainability contribution of certain improvement initiatives in a short and long-term perspective (Rotmans, 2006). Other advantages of using indicators for sustainability assessment include their role for comparison of alternatives and highlighting potentials for optimization (Azapagic and Perdan, 2000); helping to structure, summarize and condense complex information for meaningful interpretation (Waas et al., 2014); inducing learnings about significant sustainability aspects and impacts within or outside the company (Krajnc and Glavic, 2003). In summary, indicators enable detection, monitoring, quantification, assessment and interpretation of the performance of organizations, operational processes and products in terms of their potential (expected) or achieved (actual) sustainability impact.

2.2. Performance indicators for decision-making

Waas et al. (2014) define an indicator as “the operational representation of an attribute (quality, characteristic, property) of a given system, by a quantitative or qualitative variable (parameter, measure) …“. Sustainability indicators can be categorized according to the TBL categories, measuring the performance or impact of the improvement actions within environmental, social and economic domains. Examples of indicators are ‘number of accident-free days’, ‘number of suppliers with certified according to ISO14001’, ‘employee satisfaction’, ‘percent of primary raw materials replaced by secondary raw material in a product', 'total water consumption', 'climate change', 'resource depletion' and more (additional indicators available from LCA, S-LCA, GRI, etc.). Furthermore, sustainability-related indicators can be categorized into so-called 'leading' and 'lagging' indicators.

Lagging indicators are often referred to as reactive indicators, as they help measuring the effect of actions that are already approved and undertaken by the company. They are used for past performance assessment to measure the final outcomes of the implemented initiatives. Lagging indicators are widely employed by different methodologies, e.g. LCA (climate change indicator) and in corporate reporting, e.g. GRI (CO_2 indicator) as they serve as a good proxy for corrective actions (Epstein and Roy, 2001).

In contrast to lagging indicators, leading indicators are referred to as proactive indicators, because they can be used to plan and monitor the effectiveness of proposed actions and give advance guidance and warning, hence the possibility for companies to adjust and improve the solution (Pojasek, 2009). Leading indicators serve as preventive 'signs', i.e. they assist decision-makers with information to introduce improvements in the early stages of decision-making process, thus allowing greater control over 'allocation' of future impacts (Fig. 1). Distinctively, the uncertainty of data in the early stages may be greater, while the measurability decreases with time along the causal chain from input to impact (von Geibler et al., 2016).

Following McAloone and Pigosso (2018) on the use of indicators for product development, leading environmental performance indicators aim to produce simpler measures (compared to, for example, LCA results) of environmental aspects that can inspire effective actions towards improving products' environmental performance. Examples of leading indicators include 'take back cost of used products', 'product hazardous materials', 'total number of fasteners in a product', and more. Leading indicators are, therefore, generally thought of as input or process indicators that link more closely to operations and products, while lagging indicators relate more to outcomes achieved (Fig. 1).

Leading indicators go beyond data and measurements as they become 'subjective', i.e. have to relate to some situation, serve some person, and serve some purpose. Indicators help to structure information in a meaningful way, which leads to knowledge creation about a certain context, thus can support decision-makers in the identification and understanding of the relationship between the decisions to be taken and the potential impact on performance (Epstein and Roy, 2001) (Fig. 2).

Researchers Epstein and Roy (2001) and Morioka and Carvalho (2016) advise using leading indicators for performance measurements more extensively, as they provide insight into the organization's, operation's or product's potential impact and provide indications about future performance. Lagging indicators, while being equally important, provide information on past performance of the system, however may not offer useful information about the exact causes of such performance, thus may not be effective for decision-making and management of processes (Pojasek, 2009).

Following the importance of the role of performance indicators in sustainability assessment and the importance of leading performance indicators in effective management of processes, it can be argued that the approach for assessing the sustainability of CE initiatives in the early stages of a decision-making process should be based on leading performance indicators. Therefore, this study focuses on the development of a consolidated database of leading performance indicators to be employed for ex-ante sustainability screening of CE initiatives. The database comprises leading performance indicators that were classified according to TBL dimensions, CE strategies applicable on a micro-level and business processes. Therefore, the core of the development of the database was the process of identification of leading sustainability-related performance indicators and their classification according to the identified criteria. The process is described in detail in Section 3 – Research methodology.

3. Research methodology

This study focuses on the development of a consolidated database of leading performance indicators to be employed for ex-ante sustainability screening of CE initiatives. The goal of this research was to identify leading sustainability-related performance indicators in the literature and classify them according to business processes and CE strategies, with the ultimate aim to support decisions for CE planning and implementation. Therefore, the question in focus was: "What are the existing sustainability-related leading indicators that can be used to measure the sustainability performance of CE initiatives?"

3.1. Data collection

A systematic literature review was performed to answer the question in focus. The research approach consisted of, firstly, extracting the existing indicators from the literature and, secondly, classifying performance indicators according to the defined criteria. Systematic reviews are conducted with the aim of identifying all research within a specific scientific area to give a "balanced and unbiased summary of the literature" (Nightingale, 2009). Systematic literature reviews follow a specific procedure that is rigorously planned, conducted and documented (Biolchini et al., 2005), thus minimizing the risk of bias in selecting and extracting data from the review (Nightingale, 2009).

The systematic literature review followed the procedure proposed by Biolchini et al. (2005) consisting of: (1) review planning; (2) review execution; and (3) results analysis (Fig. 4). In the first step of the procedure, review planning, a systematic literature review protocol was prepared to document the aims and objectives of the review, inclusion and exclusion criteria, the way in which

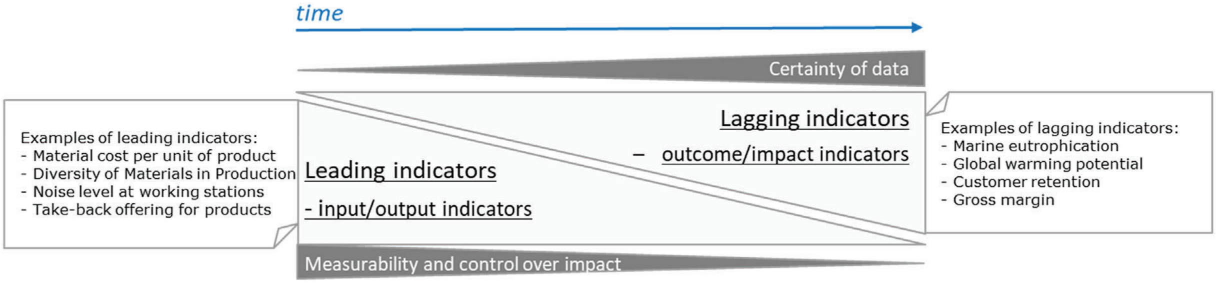


Fig. 1. Distinction between leading and lagging indicators and their relationship to time. Source: own figure, based on Pojasek (2009) and von Geibler et al. (2016: 1).

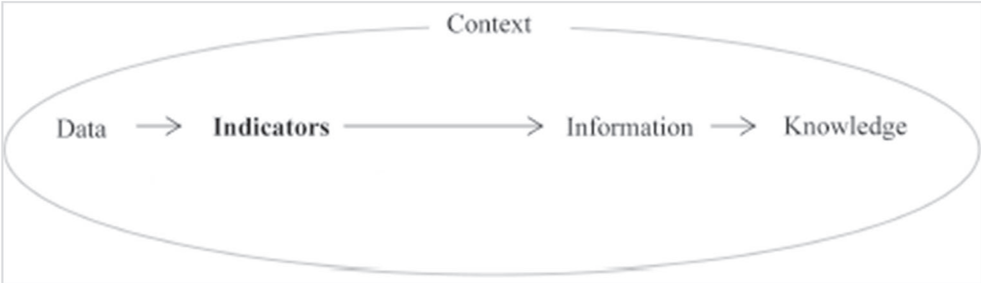


Fig. 2. Transitional role of indicators from data to knowledge formation. Source: modified from Waas et al. (2014).

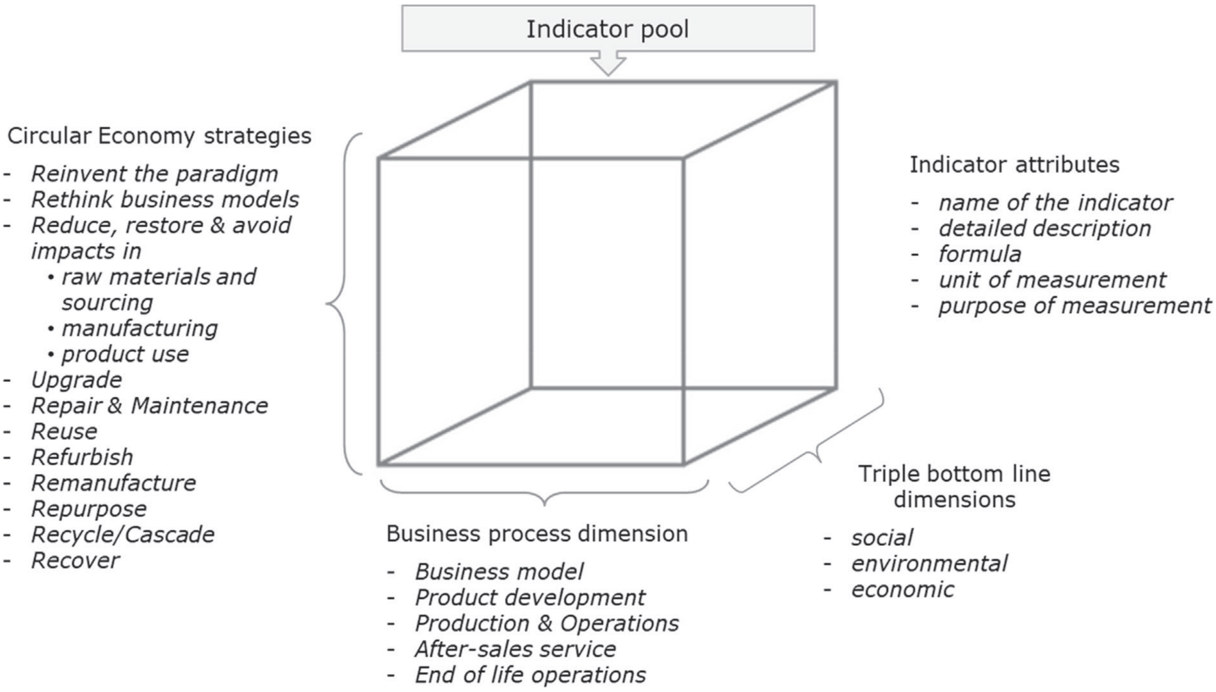


Fig. 3. Data systematization process: classification of performance indicators according to the circular economy strategies, business processes and TBL dimensions.

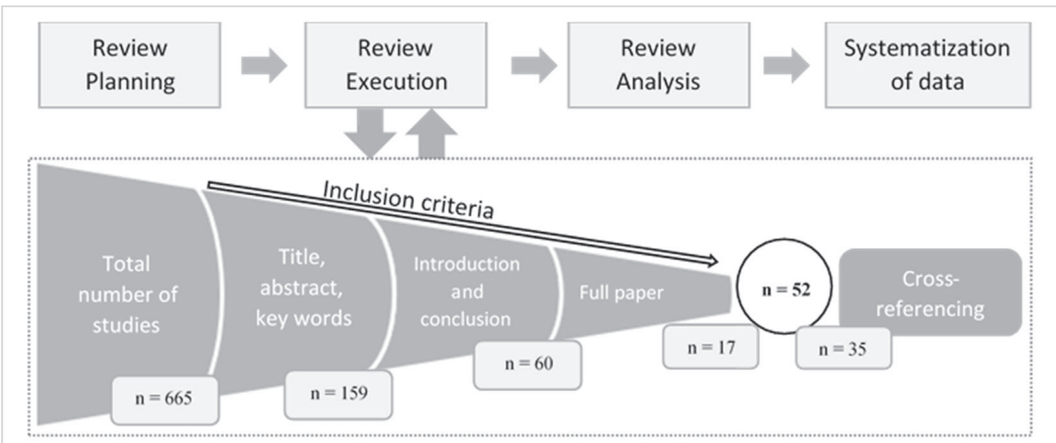


Fig. 4. The research approach: the systematic literature review process and selection of relevant studies.

studies were identified and how the results were registered. During the second step, review execution, the identified studies were evaluated and screened against the inclusion criteria defined in the protocol. Lastly, the selected studies allowed retrieving relevant data to be analysed and registered according to the procedure (Biolchini et al., 2005).

The main goal of the systematic literature was to identify and consolidate information on leading performance indicators that form a foundation for the database to be used for decision-making. The review focused on identification, selection and systematization of leading sustainability-related performance indicators. A literature search was performed in the databases Scopus and ISI Web of Knowledge, due to availability of advanced web search mechanisms, high volume of indexed papers and proven relevance in the fields of sustainability and engineering (Adriaanse and Rensleigh, 2013; Falagas et al., 2007; Gavel and Iselid, 2008). Search strings were composed of the main keywords and their synonyms, as identified and supported by literature.

According to works of Ahi and Searcy (2015), Costa et al. (2014) and Veleva and Ellenbecker (2001), terms as ‘performance measure’, ‘performance evaluation’, ‘performance assessment’ and ‘performance indicator’ are used interchangeably, therefore were all included as synonyms to the key word ‘key performance indicator’, thus comprising the first part of the search string. In relation to sustainability assessment, the literature is in consent of sustainability should be viewed and measured from a holistic perspective, e.g. encompassing social, environmental and economic dimensions (Bell and Morse, 2008). Therefore, it allows to interpret sustainability as a ‘three-pillar’ or ‘triple bottom line’ (TBL) concept (Pope et al., 2004). Consequently, the second part of the search string consisted of words ‘sustainability’, ‘triple bottom line’, ‘social’, ‘environmental’ and ‘economic’. The third part of the search string consisted of a number of certain business processes that the current research encompasses. The business processes are seen as the ‘arenas’ within which CE initiatives are developed and materialised, i.e. circular solutions are to be planned for and evaluated during and across business processes. The business processes considered in this research were ‘business model development’; ‘product development’; ‘production and operations’; ‘after-sales service’; and ‘end of life operations’. In Scopus, the keywords were searched for in the titles, abstract and keywords. After a set of refinement rounds, it was decided to limit the research fields (‘subject area’ in Scopus) to cover environmental science, engineering, business, economics, social sciences and decision sciences. The search included both journal and peer-reviewed conference papers, in order to capture the recent developments in the field. Furthermore, no restrictions were applied to the publication year, in order to guarantee comprehensiveness of the results. As Nightingale (2009) points out, the search strategy should be ‘sensitive’ rather than ‘specific’ to increase the chance of getting ‘important’ papers despite the possibility of getting a large number of irrelevant papers. The search string used in Web of Science was composed and adapted to the database's rules. After a set of refinement rounds, it was decided to search for the key words only in the titles of the studies (refer to Appendix A for exact search strings used in Scopus and Web of Science).

The inclusion criteria, defined in the review planning protocol, were used to identify, evaluate and select the relevant studies. The inclusion criteria ensured the homogeneity of the data and reduced confounding. The studies met the following inclusion criteria: 1) proposition, application or review of a leading indicator for sustainability assessment; 2) focus on manufacturing companies or micro-level (product, process, service). With the first inclusion criteria, the review intended to exclude lagging indicators used for sustainability assessment, such as global warming potential or abiotic toxicity (often used in LCA studies), whereas with the second inclusion criteria, any indicator that focuses on municipal or national level were excluded. Considering the inclusion criteria, the publications were qualitatively selected according to the gradual application of three filters: filter 1 – read the title, abstract, key words; filter 2 - read introduction and conclusion; filter 3 - read the full paper.

After all the studies were screened and the indicators identified, they were registered with the following attributes: name of the performance indicator, a detailed description, formula, unit of measurement, recurrence in literature and source. References, cited in the publications identified through the search, were used as secondary sources to identify additional relevant publications. This procedure is sometimes called a ‘snowball technique’ or cross-referencing (Lewis-Beck, 2004). This process led to identification and analysis of a number of studies that contributed to the data extraction.

3.2. Data systematization

The second phase of the performance indicators systematization included the classification according to a number of pre-defined categories, such as circular economy strategies, business processes and TBL dimensions (as shown in Fig. 3):

Sustainability or triple bottom line dimensions: environmental, social and economic, where all three pillars are considered equally important when making decisions and measuring performance in the sustainability context (Badurdeen et al., 2015; Joung et al., 2013). These are categories widely used by other sustainability assessment and measurement frameworks. Therefore, this classification of performance indicators allows for a holistic assessment of CE initiatives and enables a straightforward association of each indicator with a specific sustainability dimension and an aspect under it.

- *Social dimension* is defined as the dimension that addresses identification, accounting and management of values and needs of different stakeholders of a company (UN, n.d.). The stakeholders can be identified as internal and external groups of people that interact with and directly or indirectly affected by the company and its activities (Labuschagne et al., 2005). In the context of social business sustainability, the key stakeholder groups required by most global standards and frameworks (such as GRI, UNCSD, S-LCA) are employees, customers, suppliers and community (local, national, or global). Each group requires addressing a number of related aspects, such as but not excluded to: employment conditions, health and safety of employees and customers, human rights, equity, etc. Therefore, the categories under social dimension included in the database are: community relationships; employee empowerment; employee health and safety; employee training and education; employment conditions; equality; supplier relationships; user relationships.
- *Economic dimension* represents positive value creation and distribution by a company supported by long-term relationships with customers, partners and suppliers (Elkington, 1998). The aspects covered under economic dimension and frequently used in corporate reporting are: costs, revenues, investments, innovation and technologies, knowledge management, etc. The aspects included in the database address tactical and operational matters and are: operational costs; tactical costs; user costs; product quality; revenues.
- *Environmental dimension* concerns the identification and management of organization's aspects and impacts to ensure long term positive impact on living and non-living natural systems (Bell and Morse, 2008; Sauvé et al., 2016). Aspects that belong under environmental dimension capture resource consumption (material, energy, water, land), emissions to water, soil, air, and chemicals (Fiksel et al., 1998; Joung et al., 2013) and are most common aspects in performance measurements and reporting frameworks (e.g. by GRI Sustainability Reporting Standards; OECD sustainable manufacturing indicators; ISO 14031:

Environmental performance evaluation standard). Aspects under environmental dimension included in the database are: material, energy and water consumption; solid and liquid waste generation; air, water and soil pollution; gaseous emissions; land use; material safety; product architecture (i.e. physical properties and attributes of a product, which, for instance, can influence the cost of maintenance or repairability).

Each performance indicator was classified according to a corresponding dimension, mainly justified by a unit of measurement the indicator had assigned to it. We, however, acknowledge that most of the retrieved sustainability-related indicators are cross-dimensional (Badurdeen et al., 2015). For instance, hazardousness of materials in a product can have an impact on both, environment and consumer; however, the indicator measuring the weight or number of hazardous materials in a product was assigned to 'material safety' aspect under environmental dimension. Resource origin is another example of cross-dimensional aspect between environmental and social dimensions. The indicator 'amount of conflict resources' measuring the amount of resources used in a product or production that are extracted in a conflict zone that may perpetuate violence (European Commission, 2017) was assigned to both, the environmental and social dimension, while the indicator 'suppliers that have completed information on raw material and resource origin' was assigned to the social dimension.

CE strategies applicable in a manufacturing context served as another category for indicator classification. There are numerous frameworks that propose a vision for how to operate in a CE context. Those frameworks propose strategies based on their generic applicability, such as the ReSOLVE framework (EMF, 2013), applicable to specific sectors (i.e. textile) ("The new textile economy" by EMF, 2017), or to specific operational processes and products (supply chain, design of products and business models for circularity, etc.) (Bocken et al., 2016). In this research, a generic reference model (i.e. applicable to any sector, process or product type within manufacturing context) was adopted with the following CE strategies as depicted in Fig. 3 and listed in Appendix B with corresponding definitions. The framework of CE strategies adopted in this study is an instantiation of Potting et al. (2017), which was selected because it provided an overview of the spectrum of available circular strategies ranging from incremental to transformative. Each performance indicator was classified according to a corresponding CE strategy. The classification was done based on the correlation between the activity implied by a CE strategy and the focus of indicator measurement. For instance, the indicator 'cost of remanufacturing" was assigned to the CE strategy 'Remanufacture'; the indicator 'water consumption during use phase of the product' was assigned to the CE strategy 'Reduce, Restore & Avoid impacts in Product in Use stage'; while the indicator 'weight per distance travelled' was assigned to every CE strategy as transport is an aspect applicable across strategies. The classification of performance indicators according to various CE strategies allows the decision maker to extract the indicators meaningful to the circular solution in focus.

Business processes are a set of structured activities that a company manages in order to accomplish a specific purpose, for instance, to produce a product or service (Ray et al., 2004). Business processes can be classified as primary, related to operational activities (e.g. product development, inbound and outbound logistics, manufacturing, service provision) and secondary, related to management activities (e.g. corporate governance and strategic management) (Persson and Stirna, 2009). The business processes considered for indicators classification in this study are related to primary organisational activities, such as product development (PD), production and operations process (including supply, distribution and retail), after-sales service (including installation of product, support of product, upgrade and repair services), end of life operations (EoL) (including remanufacturing and recycling) and business model (BM) development. These processes belong to the primary business processes and are typical for any manufacturing company (Ray et al., 2004). The rationality behind the classification of performance indicators according to these business processes was the extent to which an indicator can be influenced by a decision taken during a particular business process. For example, the number of modules in a product is decided upon during a product development process; therefore, the indicator 'number of module sin a product' was assigned under 'product development' process.

4. Results

The results are presented and discussed in several sub-sections. Sub-section 4.1. provides the detailed analysis of the literature collected and reviewed during the systematic literature review; sub-sections 4.2., 4.3. and 4.4. address the results of indicator classification according to the defined categories: 4.2. – for TBL classification, 4.3. – for business process classification, 4.4. – for CE strategy classification.

4.1. Background information on the literature

Using the procedures discussed above, a total of 665 articles (521 for Scopus and 144 for Web of Science) were originally identified through the search in both databases. At the end of the screening process guided by the inclusion criteria, the final number of papers that were used to retrieve performance indicators was 17; however, 35 relevant papers were also included as a result of paper analysis from cross-referencing (Fig. 4). By applying the inclusion criteria, all the papers had their title, abstract and key words analysed, resulting in 506 papers (76% of total) being rejected. The chosen 159 papers (24%) had their introduction and conclusion read, resulting in 60 papers chosen. Finally, the 60 papers were fully read, from which 17 were chosen for the retrieval of performance indicators. In continuation of this study, around 70 papers found through cross-referencing were analysed against the inclusion criteria, with 35 being consequently chosen for performance indicator extraction. Thus, the total number of papers that satisfied the inclusion criteria amounted to 52.

The selected papers were published in a total of 25 different journals, 3 handbooks and 8 scientific conference proceedings in the period 1994–2018 with larger dominance of publications from 2012 to 2018 (Fig. 5). As seen in Fig. 5, showing the distribution of papers by conference (grey bars), one paper was identified in every conference with the only exception of the proceedings of International Conference on Industrial Engineering and Engineering Management (IEEM) and IFAC conference proceedings, from which three and two publications were extracted correspondingly. The largest number of papers (11 publications) were extracted from the Journal of Cleaner Production, which can be explained by the Journal's strong correlation with cleaner production, environmental issues, and sustainability concerns (Fig. 5, blue bars). Furthermore, the International Journal of Production Research, Ecological Indicators and International Journal of Life Cycle Assessment presented two publications each, which might be attributed to the primary focus of above-mentioned journals and its relation to the present question in focus (performance indicators for sustainability assessment in a manufacturing context). The remaining publications came from a variety of journals addressing different themes, such as mechanical and sustainable design, resources, production economics, and clean technologies.

From the 52 publications, approximately 400 leading

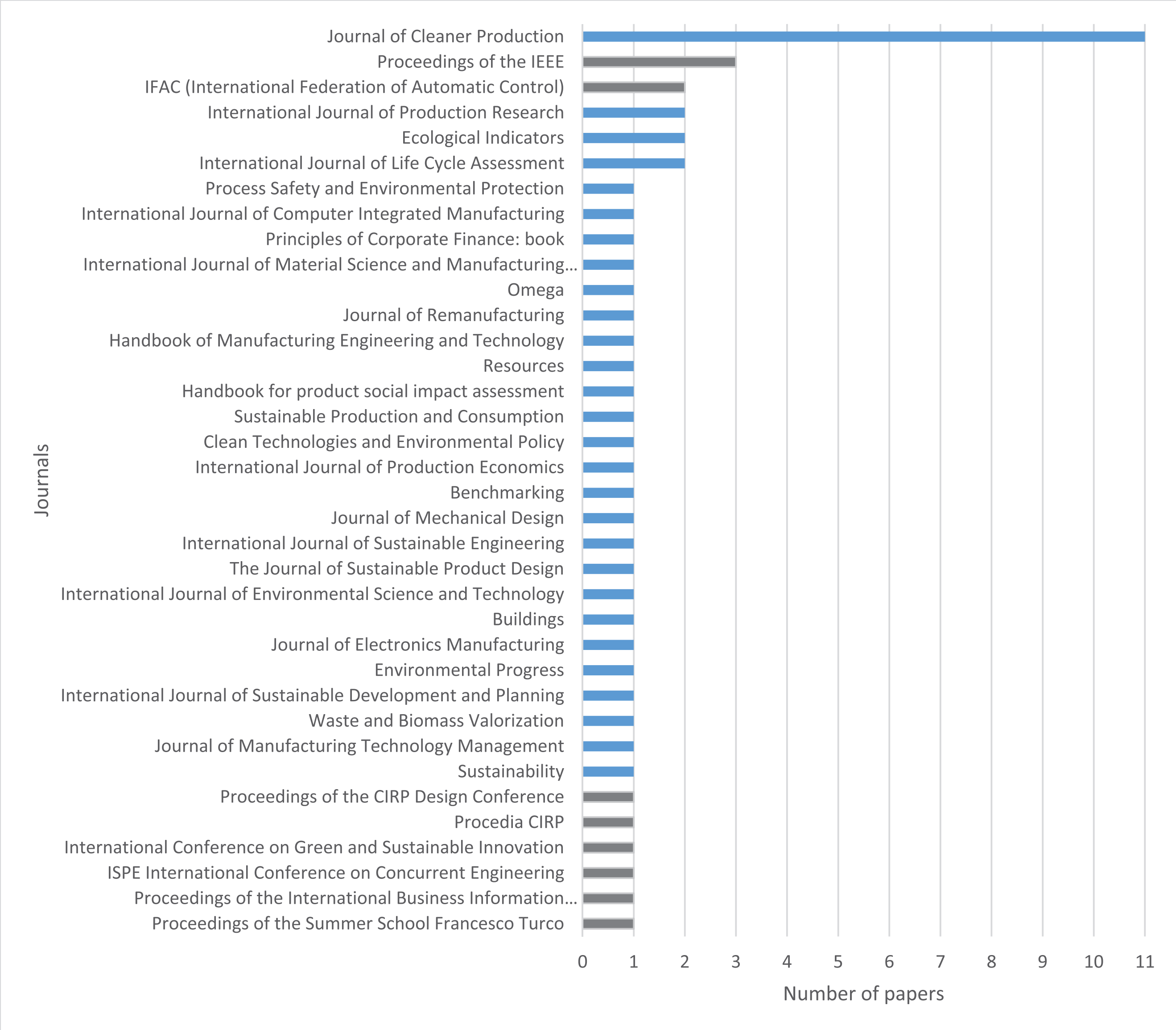


Fig. 5. Distribution of selected publications by journal (in blue) and by conference (in grey). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sustainability-related performance indicators were retrieved and reviewed. The duplicates were removed and the indicators were registered in the database developed in a spreadsheet with a total number of 279 indicators. The consolidation process included registration of each performance indicator in a database with the corresponding attributes, such as name of the indicator, a detailed description, formula and unit of measurement. Approximately 90% of the performance indicators were accompanied by explicit units of measurement, however the description and formulas were not always provided. These missing attributes were defined and registered in the database complemented by a description of ‘purpose of measuring’, to aid the understanding of importance of the indicator and interpretation of measure. Important to note that almost 95% of extracted indicators are quantitative despite the fact that qualitative indicators were not targeted to be excluded during the literature review.

After the review process, the indicators were classified according to the pre-defined dimensions, i.e. TBL dimensions, business processes and CE strategies. Since this research is exploratory in nature, we highlight the distribution of performance indicators according to the pre-defined criteria to show recent developments in an indicator categorization and their deployment in sustainability assessments.

4.2. Analysis of performance indicator classification according to TBL dimensions

Each performance indicator was classified according to the TBL dimension: social, environmental and economic, respectively. Furthermore, each performance indicator was assigned to an aspect within a particular dimension (Fig. 6), thus illustrating what sustainability dimension and what aspect of that dimension the indicator measures the performance of. As an example of how categorization was done, the performance indicator ‘total packaging costs’ was classified as an indicator primarily related to the ‘Operational cost’ aspect under economic dimension, mainly

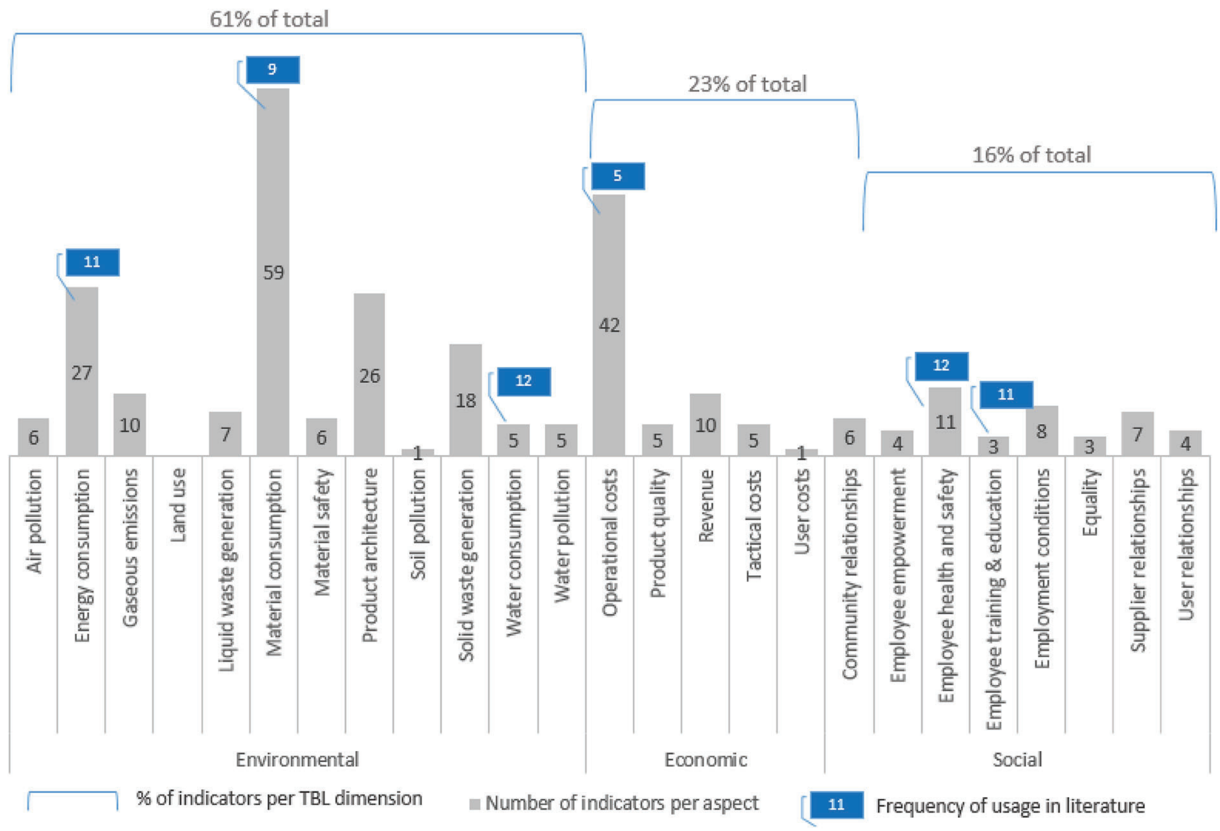


Fig. 6. Total number of performance indicators capturing TBL dimensions and corresponding aspects, where blue bars highlight aspects, covered by indicators most frequently proposed in the literature. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

justified by the assigned to it monetary unit of measurement. However, it also relates to the 'Material consumption' aspect under environmental dimension. For the purpose of a clearer identification of the sustainability dimension a particular indicator belongs to, the classification was done according to the descriptions of sustainability dimensions provided by the literature and corresponding units of measurement (see Section 2). To further explain the classification logic, the indicators that addressed consumption of materials, energy, chemicals, water, land, emissions and pollution were all classified as environmental indicators; the indicators that addressed costs and revenues were classified as economic indicators; the indicators that addressed stakeholder relationships, employment conditions, customer and community relationships were classified as social indicators.

The total number of performance indicators distributed per TBL dimension and per corresponding aspect are shown in Fig. 6. The environmental dimension has the largest number of aspects as well as the largest number of indicators assigned under those aspects. Performance indicators from environmental dimension represent 61% (170 out of 279) of all the indicators extracted from literature with the highest number of performance indicators measuring performance on material consumption, energy consumption, product architecture and solid waste generation. The 'product architecture' can be considered as a neutral aspect as it relates to design attributes of a product, nonetheless it has a critical effect on the way a product performs. Performance in 'product architecture' is especially crucial in the context of CE, as it influences whether the product can be repaired or recycled, consequently affecting the efficiency of those processes in terms of waste generation, energy and material consumption, and cost. Furthermore, performance indicators that measure performance on material, energy and water consumption were most frequently mentioned under their dimensions in the literature (Fig. 6). The 'Soil pollution' aspect was addressed by only one indicator, 'pesticide use', while none of the retrieved indicators covered 'land use' aspect.

A total of 23% (63 out of 279) of the performance indicators were classified under the economic dimension with the aspect 'operational costs' being the richest on indicators. It is also the aspect with the most frequent mention of the performance indicator 'total material costs' (5 publications). Other economic indicators measure performance on such aspects as 'tactical costs' (e.g. 'cost of supplier education and training'), 'revenues' (e.g. 'revenues from refurbished products'), 'user costs' (e.g. 'cost of energy during use phase of the product'), 'product quality' (e.g. 'first technical wear-out life'). 'Product quality' aspect is considered under economic dimension due to its materiality in influencing customer satisfaction, and profitability, consequently (Gaiardelli et al., 2006).

The social dimension accounts for the least number of performance indicators corresponding to 16% (46 out of 279) of all indicators retrieved from the literature. Most indicators under social dimension relate to employee-related aspects (working conditions, health and safety, training and education), thus confirming the 'tradition' from manufacturing sector of concentrating social performance measurements on 'inside-out' social aspects (Chengcheng Fan et al., 2010; Feil et al., 2015). Remarkably, it is also the aspect with the most frequently mentioned indicators in the literature, with the indicator 'health and safety training per employee' and 'total number of hours of capacity and skill development training per employee' mentioned in 12 publications (Fig. 6). Although the developments in taking social aspects beyond operational activities, such as adoption of CSR policies and Global Compact Principles, has contributed to the development of indicators capturing community, supplier and user relationships (Husgafvel et al., 2014), their number is relatively small.

4.3. Analysis of performance indicator classification according to business processes

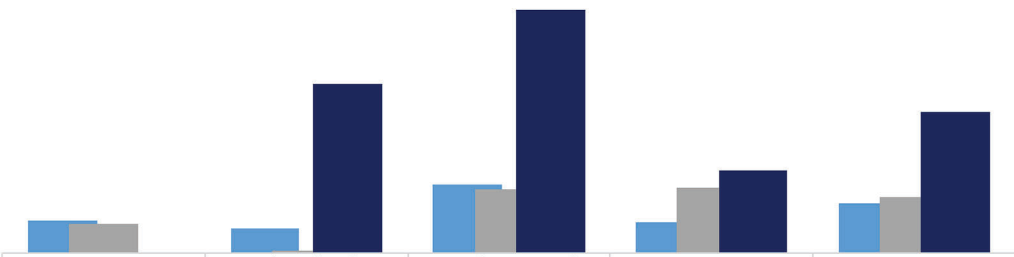
Business Processes served as another category for indicators classification. As an example of how classification was done, the indicator ‘waste converted to reusable material’ was classified under ‘End of Life operations’ process, since the amount of waste converted to reusable material can be influenced by a decision taken during EoL operations. The distribution of performance indicators across business processes and corresponding TBL dimensions is shown in Fig. 7. The most extensively covered process is ‘production and operations’, represented by 76% (211 out of 279) of performance indicators, 65% of which belong to the environmental dimension. This might be, firstly, due to a larger focus in the literature on sustainable manufacturing performance measurements, secondly, due to the expansion of sustainability-related metrics from manufacturing, to supply chain orientation, with attention turned to a more ‘inclusive’ and ‘external’ consideration of sustainability performance during supply, distribution and retail operations (Ahi and Searcy, 2015). This is confirmed by the literature the identified indicators were drawn from. Thus, the environmental indicators include ‘total material consumption’, ‘total energy consumption’, ‘total waste generation’, (Amrina and Yusof, 2011; Kafa et al., 2013; Lu et al., 2010), ‘fuel consumption in transportation for raw materials’ (Olugu et al., 2011), most originating from literature on sustainable and green supply chain measurements. Similar rationality applies to social indicators, which tend to account for ‘internal’ stakeholders aspects, such as employee health and safety, employment conditions and training and education (Kafa et al., 2013). Despite the supply chain view, which suggests a broader scope of social aspects, social dimension is still scarce on indicators, which are largely represented by the indicators applicable to a manufacturing, narrower, scope (Ahi and Searcy, 2015).

Similarly, the environmental dimension is well covered by performance indicators under ‘product development’, ‘after-sales service’ and ‘EoL operations’, while economic and social indicators are lagging behind. The abundancy of environmental indicators for ‘product development’ might be associated with a great consideration of eco-design principles in product development as well as applicability of life-cycle analysis for product impact assessment (Bhander et al., 2003; Fiksel and Wapman, 1994; Issa et al., 2015). Indicators suggested in the literature cover a range of aspects focused on: sustainable product ‘behaviour’ (Fiksel et al., 1998) with indicators such as ‘power use during operation’ and ‘product disposition cost’; product end of life ‘management’ (Jiménez-Rivero and García-Navarro, 2016; Staikos and Rahimifard, 2007) with suggested indicators such as ‘collection costs’, ‘refurbishing costs’, ‘unit energy price from energy recovery’; product development process with indicators suggested for each life cycle stage of a product (Arena et al., 2013; Issa et al., 2015; Okechukwu et al., 2014; Ussui, 2013).

While most of the ‘product-related’ publications acknowledged the importance of sustainability consideration during product development process, sustainability-related aspects were often reduced to environmental measurements, with little or no attention given to metrics capturing social performance, discerning to the ‘intangible’ and ‘complex’ nature of social aspects and their inter-relationships (von Geibler et al., 2006). Unsurprisingly, the social performance metrics is primarily concentrated on measuring affordability of a product (e.g. price) or to the product ‘safety’ (e.g. presence of toxic and hazardous materials) (Hallstedt, 2017; Lu et al., 2010), which is supported by the indicators retrieved in this study. Fig. 7 confirms literature and shows a striking imbalance of TBL dimensions for ‘product development’ BP, where only 1 indicator (‘existence of product manual with environmental instructions’) from social dimension was found to belong to, while number of environmental indicators are nine times the number of economic.

High occurrence of environmental indicators for ‘after-sales services’ and ‘EoL operations’ can be explained by ‘repeated’ indicators, i.e. product metrics being closely interconnected with production and post-production metrics, often linked to the life cycle thinking approach (Lu et al., 2010). For example, ‘material amount’ is considered in both, product development process and production and operations process (Badurdeen et al., 2015). Likewise, some indicators are mirrored between production and operations process and EoL operations; this is because remanufacturing process during EoL operations becomes a ‘production’ process for a remanufacturable product as well as recycling becomes ‘production’ process for a recyclable material (Atlee and Kirchain, 2006). This, consequently, implies that energy and materials need to be supplied for remanufacturing and recycling process as well as it entails workforce and transportation (Saavedra et al., 2013).

Business model is the most poorly represented by performance indicators. Only 18 economic and 16 social indicators were



	Business Model	Product development	Production and Operations	After-sales service	EoL operations
Economic	18	13	38	17	28
Social	16	1	36	37	31
Environmental	0	95	137	46	79
Total	34	109	211	100	138

Fig. 7. Total number of performance indicators distributed according to business processes.

extracted from the literature and applicable to a business model level, while environmental indicators were not recorded at all (Fig. 7). From all 52 publications used to retrieve performance indicators, only one publication addressed environmental metrics for business model (Watanabe et al., 2016), however after the publication was reviewed, the metrics suggested were found to be applicable to production level rather than business model level.

Important to note that many indicators could be affected by a decision during several business processes, therefore appear several times under different business processes. Refer to Table 1 for examples of performance indicators and their distribution according to business processes and aspects under TBL dimensions. The complete database of leading sustainability-related indicators is available for download following the address https://doi.org/10.11583/DTU.8034188.v1.

4.4. Analysis of performance indicator classification according to circular economy strategies

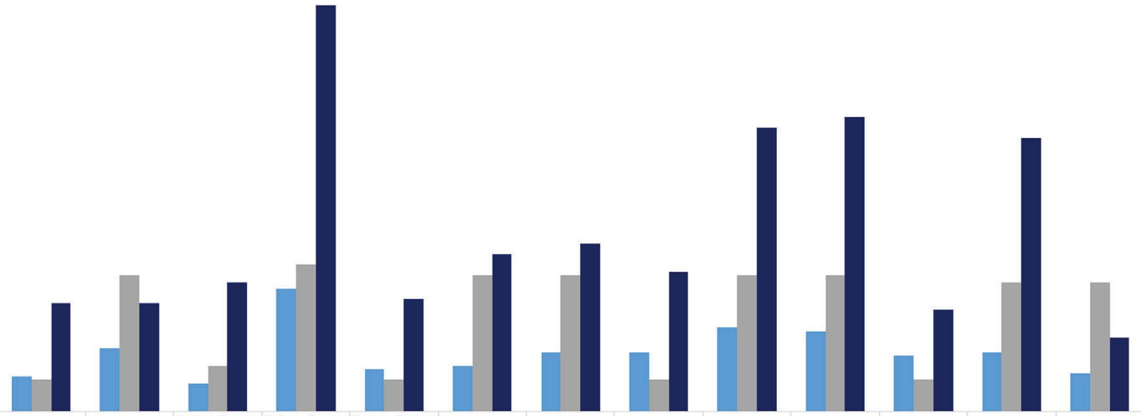
Classification of performance indicators according to CE strategies allows extracting sustainability-related indicators meaningful for the circular solution or configuration of solutions to be analysed in a specific case. Fig. 8 presents the results of indicator classification according to CE strategies used in this study. As seen in Fig. 8, the environmental dimension is dominating in indicator number for the majority of CE strategies, while the economic and social dimension differ depending on the CE strategy. The most covered by performance indicators CE strategy is 'reduce, restore and avoid impacts in manufacturing' with 193 indicators (69% of the total number) capturing environmental dimension. Other CE strategies with a greater coverage by indicators are 'upgrade', 'repair and maintenance', 'refurbish', 'remanufacture' and 'recycle'. The CE strategy with least number of indicators is 'reinvent the paradigm'.

Environmental indicators' prevalence under the CE strategy 'reduce, restore and avoid impact in manufacturing' can be explained by correlation between nature and origin of indicators (environmental indicators coming from performance measurements in production and supply chain operations) and activity implied by this particular CE strategy (i.e. improving circularity potential and process efficiency in manufacturing process through consuming fewer natural resources or energy (e.g. pre-user recycling, material and energy efficiency, waste and emission treatment)). Analogous situation exists for the majority of CE strategies, where environmental indicators prevail over indicators from other dimensions (see Fig. 8 and Table 2). It can be elucidated that such distribution is well aligned with the 'activities' explicated by the majority of CE strategies (definitions of each CE strategy are summarized in Appendix B). Accordingly, CE strategy 'repair and maintenance' denotes activities that aim to restore faulty components of a defective product to return it to a functional state. This may require partial disassembly, hence usage of energy, materials, lubricants for the operation (Saavedra et al., 2013) and workforce to complete the task. Noteworthy, indicators devoted to capturing transportation and packaging aspects were assigned to the majority of CE strategies, as these aspects are important across strategies, i.e. mainly strategy-independent.

While most of the CE strategies seem to be unequivocal in what they entail based on their definitions, the CE strategy 'reinvent the paradigm' and 'rethink business model' might need a detailed elaboration on what they necessitate. 'Reinvent the paradigm' concerns smarter business concepts that promote resource decoupling, thus making a focus on offering dematerialized and/or multifunctional solutions (Appendix B). This strategy requires a shift towards a 'radical' reinvention of products supported by technology and infrastructure (e.g. dematerialized solution offered by Spotify as opposed to a CD) (Potting et al., 2017). Therefore, the environmental indicators capturing this CE strategy address resource consumption (aligned with resource decoupling) for producing and offering such solution; the social indicators address user relationships and the economic indicators address mostly operational costs and quality of products (Table 1). The CE strategy 'rethink business model' advocates shift of value offering from selling products to selling access and performance enabled by product-service system (PSS) business models. The products may

Table 1
Representative examples of performance indicators and their distribution according to business processes and triple bottom line dimensions and corresponding aspects.

Business Process	Performance Indicator	Triple bottom line dimensions and corresponding aspects		
		Environmental	Social	Economic
Business Model	- Revenues from refurbished products			- Revenue
	- Take-back offering for products		- User relationship	
	- Products consumed locally		- Community relationship	
	- Maintainable period after sales		- User relationship	- Product quality
	- Cost of transportation in reverse supply chain	- Energy consumption		- Operational costs
Product Development	- First technical wear-out life			- Product quality
	- Existence of Manual with environmental instructions		- User relationship	
	- Product Hazardous Materials	- Material safety		
	- Number of components	- Product architecture		
	- Amount of Conflict Resources (CR)	- Material consumption	- Community relationship	
	- Packaging costs			- Operational costs
Production and Operations	- Total energy costs			- Operational costs
	- Noise level at working station		- Employee health and safety	
	- Suppliers without environmental, health and safety standards		- Supplier relationship	
	- Intensity of transportation	- Energy consumption		
	- Waste converted to Reusable Material	- Solid waste generation		
After-sales service	- Volume of chemicals and solvents	- Material consumption		
	- Efficiency of packaging design	- Material consumption		
	- Weight per Distance Travelled	- Energy consumption		
	- Consumer warranty cost			- Operational costs
	- Availability of customer support option		- User relationship	
End of Life operations	- Total sorting cost			- Operational costs
	- Noise level at working station		- Employee health and safety	
	- Energy consumption for disassembly	- Energy consumption		
	- Replaced parts	- Material consumption		



CE strategy	Reinvent the paradigm	Rethink business model	Reduce, Restore & Avoid impacts in Raw material and Sourcing	Reduce, Restore & Avoid impacts in Manufacturing	Reduce, Restore & Avoid impacts in Product in Use stage	Upgrade	Repair and Maintenance	Re-use	Refurbish	Remanufacture	Repurpose	Recycle	Recover
Economic	10	18	8	35	12	13	17	17	24	23	16	17	11
Social	9	39	13	42	9	39	39	9	39	39	9	37	37
Environmental	31	31	37	116	32	45	48	40	81	84	29	78	21
Total	50	88	58	193	53	97	104	66	144	146	54	132	69

Fig. 8. Total number of performance indicators distributed according to Circular Economy strategies.

not radically change, however the relationship between customer/user and the product changes (e.g. product ownership is retained by the manufacturer or service provider and the customer pays to have access to the product, like in a bike sharing model) (Potting et al., 2017). The environmental indicators for this CE strategy address aspects of material consumption during service provision or use of a PSS solution, while the economic indicators address operational costs and revenues. Social indicators dominate, capturing performance on user and provider aspects, complemented by metrics on local communities and other stakeholders. Examples of social indicators under this CE strategy are ‘programs to enhance community health or safety’, ‘purchase of locally produced and offered goods and services’, which cover aspects of local communities, as an example. Several publications extracted from the literature review concerned sustainable development and measurement of PSS solutions (Chou et al., 2015; Hu et al., 2012; Sousa-Zomer and Cauchick Miguel, 2015; Xing et al., 2013). Important attention is given to the social dimension that should comprise indicators addressing user aspects (Sousa-Zomer and Cauchick Miguel, 2015). This may provide a basis for more work on consolidation of user-centric indicators for PSS measurements, hence being applicable to CE strategy ‘rethink business model’.

5. Discussion

The analysis presented above has highlighted several fundamental issues that provide an important perspective on the contribution of this article. First, the number of papers that satisfied the inclusion criteria in the systematic literature review constituted to only 2.5% of the total number of publications retrieved from the two search databases. Considering the inclusion of business processes into the search strings, it can be concluded that the *rejected* publications either proposed lagging indicators as sustainability performance measures or did not propose any indicators at all. These findings are in line with claims about the lack of consideration of leading indicators to support decision-making, including sustainability decision-making (Morioka et al., 2016; Morioka and Carvalho, 2016). Lagging indicators are widely employed by different assessments, e.g. environmental life cycle assessment (climate change indicator), business performance assessments (gross margin indicator) or organizational performance assessments (customer retention indicator) (Arena et al., 2013; Pojasek, 2009). While lagging indicators are essential for corporate reporting, as they indicate the performance and are generally applicable across the sectors, the caveat about using lagging indicators is that they might not indicate where to focus on to improve the performance (Epstein and Roy, 2001).

Second, there is a challenge directly related to the ambiguity of use of the term ‘sustainability’ in the manufacturing context, which is often reduced to environmental considerations. The results of this review highlight the prevalence of environmental indicators over economic and social, which is confirmed by the literature (Ahi and Searcy, 2015; Joung et al., 2013). This might be attributed, firstly, to the focus of the research dominating the sustainability field over the past 30 years. Since the release of the Brundtland Report in 1987, calling to pursue sustainable development, manufacturing industries began exploring tools and techniques to conduct sustainable manufacturing (Veleva and Ellenbecker, 2001). The goal then consisted of not only achieving and measuring the business success, but also finding a logic to measure progress towards triple-bottom line advancements. Secondly, many governments enacted regulations requiring manufacturing companies to track and report on many aspects on their environmental impacts (Ahi and Searcy, 2015). As a result, performance measurement systems included environmental indicators related to ‘internal’ operations, tracking energy, material, and water consumption and waste generation, which unquestionably reflected the efficiency of internal processes (Shahbazi et al., 2018). An interesting observation can be recorded in relation to indicators used in supply chain measurements. Ahi and Searcy (2015) made a comprehensive review of performance metrics used in sustainable supply chain (including supplier, manufacturer, distributor and retailer dimensions) measurements, reporting on the dominance of environmental indicators, followed by economic and lastly by social indicators. Indicators reviewed in their study showed that, despite of the supply chain focus, most of the indicators aligned with production-related indicators, such as ‘total material consumption’, ‘amount of waste generated’, etc. This uniform applicability of indicators can be explained by a ‘focal company’ view – a company

Table 2
Representative examples of performance indicators and their distribution according to CE strategies and triple bottom line dimensions and corresponding aspects.

Circular Economy strategy	Performance Indicator	Triple bottom line dimensions and corresponding aspects		
		Environmental	Social	Economic
Reinvent the paradigm	- First technical wear-out life			- Product quality
	- Availability of customer support option		- User relationship	
	- Active functions	- Product architecture		
Rethink business model	- Materials used during after-sales servicing of products	- Material consumption		
	- Spare Parts and Consumables	- Material consumption		
	- Maintainable period after sales		- User relationship	- Product quality
Reduce, restore & avoid impact in raw material and sourcing	- Suppliers that have completed hazardous substances information		- Supplier relationship	
	- Fraction of Renewable Raw Materials	- Material consumption		
	- Total material costs			- Operational costs
Reduce, restore & avoid impact in raw manufacturing	- Cost of transportation during Manufacturing			- Operational costs
	- Vibration at working station		- Employee health and safety	
	- Packaging materials from suppliers	- Material consumption		
Reduce, restore & avoid impact in raw product use & operation	- Cost of user education on use and post-use opportunities			- Tactical costs
	- Noise from product in use	- Energy consumption		
	- Existence of Manual with environmental instructions		- User relationship	
Upgrade	- Laminated or Compound Materials	- Material consumption		
	- Processing cost per unit			- Operational costs
Repair & maintenance	- Revenue from upgrade, repair and maintenance services			- Revenue
	- Specific Energy Consumption in operations	- Energy consumption		
Reuse	- Fraction of Reused Components	- Material consumption		
	- Total acquisition cost			- Operational costs
Refurbish	- Cost of non-destructive disassembly (CND)			- Operational costs
	- Energy consumption for disassembly	- Energy consumption		
	- Product Solid Waste Fraction	- Solid waste generation		
	- Mist/dust level at working stations		- Employee health and safety	
Remanufacture	- Cost of transportation in reverse supply chain			- Operational costs
	- Exposure to corrosive/toxic chemicals		- Employee health and safety	
	- Fraction of Reused Components	- Material consumption		
Repurpose	- Active functions	- Product architecture		
	- Product Hazardous Materials	- Material safety		
Recycle	- Cost of recycling			- Operational costs
	- Transportation cost from facility to recycling plant			- Operational costs
	- Waste converted to Reusable Material	- Solid waste generation		
	- Specific Water Consumption	- Water consumption		
Recover	- Load mode of transport	- Energy consumption		
	- Energy generated with process streams	- Energy consumption		
	- Cost of disposal			- Operational costs

that is in control of design of products and services offered (i.e. the brand owner), however with production processes situated elsewhere in supply chain. Focal companies, therefore, tend to govern a supply chain to ensure the brand reputation is uncompromised due to unsustainable behaviour (Reefke and Trocchi, 2013). The divergence of definitions of supply chain and its boundaries elucidate a substantial confusion when searching for indicators addressing supply and distribution side of production. While larger focus on environmental aspects and impacts is definitely a positive implication, interchangeability between terms ‘environmental’ and ‘sustainable’ could lead to a ‘simplification’ of sustainability. Furthermore, a mass of publications revealed confusion in terms of inconsistent nomenclatures and indicator definitions per se, suggesting ‘customer satisfaction’ or ‘increased safety’ as indicators while the former is a dimension of performance and latter is merely an objective or goal to be achieved.

Despite the prevalence of the environmental dimension and a broad range of aspects addressed under it, none of the retrieved indicators covered the ‘land use’ aspect, and only one indicator covered ‘soil pollution’ aspect. These categories could be important to address from perspective of manufacturing actors belonging to bio-economy sector, i.e. industries that use biological resources from land and sea to produce, for example, food (European Commission, 2018).

There is clear asymmetry between the TBL dimensions covered by indicators. The social dimension is underrepresented by indicators, which mostly capture ‘internal’ matters, such as employee empowerment and employment conditions. This could be due to the fact, that ‘internal’ social aspects are more ‘quantifiable’, with indicators ‘overtime work’, ‘temperature level at working stations’ and ‘employee health and safety training hours’ lending some credence to this argument. ‘External view’ indicators capture social aspects, such as community, supplier-user relationships, however are low in numbers, especially in the user related aspect. This can be due to a ‘qualitative’ nature of ‘external’ aspects, often difficult to measure objectively. Considering the importance of users and communities in the CE context, who are seen as enablers of CE (Kirchherr et al., 2017), it may be necessary to include metrics addressing community and user relationships devoted to, for example, quality of life as well as user privacy.

In relation to economic indicators, there is an evident preference for measuring cost-related aspects, such as operational and tactical costs (‘energy cost in manufacturing’, ‘total holding costs’, ‘material cost per unit of product’, etc.), which can be explained by, in part, wider focus on efficiency (i.e. eco-efficiency) and cost minimization in manufacturing industry (Joung et al., 2013), but also by being a natural part of accounting and cost-benefit assessments. Likewise, it may be pointed out that there is a need to address the development of economic indicators capturing the user perspective (e.g. costs and revenues), which again are important in the CE context, as users become more active players in the system by delivering value back (Haase et al., 2017; Xing et al., 2013).

The results of classification of indicators according to business processes revealed several shortcomings. Despite the availability of indicators capturing all three TBL dimensions, there is a lack of indicators available for the use during product development and business model development processes. As for the product development process, environmental indicators are dominant and reported mostly on by the literature from eco-design and life cycle community (Arena et al., 2013; Fiksel et al., 1998; Issa et al., 2015). This can be explained by the evidence that product design stage is a critical time for addressing environmental, social and economic impacts of a product during its all life cycle stages (McAloone and Pigosso, 2018); therefore, sustainability-related indicators can support designers in assessing the potential sustainability performance of the product prior to its production and subsequent utilization. Environmental indicators available for product development are largely devoted to measuring material type and consumption, resource consumption, waste and pollution generation, and physical properties and attributes of products (i.e. product architecture) (Badurdeen et al., 2015; Hallstedt, 2017). Issa et al. (2015) made a comprehensive review of leading environmental product-related indicators, which were collected in a database and classified according to life cycle stages and environmental aspects. The aim of their study was to support product developers to implement eco-design in a measurable way. Contrariwise, social indicators are scarce for the product development process, with only few studies addressing the social dimension by proposing checklists or guiding questions to be deployed during product development process (Hallstedt, 2017). There is clear need to develop and introduce social indicators (qualitative and quantitative) that can be used during product development process in order to ensure three-dimensional consideration of sustainability.

As for business model development, the total number of indicators are deficient. While economic and social dimensions are equally covered, environmental indicators are non-existent. Various publications focus on designing business models for sustainability that often rest on the notions of creating significant positive environmental and social impacts while maximizing values for all stakeholders (Bocken et al., 2014; Lüdeke-Freund, 2010), however propositions of how to measure potential sustainability contribution of such business models are still lacking (Evans et al., 2017). Lack of explicit indicators for the business model level can be justified by a relatively recent deployment of business model as a term (Wirtz et al., 2016), with scattered identification of what dimensions a business model should consist of and what its main features are. Pieroni et al. (2019) report that decision-making during business model development mostly relies on qualitative data. Availability of sustainability indicators (qualitative and quantitative) is fundamental in the business model design stage to ensure that a company assesses value for sustainability (through operations, products or both) (Ludeke-Freund et al., 2017).

The results of the classification of indicators according to CE strategies revealed several patterns. Firstly, most CE strategies (e.g. ‘reduce, restore and avoid impacts in: raw material and sourcing; -manufacturing; - product in use stage’; upgrade’, ‘repair and maintenance’, ‘re-use’, ‘refurbish’, ‘remanufacture’, ‘repurpose’, ‘recycle’ and ‘recover’) have a fair alignment between activities they explicate and indicators for performance measurement of those activities. For example, the indicator ‘energy consumption for disassembly’ addresses the activity explicated by the CE strategies ‘refurbish’, ‘remanufacture, and ‘recycle’; while the indicator ‘first wear-out life’ addresses the aspects explicated by the CE strategies ‘reinvent the paradigm’, ‘rethink business model’, and ‘reduce, restore and avoid impacts in product in use stage’. Environmental indicators prevail for the majority of CE strategies due to the overall dominance of environmental indicators extracted from the literature.

Noteworthy, CE strategies with focus on product use (i.e. ‘reinvent the paradigm’, ‘reduce, restore and avoid impacts in product in use stage’, ‘re-use’, and ‘repurpose’) are scarce on social indicators, despite the importance of the user's role and impact during use of and interaction with a product. At the same time, there is a reasonable coverage by social indicators for CE strategies ‘rethink business model’, ‘reduce, restore and avoid impacts in manufacturing’, ‘upgrade’, ‘repair and maintenance’, ‘refurbish’, ‘remanufacture’, ‘recycle’ and ‘recover’. This might be attributed to the fact that the activities explicated by those strategies are labour-intensive, therefore, social indicators capture employee-related aspect to a wider extent than, for example, strategies explicating

Table 3
Summary of the key findings identified through the study.

Research area	Key findings
Sustainability performance indicators	- There is a need for a wider deployment of leading performance indicators in sustainability assessments. Leading indicators offer useful information about the potential sustainability performance of a solution, thus are effective for early decision-making and management of processes.
Environmental dimension of sustainability	- Land use oriented and soil pollution indicators are non-existent. This category of indicators is crucial to address from the perspective of manufacturing actors from bio-economy sector (e.g. using biological resources for food production).
Social dimension of sustainability	- Indicators for social dimension are scarce and mostly focus on "internal" stakeholder groups (i.e. employees). Indicators capturing "user-related" and "community relationships" aspects should be expanded, as they are crucial considering the role of users and communities as enablers of Circular Economy.
Sustainable Business Model support	- Indicators capturing environmental performance are non-existent for business model level. Availability of sustainability indicators (qualitative and quantitative) is fundamental in business model design stage to ensure a company can create value for sustainability (through operations, products or both).
Sustainable Product Development support	- Social indicators are non-existent for product development level. In order to operationalize corporate sustainability objectives, product development techniques and tools should incorporate three sustainability dimensions simultaneously to be used by designers.
Circular Economy	- There are numerous frameworks that provide lists of CE strategies applicable in a manufacturing context. While some CE strategies seem to be unequivocal in what they entail (e.g. 'reduce impact in manufacturing'), other CE strategies might need a detailed elaboration on what they necessitate (e.g. 'reinvent the paradigm').
Sustainability indicators for Circular Economy	- Leading sustainability-related performance indicators are available for a wide range of Circular Economy strategies: ▪ distribution and nature of indicators is aligned with the 'activities' explicated by the CE strategies ▪ availability of indicators makes it possible to extract the indicators meaningful to the circular solution(s) in focus. - Indicator classification according to CE strategies and business process allows the configuration of different combinations of circular solutions to be exploited in various business processes, thus displaying a suitable set of sustainability performance indicators relevant for business and/or operational levels.

use of a product ('re-use'). As discussed in Section 4.4., the CE strategy 'rethink business model' advocates shift of value offering from selling products to selling access and performance enabled by product-service system (PSS) business models. Therefore, is it important to capture different aspects of a PSS offering, such as 'behaviour' of a product in a PSS, material and energy consumption and costs associated with the provision of a PSS (Elia et al., 2017; Kjaer et al., 2018). The findings reveal that the CE strategy 'rethink business model' is well captured by environmental and social indicators that could allow verifying the effectiveness of a PSS solution; however, this may need to be complemented by more indicators addressing the economic dimension.

In order to evaluate whether the retrieved indicators are sufficient for sustainability assessment of CE initiatives, it is important to apply indicators that are suitable for a combination of business processes and CE solutions. Therefore, this research is a first attempt to propose the assessment of the potential sustainability performance of CE strategies in the early decision-making stage and is mainly differentiated by: (i) its focus on leading indicators; (ii) the consideration of the TBL approach: (iii) the emphasis on primary business processes that are typical for any manufacturing company; (iv) the consideration of variety of CE strategies applicable in a manufacturing context. The summary of key findings identified in the study are presented in Table 3.

6. Conclusions

This research aimed to identify and systematize leading performance indicators that could be used to measure the potential sustainability performance of CE strategies, in order to support decision-making process in manufacturing industry. The research methodology was rationalized by a systematic literature review with the goal of identification and collection of leading performance indicators covering environmental, economic and social dimensions for a range of business processes. As a result, identified publications were critically assessed and 279 leading performance indicators were extracted and systematized in a database, with consequent classification according to: TBL dimensions and their related aspects; business processes; and CE strategies. This classification allows the configuration of different combinations of circular solutions to be exploited in various business processes, thus displaying a suitable set of sustainability performance indicators to be measured early in the decision-making stage. All the indicators available in the repository have their name, detailed description, formula, unit of measurement, and purpose of measurement registered.

The main findings of this research are: (i) sustainability assessments often rely on lagging indicators, which may not provide the exact indication for practitioners on where to make an improvement; (ii) sustainability performance indicators frequently measure 'internal' company's affairs: cost, eco-efficiency and social matters; (iii) the environmental dimension is the most covered by indicators; (iv) product development is well represented by product-related performance indicators, the majority of which are environmental indicators, while social indicators are scarce; (v) there is a lack of indicators to support decision-making during the business model development process, with indicators for environmental dimension being non-existent; (vi) there are suitable sustainability indicators for each CE strategy adopted in this study.

By systematizing a comprehensive database of leading sustainability-related performance indicators, the research offers contributions to: (i) academia – by proposing to advance discussions towards a wider inclusion of leading indicators into sustainability assessments as well as to proceed with indicator developments; (ii) industry – by providing a set of leading performance indicators to be deployed in decision making during various business processes and for CE strategies. We assert that leading performance indicators provide a better insight into strengths and weaknesses of the circular solution thus would enable more informed and balanced decision-making for sustainability.

Some limitations of this research can be pointed out. Firstly, the indicators were extracted directly from the academic literature without consulting the 'grey' literature sources and practitioners' archives. This limitation can be addressed by expanding the search scope to include corporate surveys and 'grey' source databases. Secondly, the CE strategies framework modified from Potting et al. (2017) served as one of the indicator classification criteria. Use of the CE strategy framework has guided the authors in the classification logic, largely affected by the number of strategies chosen in the framework as well as the descriptions of what they entail. It is apparent that utilization of any other CE strategy framework would lead to a different distribution of performance indicators. Finally, usage of a straightforward TBL approach for indicator classification may possess the risk of separating the indicators rather than integrating them for a holistic interpretation of sustainability. We do, however, acknowledge that most indicators capture cross-dimensional concerns (e.g. socioeconomic issues of supplier selection), which may be investigated by finding interdependencies between indicators in future research.

This study is a first step to identify and classify leading sustainability related-indicators according to business processes and CE strategies. We assert that transforming to CE is a complex process that requires thoughtful planning and evaluation, which necessitates the ability of decision makers to have better insights into organisational processes and circular solutions that will most likely contribute to sustainability. Leading performance indicators should be viewed as carriers of useful and measurable information to support the process of decision-making under complex circumstances. In order to effectively capture and measure the potential sustainability performance of CE strategies, it is important to aid the identification of the core performance indicators suitable for a particular CE solution or a combination of thereof during a particular business process. The database of performance indicators is a first building block of a foundation for sustainability screening framework that also comprises the procedure for a systematic indicator selection and procedure for decision-making for sustainability in a CE context. Therefore, the next step within the frame of this research is to develop a framework for a systematic indicator selection, to facilitate meaningful application in industry. The proposed approach will subsequently be tested with actors from manufacturing companies, to identify the usefulness of the proposed indicators and usability of the selection procedure. This study is a part of a broader research activity, aimed at developing a framework to support early decision-making for CE with a holistic sustainability consideration. This support framework should underpin the universal yet context-dependent and transdisciplinary nature of sustainability, with CE as promising means to reinforce the sustainability pursuit.

Acknowledgements

This article is one of the outcomes of the research project CIRCit (Circular Economy Integration in the Nordic Industry for Enhanced Sustainability and Competitiveness), which is part of the Nordic Green Growth Research and Innovation Programme (grant number: 83144), jointly supported by NordForsk, Nordic Energy Research, and Nordic Innovation. The authors would like to thank the CIRCit consortium partners for enriching discussions about CE and sustainability.

Appendix A

Search strings consisting of the key words used in Scopus and Web of Science

All in all the search string in Scopus is as presented and results in 521 documents	All in all the search string in Web of Science is as presented and results in 145 documents
((TITLE-ABS-KEY ((“key performance indicators” OR “performance measure*" OR “performance indicator” OR “performance evaluation” OR “performance assessment”) AND (“sustainab*" OR “triple bottom line” OR “social” OR “environment*" OR “econom*") AND (“business model” OR “product dev*" OR “end of life” OR “value chain”)))) AND (LIMIT-TO (SUBJAREA, “ENGI ") OR LIMIT-TO (SUBJAREA, " ENVI ") OR LIMIT-TO (SUBJAREA, " BUSI ") OR LIMIT-TO (SUBJAREA, " SOCI ") OR LIMIT-TO (SUBJAREA, " ECON ") OR LIMIT-TO (SUBJAREA, " DECI "))	TI=(key performance indicators OR indicator OR metric OR index OR indices OR measure* OR assessment OR evaluation) AND TI=(sustainab* OR triple bottom line OR environment* OR social OR economic) AND TI=(business model OR product development OR “end of life” OR value chain)

Appendix B

Circular Economy strategies: the list of strategies used for indicator classification and their definitions. Source: modified from Potting et al. (2017).

Reinvent the paradigm	- can be seen as the one of a radical type, with practices that advise striving for full decoupling of resources by “reinventing” the production and consumption patterns. Here the business is centered on providing the same function or combined functions to the customers, often enabled by radically different products (virtualized multifunctional non-physical), technology or both. Furthermore, the focus can also be on promoting sufficiency, e.g. promoting moderate consumption through education and consumer engagement. Potting et al. (2017)
Rethink business model	- a strategy that focuses on making product use more intensive by rethinking the way of delivering the function and/or value proposition (e.g.: performance or access based models, sharing platforms). Products tend to not radically change, although the technology can evolve. (Bakker et al., 2014; Bocken et al., 2016)
Reduce, restore & avoid impact in Raw material and Sourcing	- a strategy that aims at reducing, restoring and avoiding impacts in raw material and sourcing. The activities include material selection for products and packaging by using alternative materials as: renewable, recyclable material; materials from secondary source sourcing (recycled materials, Industrial Symbiosis); restorative sourcing (use of materials previously designated as ‘waste’ as input, e.g. waste re-mining from landfill or using ocean plastics); use of non-toxic or benign materials; use of the lowest suitable grade of materials suitable for the application. Lieder and Rashid (2016)
Reduce, restore & avoid impact in Manufacturing	- a strategy that aims at improving circularity potential and process efficiency in product manufacture through: consuming fewer natural resources or energy, appropriate treatment of emissions and waste, recycling and reusing wastes and scrap on site (pre-consumer, or internal recycling and reuse), recovery of energy and nutrients; eco-friendly transport and driving. Lieder and Rashid (2016)

(*continued*)

Reinvent the paradigm	- can be seen as the one of a radical type, with practices that advise striving for full decoupling of resources by "reinventing" the production and consumption patterns. Here the business is centered on providing the same function or combined functions to the customers, often enabled by radically different products (virtualized multifunctional non-physical), technology or both. Furthermore, the focus can also be on promoting sufficiency, e.g. promoting moderate consumption through education and consumer engagement. Potting et al. (2017)
Reduce, restore & avoid impact in Product in Use	- a strategy aiming at improving circularity potential and efficiency in product use and operation through: wiser use and operation of products (usually enabled by data technologies: tracking, sensors), efficient resource consumption during operation (energy, water, consumables). Lieder and Rashid (2016)
Recirculate products and parts by: - Upgrade	- a strategy aiming at extending existing use cycle by adding value or enhancing the function of a product in respect to previous versions (can involve aesthetic or functional upgrades which usually do not involve disassembly). For the purpose of the tool, the upgrade implies returning/keeping the product at the original user. Parkinson and Thompson (2003)
Recirculate products and parts by: - Repair and maintenance	- a strategy aiming at extending existing use cycle by countering wear and tear, and correcting faulty components of a defective product/part to return it to its original functionality. The process may require partial disassembly, cleaning, and inspection. For the purpose of the tool, the repair and maintenance implies returning/keeping the product at the original user. (Thierry et al., 1995)
Recirculate products and parts by: - Reuse	- a strategy aiming at extending to new use cycle by reusing a part/product (discarded/not in use) that is still in good condition and can fulfil its original function in a different use context (new customer/user). Before the part/product is offered for reuse, it may involve a minimum amount of condition monitoring such as cleaning or repackaging. No warranties are provided and no disassembly is involved). Ijomah (2009)
Recirculate products and parts by: - Refurbish	- a strategy aiming at extending to new use cycles by returning a part/product (discarded/not in use) to a satisfactory working condition that may be inferior to the original specification. Refurbishing may involve: cleaning, partial disassembly, repairing, resurfacing, repainting, re-sleeving. Saavedra et al. (2013)
Recirculate products and parts by: -Remanufacture	- a strategy aiming at extending to new use cycles by returning a product (discarded/not in use) to at least Original Equipment Manufacturer (OEM) performance specification and quality. Remanufacturing normally is more rigorous and costly than refurbishment and involves total disassembly and reassembly. In the case of traditional product sales, a warranty that is at least equal to that of a newly manufactured equivalent may be issued). Saavedra et al. (2013)
Recirculate products and parts by: - Repurpose	- a strategy aiming at extending to new use cycles by using a product (discarded/not in use) or its parts for different functions. Before the part/product is offered for repurpose, it may involve a minimum amount of condition monitoring such as cleaning or repackaging. Reike et al. (2018)
Recirculate materials by: - Recycling	- a strategy aiming at extending material lifespan by processing them in order to obtain the same or comparable quality of material to be applied back in the industrial processes. In this framework recycling concerns recycling of materials coming from used products, e.g. post-consumer recycling as opposed to pre-consumer recycling done in manufacturing stage. (Allwood et al., 2011)
Recirculate materials by: - Recovery	- a strategy aiming at recovering energy or nutrients from composting or processing materials (e.g. incineration of combustible waste, pyrolysis, anaerobic digestion or composting to recover biological nutrients. (Reike et al., 2018)

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3.2. Results for Study B

3.2.1. A procedure to support a systematic selection of leading performance indicators

By triangulating the findings from the literature with the results of the multiple-case study, a procedure for indicator selection was developed and refined, thus contributing to RQ.3: How to support a systematic selection of relevant sustainability performance indicators for early stage sustainability screening of CE initiatives? The final version of the procedure with corresponding steps and their argumentations is summarized below. The final procedure for indicator identification, selection and application consists of the three major steps and several sub-steps as depicted in Figure 8.

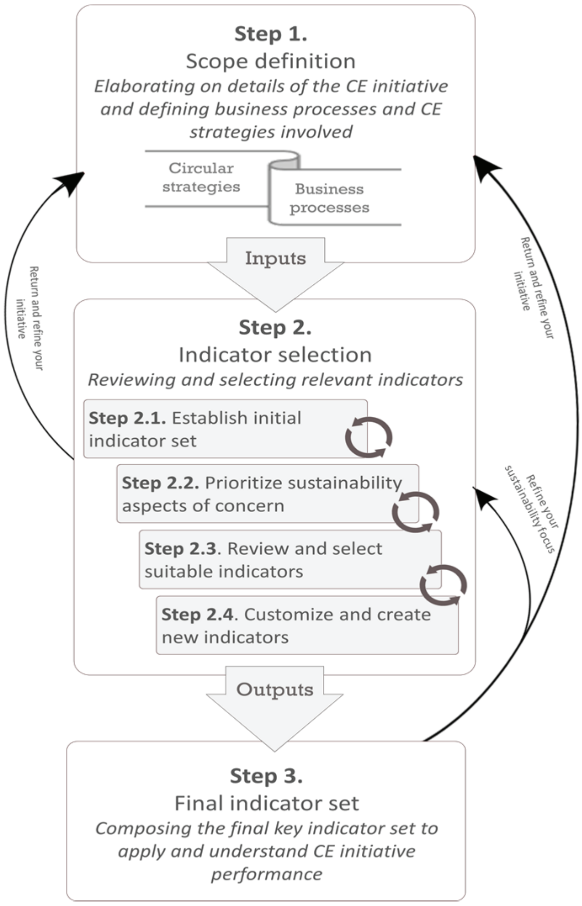

Figure 9. The final version of the indicator selection procedure – enhanced after empirical application, with key steps and elaborated activities (as published in Kravchenko, Pigosso and McAloone, 2020)

Step 1: Scope definition – elaborating on a CE initiative

Step 1 serves as an input to indicator selection and prioritization process, because it helps scoping a CE initiative in focus and determine key actors for indicators selection. Firstly, this step requires detailing a proposed CE initiative by indicating what CE strategies are involved and what business processes are affected. This is facilitated by a set of guiding questions about activities envisaged for a CE initiative in focus, which helps selecting relevant CE strategies and business processes. This step was developed taking into account the feedback from the case studies as following: industrial practitioners might not operate with the same definitions of CE strategies considered in the research; therefore, the questions about activities help arriving at CE strategies to be used for indicator selection. Once identified, these selections can be used as inputs to Step 2 to explore initial sets of suitable indicators. Step 1 also facilitates formulation of a set of key questions using the combinations of identified CE strategies and business processes, which can support indicator selection process. This helps creating the alignment between the selected indicators (later in the process) and the scope, which affects the likelihood of inclusion of sustainability indicators in the decision process (Shields, Šolar and Martin, 2002; Watz and Hallstedt, 2020). Additionally, Step 1 requires establishing a baseline ('as-is') system as a point of reference to compare the potential sustainability performance of a proposed CE initiative using the indicators. A possibility to compare several initiatives should indicate what TBL aspects are positively and negatively affected, to assist the improvement and selection of the initiative closely aligned with the company's corporate approach to sustainability (Arena, Azzone and Conte, 2013).

Step 2: Reviewing and selecting relevant indicators

This step focuses on indicator review and selection, which is done through several sub-steps allowing to gradually selecting the most relevant indicators for the proposed CE initiative using the scope outlined in Step 1. This step is supported by the 'Leading performance indicator database', which should be used to establish an initial indicator set and select priority aspects and relevant indicators. In sub-step 2.1., a combination of 'selection' filters should be applied according to the combinations of identified CE strategies and business process, guided by the key questions formulated in Step 1. Filtering allows to automatically reducing the number of indicators applicable to the selected combinations, thus removing unsuitable indicators for the scope that is in focus. Sub-step 2.2. was proposed to reduce the complexity of the review process associated with indicator diversity due to the inclusion of economic, environmental and social aspects. Therefore, the sub-step highlights the prioritization of sustainability aspects, i.e. aspects of high priority, the prioritization of which should be guided by the contextual settings, such as the specifics of the sector, company, process, product or service, the selected circular economy initiative or by the results of past sustainability assessments (e.g. a life cycle impact assessment, social life cycle assessment). Although the significance of a balanced TBL inclusion (Gibson, 2010), it may be beneficial to focus on one dimension (e.g. environmental) at a time (Arena et al., 2009), analysing a broad spectrum of the aspects (e.g. energy and waste, toxicity and wastewater, etc.) under a single TBL dimension. The prioritization requires a dialogue between decision makers about what sustainability aspects are significant for the proposed initiative and the company. This sub-step is iterative, which implies that it is possible to proceed with other steps to select relevant indicators for one dimension only and return to sub-step 2.2. to prioritize other dimensions to ensure a holistic TBL consideration.

Sub-step 2.3. was developed to assist review of each indicator available from sub-step 2.2. The review and evaluation of indicators is a thorough process that requires operating with and iterating the details and key priorities outlined in previous steps. The indicators attributes registered in the database, such as descriptions of each indicator, units of measurement and the purpose of measuring, provide an in-depth understanding of each indicator, thus supporting the review process. Moreover, a set of guiding questions was developed to support the review process, focusing on analytical validity (relevance for the contextual settings), and data availability (measurability). These questions aimed at supporting selection of highly relevant indicators consistent with the corporate and decision-makers needs and ability to use in the development processes. Moreover, the guidance ensures selection of a manageable number of indicators, which should be between 7 and 15 (maximum 20) to provide a basis for actions (Veleva et al., 2001). Due to the nature of indicators in the database being non-sector specific, some indicators may need to be customized or created (Issa et al., 2015), therefore, sub-step 2.4. was proposed. Indicator customization and creation step is encouraged to help addressing particularities of: i) a proposed CE initiative and its objectives; ii) the sector; iii) corporate processes, products and operations. For customization, an existing indicator can be adapted, while a new indicator can be created to reflect the above-mentioned particularities. Sub-steps under Step 2 are iterative steps, which allows reiterating key considerations and issues related to a particular CE initiative and its details; iterations encourage learning about own operations and products and what matters the most for the particular context (Pavlov and Bourne, 2011).

Step 3: Composing the final indicator set

To support indicator application for sustainability screening, a final checklist was proposed to ensure the final indicator set is relevant and comprehensive for the scope selected in Step 1. The checklist should be used to evaluate the final set on its comprehensiveness in terms of a number of indicators, their relevancy, and coverage of the TBL dimensions. After the review step, the final set should be implemented and used to compare the performance of the proposed initiative with the baseline and other alternatives.

Reflection on the contribution

By completing the procedural steps, manufacturing actors should be able to select relevant indicators for measuring sustainability performance of the proposed CE initiatives in a systematic way. Motivated by the lack of integration of the TBL measurements in the early stages of CE development as well as the insufficient focus of measurement frameworks on supporting a dynamic indicator selection process (as highlighted in gaps in Chapter 1.1.), this study brings attention to the contextual selection of sustainability indicators. The contribution of this study lies in the following: firstly, it provides an opportunity to identify and apply relevant indicators for *a combination of CE strategies*, which addresses the methodological challenges brought up by the literature (Blomsma and Brennan, 2017; Elia, Gnoni and Tornese, 2017); secondly, it employs a business processes view, which helps detecting indicators to *support decisions across business processes* to synchronize the development of a CE initiative (Bocken *et al.*, 2016). Thirdly, it supports a *contextual selection* of relevant indicators (sub-steps under Step 2), which increases the likelihood of indicator inclusion in the decision process (Shields, Šolar and Martin, 2002). The relevancy of an indicator is defined by both, its relevancy for the corporate objective and for the end user of the indicator (e.g. product designer) (Pavlovskaia, 2014). The procedural steps, therefore, emphasize the contextual settings (e.g. corporate objective and sectorial particularities, decision makers expertise, past sustainability assessment results, etc.) to support indicator selection and application. Additionally, the procedure does not only support selection and review of single indicators, but indicators as a set, which helps to ensure a manageable number of indicators as well a balance between different TBL dimensions and/or different aspects within the dimensions (Niemeijer and de Groot, 2008).

The detailed process of the procedure development, examples of the application with case companies and their final indicator sets as well as the reflection on the key learnings and limitations of the study were documented in a journal publication - Paper 2, which is embedded next.

Paper 2: *Kravchenko, M., Pigosso, D. C. A., & McAloone, T. C. (2020)*

Procedure to Support Systematic Selection of Leading Indicators for Sustainability Performance Measurement of Circular Economy Initiatives.

Sustainability, 12*(3), 951* *https://doi.org/10.3390/su12030951* *sustainability*

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A Procedure to Support Systematic Selection of Leading Indicators for Sustainability Performance Measurement of Circular Economy Initiatives

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Received: 8 January 2020; Accepted: 22 January 2020; Published: 28 January 2020

Abstract: Circular economy (CE) is considered a vital model to tackle resource scarcity and reduce waste by promoting strategies that redefine production and consumption systems. Industrial actors integrate CE principles in their strategic and operational practices to overcome these challenges, simultaneously aiming at enhancing their sustainability performance. Despite numerous frameworks to guide organizations in innovating towards CE, very few have embedded explicit sustainability considerations to assist practitioners in understanding the potential sustainability performance of the CE initiatives early in the development process. To assist a structured process of measuring sustainability performance, the main goal of this paper is to propose a procedure for a systematic selection of suitable leading performance indicators to support an informed sustainability-oriented decision-making process. To fulfill this aim, a hypothetical-deductive approach has been followed to, firstly, develop the selection procedure, and secondly, evaluate and improve it using a case study approach. The findings reveal that the procedure enables a systematic selection of relevant indicators by taking into account the manifold combinations of CE strategies and business processes, characteristics of the company and its sustainability objective. Different from many other approaches, the novelty lies in relying on a dynamic, as opposed to 'prescriptive', indicator selection process to induce learning about sustainability considerations significant for a particular CE initiative and corporate context.

Keywords: sustainability performance; leading indicators; selection procedure; circular economy; decision-making support

1. Introduction

A challenging and fast-changing global market pushes companies to become proactive by exploring and exploiting new mechanisms to enhance their competitive advantage. Competitive advantage is rooted in a company's capability to manage tangible and intangible resources [1], constantly responding to global demands and issues, including natural resource constraints, pollution and fair wealth distribution. It is no longer a question of whether the pursuit of an economic activity ought to be done sustainably, rather it is a process of exploring (what), planning (where) and implementing (how) various sustainability strategies. Along the process, manufacturing companies in Europe have shown a significant improvement in reducing their environmental impact per economic output generated [2], however, the challenge is still great, with respect to minimizing the impact, when taking into account upstream (e.g., supply of resources) and downstream activities (e.g., end of life processes). One promising approach to overcome these challenges is seen in a new economic model, circular economy (CE), which implies a radical innovation of production and consumption systems with the goal of decoupling resource consumption from value creation [3]. For the European manufacturing industry, which spends an average of 40% of its costs on raw materials and about 15% on energy and water [4], adopting CE practices focused on resource productivity can positively impact economic and environmental performance. Furthermore, CE entails strategic transformation, by means of which the industries will be able to create new revenue streams and retain the value embedded in their products and assets for longer [5].

Different conceptual and practical frameworks have been proposed to guide companies on how to embed CE principles, often called CE strategies, into their business context [6], with the emphasis on the simultaneous transformation of strategic and operational practices. Acknowledging the complexity of such transformation, numerous studies have developed tools to support business model innovation for CE [7,8], product design for CE [9,10], value chain design and mapping [11,12]. Due to the inherent focus of CE on combining business logic with environmental performance (i.e., reduced burden), many studies refer to CE as one of the most important strategies to achieve sustainable development: [13] and [10] state that circularity in business models, products and supply chains is a "precondition for sustainable manufacturing and sustainable economy". Nonetheless, to ensure a CE solution can contribute positively to sustainability, it needs to be planned with sustainability considerations and intentions in mind [14] and assessed on its sustainability performance prior, during and after implementation [15]. So far, studies have concentrated on proposing methods to assess CE performance at a corporate level [16,17], at a product level [18,19] or at a material level [20]. However, due to the intrinsic focus of CE on value and material preservation [21], most of the proposed methods focus on measuring material consumption [22], with recycling being the most dominant CE strategy considered [23]. Additionally, the challenge lies in measuring the social dimension, which remains largely uncovered by the proposed indicators and methodologies [21,23]. To address these limitations, [24] have attempted to understand whether existing leading sustainability-related manufacturing indicators can be employed to measure a wide range of CE strategies from a social, economic and environmental perspective. By being able to retrieve more than 270 indicators and categorize them according to CE strategies ranging from dematerialized and function-oriented strategies through recycling and recovery, the findings revealed that each strategy can be measured by a set of indicators that cover each TBL (triple bottom line) dimension. However, to ensure a meaningful set of indicators is applied anytime a specific CE initiative is being developed, support should be developed. Research on sustainability assessment and indicators [25,26] highlights the importance of a dynamic information selection processes as opposed to 'prescriptive' approaches, because, firstly, every project will have different sustainability concerns [25], and, secondly, decision makers will be able to make more informed decisions if they use information they have critically analyzed and prioritized.

The main goal of this paper is, therefore, to advance the assessment of CE by deploying leading sustainability performance indicators. This is done by proposing a step-by-step procedure to support a systematic selection of suitable sustainability-related performance indicators for CE initiative screening. The selected indicators are intended to help in measuring the potential performance of a CE solution in the early stages of its development, thus enabling identification of major areas to introduce improvements to before the implementation. A new approach to procedure development takes into account the complexity of multiple sustainability criteria to be considered whenever a new CE solution is proposed by bringing together elements of different TBL dimensions, thirteen CE strategies, and five business processes. Furthermore, the approach considers specifics of the company (its sector, processes, products, and services) to ensure the assessment process is meaningful for the decision context. Thus, this study contributes to the field of indicator-based sustainability assessment considering the innovative lens of CE, by taking into account the needs and roles of industrial practitioners in the CE transition process.

The paper is structured as follows: Section 2 explains the research method and materials, served to underpin the development of the procedure, Section 3 describes the developed procedure with detailed step-by-step elaborations, Section 4 describes the application of the procedure in the selected companies, Section 5 provides discussions about key findings and contribution of the study, highlighting limitations and considerations for future research.

2. Research Methods

The research method adopted for this study can be described in two parts. Firstly, the research approach, including method and materials employed are detailed, before, secondly, providing an overview of the leading indicator database—previously compiled to assist selection of significant sustainability aspects and corresponding indicators—plus a summary of key recommendations that served as underpinnings for the development of the procedure to be followed, when selecting leading sustainability performance indicators.

2.1. Research Approach

A hypothetical-deductive approach [27] was followed to develop and evaluate the procedure based on a number of iterations that included a mix of research methods. This approach is used to construct an inquiry-based on existing theories and knowledge (Section 2.2.), proceeding by formulating a hypothesis that is then tested to explore the consequences of the generated inquiry [28]. The theory in this study is the procedure for indicator selection, and the hypothesis to be tested is that "the classification of sustainability-related leading performance indicators according to CE strategies, business processes and TBL aspects and the corresponding procedure can support manufacturing companies in the selection of suitable sustainability indicators for CE initiative assessment". The sustainability assessment of CE is based on an indicator approach with the foundation on the consolidated database of leading performance indicators, as a deliverable of the research Stage I, published in [24] (Figure 1). The development process, followed to create the procedure, Stage II, was initiated, firstly, by consulting the literature to identify the requirements for the indicator selection approach in the context of sustainability assessment, considering CE and business process perspectives, followed by the development of a procedure 'prototype' that was tested with experts and led to the conceptualization of the step-by-step procedure (presented in Section 3), which was tested with the help of case studies and iteratively improved, Stage III (presented in Section 4).

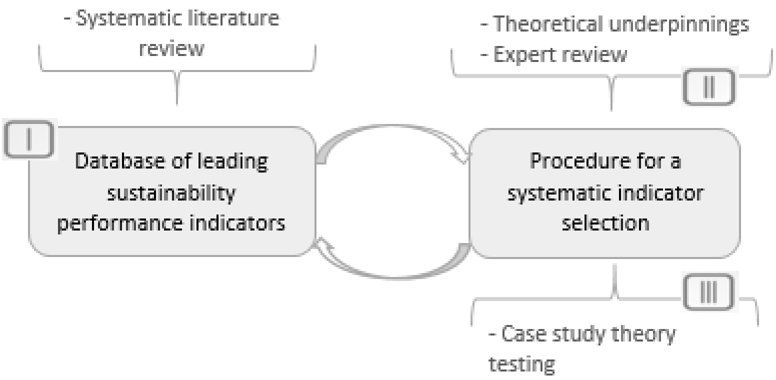

Figure 1. Conceptual framing of the procedure development process.

2.1.1. Case Study for Theory Testing

A multiple case study approach has been selected to test the usefulness of the procedure in guiding the selection of suitable indicators. The main objective of the approach was to continuously identify improvement opportunities following the feedback after each application (iterative approach). The final version of the procedure is described in Section 3. The improvement opportunities after the case study application are summarized in Table 2 Section 4.1.

To ensure the case study confirmability, transferability and credibility, the methodology provided by [29] and [30] has been followed. A case study protocol was developed, documenting the case study design and execution (e.g., criteria for case selection, data sources, data collection methods and period, data analysis).

2.2.2. Case Study Set-Up: Case Selection, Data Collection and Analysis

To qualify as suitable case study candidates, the companies had to satisfy the two main criteria: (i) the company's core activity is to design, develop and/or manufacture capital and/or consumer goods (i.e., belong to the secondary industry), and (ii) the company has identified one or several CE solutions to be implemented. Finally, the case selection was guided by initial contacts, which ensured the company expressed an interest in understanding the sustainability implications of the selected CE initiatives. As a result, our empirical investigation involved three Nordic manufacturing companies.

Each case study involved identical activities and similar types of data collection. The number of participants differed across cases (mainly due to company size), ranging from 2 to 6. The goal was to form a multidisciplinary team, which included participants who had expertise in the area affected by the selected CE solution (e.g., product designers participated whenever the CE solution concerned product design with circular materials) as well as those who had expertise in working with sustainability-related issues, e.g., environmental managers or sustainability 'steward' from the company. Data collection was initiated by using primary and secondary sources, which allowed for triangulation to elicit verification of the theory and the hypothesis [31]. Secondary data were collected by doing desk research to gain insights about the companies and their activities before meetings. Secondary data included companies' websites, reports, and other publicly available information. Primary data were collected during face-to-face interactions during online meetings and on-site visits, designed as participatory workshops, which focused on applying the selection procedure and recording feedback, as described in detail below.

Participatory workshops were conducted in three steps: (1) initial exploration session for defining the scope for indicator selection (3-h session), (2) Workshop A on indicator selection (6-h session), (3) Workshop B on indicator application and interpretation (6-h session) (Figure A1, Appendix A). The purpose of the initial exploration session was to establish a solid ground for prospective workshops by: (i) aligning CE understanding between participants and researchers, thus ensuring the internal validity of the study [32], and (ii) defining the scope for indicator selection, i.e., elaborating on a prioritized CE initiative by exploring what CE strategies it involves and what business processes it affects. Workshop A aimed to test the procedure for indicator selection, by (i) allowing researchers to demonstrate the step-by-step indicator selection procedure, (ii) creating a room for a dialog about CE and its particularities in the specific corporate context, and (iii) assisting the participants in applying the procedure to select suitable indicators for the defined scope. Accordingly, the researchers benefitted from the participants with different competencies by getting an in-depth understanding of the organizational processes and decision context, as the discussions were held around "what are the concerns of … where do we need the most help … what is under our control …". The real-life context, despite limiting the researcher's level of control [33], allows us to frame the picture about beliefs, assumptions and expectations of individuals and company, thus achieving an understanding of the influencing factors on the premises of the study and results [32]. Workshop B focused on: (i) discussion about particularities of data collection and indicator application, and (ii) collection of feedback (provided in Table C1 in Appendix C). All observations and dialogues were recorded in a written form after each interaction. The notes were later sent to the participants for data cross-checking and information accuracy. As a result of empirical investigation, the procedure has been iteratively revised to incorporate the feedback to account for the needs of industrial practitioners.

2.2. Conceptual Framing

2.2.1. Leading Performance Indicator Database

A 'Leading indicator database', consolidated as a part of the research Stage I (Figure 1), served as a foundation for developing a procedure for the systematic identification and selection of relevant indicators to measure the sustainability performance of CE solutions. The database contains 270+ leading indicators classified according to CE strategies, business processes, and TBL dimensions and aspects (Figure 2, part (a)), which allows identifying suitable indicators available for various CE initiatives, i.e., the perspective which is required to develop a particular CE initiative (e.g., product design for repair, business model development to offer performance delivery), made up of different combinations of circular strategies and business processes (as shown in Figure 2, part (b)). Relying on leading performance indicators for sustainability measurements is advantageous because leading indicators can be used to 'lead' planning and monitoring of proposed actions by providing measurable and understandable information to the planners. Leading performance indicators provide early guidance about potential sustainability performance and warning about areas of concern, thus giving the possibility for companies to adjust and improve the initiative prior to its implementation to prevent any undesired impact [34,35]. The database acts as a medium to store indicators in an organized way, as well as provides clarification for each indicator in terms of its importance, plus a formula to help calculations. An in-depth review of the retrieved indicators and their classification is provided in the study by [24], with the database available in Excel format at the permalink web-address. Figure 2 shows the abstract representation of the database, with the classification criteria (a), and the logic of locating an initial set of suitable TBL indicators (N_i) (b), which works by selecting a CE strategy/ies and a business process, a specific CE initiative involves.

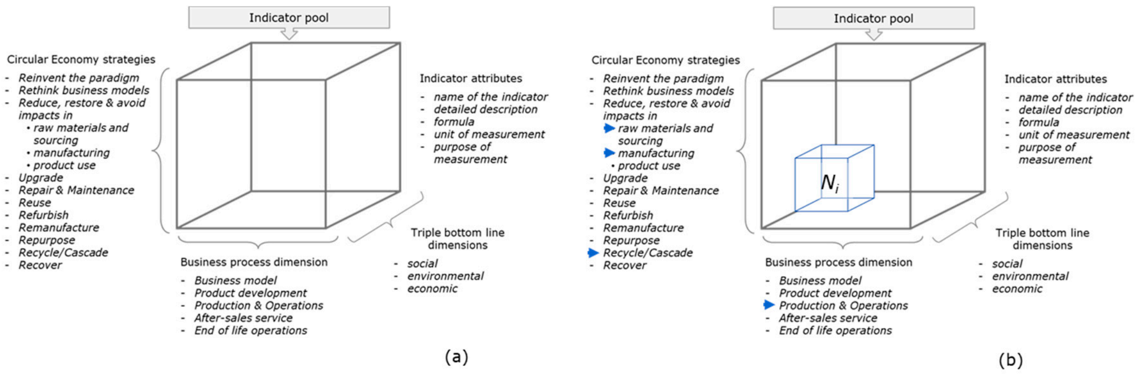

Figure 2. The abstract representation of the 'Leading performance indicator database' layout (**a**) and indicator pre-selection logic (**b**).

2.2.2. Procedure Development in the Context of Sustainability Assessment

A core consideration for the procedure was to ensure that it can facilitate a structured, yet dynamic and balanced identification of relevant sustainability indicators that can be meaningfully interpreted by the target users (e.g., industrial practitioners). The recommendations for such a process, therefore, were extracted from traditional works on indicator-based sustainability assessment. Contributions by [36] and [37] were used to construct the procedure to ensure it encourages learning and reflective analysis. To complement the procedure, guiding questions have been developed to assist the process of selection of individual indicators (similar to [38]) as well as indicator sets, as suggested by [26]. The recommendations of manageable indicator numbers have been adopted from [39] and [40]. These theoretical underpinnings contributed to understanding how to develop a procedure for meaningful indicator selection that facilitates organizational learning and ensures effective and 'rational' information use to support the development and improvement of CE initiatives in their early development stages.

Following the theoretical groundworks, the selection procedure 'prototype' was developed considering key recommendations (Table 1).

Subsequently, the 'prototype' was validated by several CE and sustainability experts with 10+ years of experience in both academia and industry and then tested internally with peers from the research group. Internal validations aimed at providing additional recommendations to the procedure, prior to its application in a case-study setting.

Table 1. List of recommendations as identified in the literature and how they were translated into specific features during the development process of the procedure.

Recommendations	Reference	Explanation	Adopted feature
Reduce uncertainty of what has be measured	[25]	Establish a pool of indicators suitable for the exact assessment scope	The procedure entails application of the 'Leading performance indicator database', where each indicator is classified according to various circular economy strategies, business processes and TBL aspects
Dynamic and reflective process	[26] [37] [38]	Support dynamic and open-ended selection process, focusing on the process rather than on results	The procedure encourages the user to work with indicator selection in an iterative way, by encouraging to define a scope, select indicators, review indicators, and align the selection with the scope
Support review of indicators	[38]	Provide guidance for the review of individual indicators	The guiding questions have been developed to support the procedure of indicator review, evaluation, creation and customization
Indicator number	[39] [40]	Ensure indicator set is manageable yet provides a solid basis for decision-making	The procedure leads the user to defining the final set of indicators that is relevant for the screening scope yet limited to the key indicators that can support decisions
Indicator application	[36]	Ensure the information about indicator is sufficient to apply and interpret it	The procedure entails application of the 'Leading performance indicator database', where each indicator has a formula, units and purpose of measurement registered

Based on the consolidated recommendations, the prototype of the indicator selection procedure was developed, incorporating three steps: (i) identifying the scope by elaborating on a prioritized CE initiative to understand what CE strategies are considered and what business processes are affected, (ii) deploying the leading indicator database to locate the initial set of indicators, using a set of guiding questions to select the most relevant ones, and (iii) customizing and creating new indicators using a set of guiding questions. These steps were later elaborated on in the final version of the procedure presented below in Section 3, Figure 3.

3. Results: A Step-by-Step Procedure for A Systematic Indicator Selection

This section presents the final version of the procedure developed to support a systematic selection of leading performance indicators for CE initiative assessment. The final version of the procedure is shown in Figure 3 and comprises several steps identified through theoretical and empirical investigation. The procedure is intended to support sustainability and environmental managers and project managers in selecting the suitable set of performance indicators to be used for CE to support early sustainability performance assessment, giving a possibility of introducing improvements prior to the implementation. The procedure consists of several steps, which explain activities to be followed before, during and after the selection process. This final version of the procedure is the result of several improvement iterations, during which the initial version, based on the literature and expert review, was improved following recommendations from case study application (Table 2 in Section 4.1.).

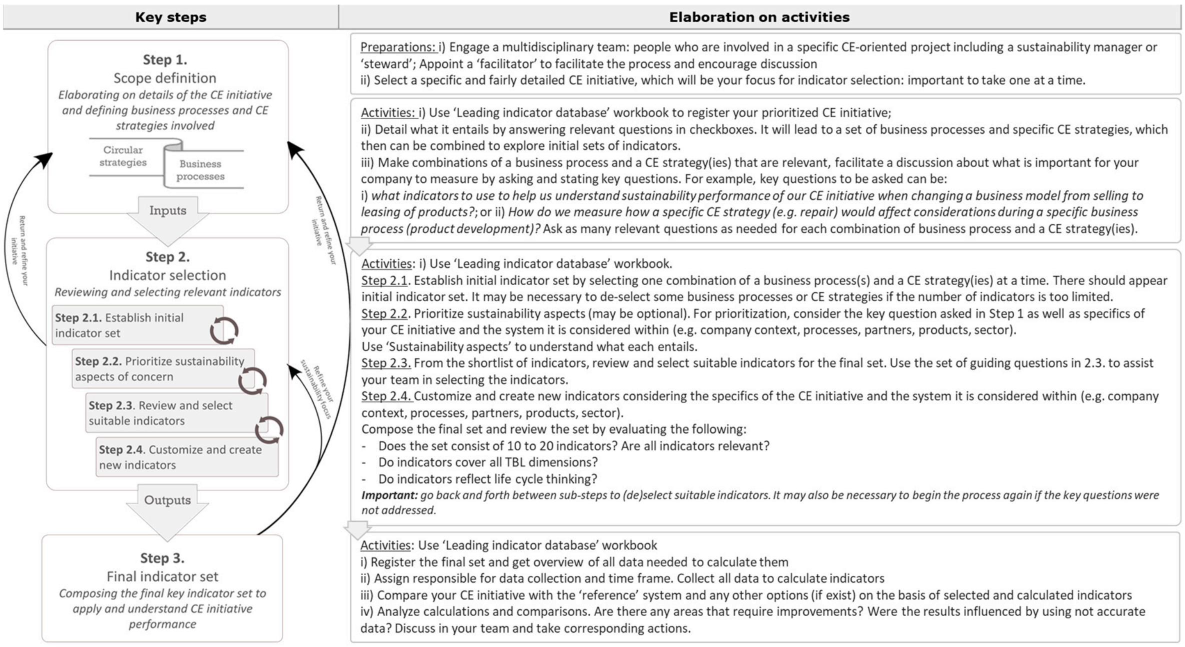

Figure 3. The final version of the indicator selection procedure—enhanced after empirical application, with key steps and elaborated activities.

3.1. Step 1: Scope Definition—Elaborating on a CE Initiative

3.1.1. Overview and Preparations

This step is focused on defining the scope for indicator selection, which requires identification, prioritization, and elaboration on a specific CE initiative to be screened with the help of indicators. Detailing a CE initiative is an important step because it influences the number and type of suitable indicators that will be available for the indicator review later in the process. The current procedure does not directly support the formulation of CE solutions suitable for a specific corporate context, i.e., whether a company should engage in service provision or in remanufacturing. Instead, it requires a set of solutions, including a CE one, be already outlined before the process of indicator selection. Major preparations for this step require, firstly, forming a multidisciplinary team consisting of people, who are involved in CE initiatives planning, including a sustainability manager or 'steward', and, secondly, selecting a specific and detailed CE initiative, which will be the scope for the indicator selection. It is important to facilitate a group discussion about what a specific CE initiative aims to achieve, what it specifically entails and what corporate (i.e., strategic, tactical and operational) decisions does it affect. The key question to be asked for this step is: "What should be measured in order to understand and potentially improve sustainability performance of the selected CE initiative?"

3.1.2. Activities

Detailing a prioritized CE initiative should be based on the identification of what CE strategies are involved and what business processes are affected. This activity is facilitated by a set of guiding questions, for instance, such as "Does the initiative involve offering 'add-on' service contracts including maintenance, supply of spare parts, buy-back agreement, consultancy?", "Does the initiative require changing commercial relationships with customers and/or suppliers?", "Does the initiative require changing or establishing reverse logistics system, and/or corresponding end of life processes and technology (e.g., technology, processes and resources (fuel, energy, water, etc.) needs for the re-processing facilities)?", etc., which helps to define specific CE strategies and business processes. Once identified, these selections can be used as inputs to Step 2 to explore initial sets of suitable indicators. Before proceeding to Step 2, it is important to formulate key questions for each selection under the prioritized initiative. This helps in creating alignment between the selected indicators (later in the process) and the scope, in that " … indicators of sustainability will only be effective if they support social learning by providing users with the information they need in a form they can understand and relate to" [41]. For instance, if a company's initiative is to provide a service for a 'full life cycle support' for a product, it could involve offering a product through leasing contract including installation, maintenance and repair, removal at the end of life to be eventually recycled into the same product. Each intervention would require a different perspective, affecting decisions to be taken during various business processes. For instance, key questions can be formulated as: (i) what indicators to use to help understand sustainability performance of the CE initiative, when changing a business model from selling products to leasing?, (ii) what indicators to use to help understand sustainability performance of the CE initiative, when designing a product that is recyclable at the end of life, and (iii) how to measure how a specific CE strategy (e.g., repair) would affect considerations during a specific business process (e.g., product development, after-sales service, etc.)? Asking as many relevant questions as needed for each combination of a business process and a CE strategy(ies) facilitates understanding of what CE actually is, as well as what effort does it require. The reason is that CE solutions do not go in isolation: CE strategies influence each other and influence decisions taken during different business processes, likewise operationalization of certain CE strategies is enabled or constrained by decisions taken during various business processes (e.g., a product-design oriented solution has to fit a company's business concept and vice-versa).

As an outcome of this step, the identified CE strategies and business processes can be combined to explore relevant indicators, which in turn should help in answering formulated questions.

As a part of this step, it is necessary that for each CE configuration a baseline ('as-is') system is defined, thus making it possible to compare a new ('to-be') scenario and a baseline ('as-is') scenario.

3.2. Step 2: Reviewing and Selecting Relevant Indicators

3.2.1. Overview and Preparations

This step requires applying the knowledge and expertise about the details of the prioritized CE initiative and specifics of the company (e.g., its sustainability priorities, specifics of the sector, facility, process, product). Similarly to Step 1, a multidisciplinary team is engaged together with a sustainability manager or 'steward', who can support the selection of indicators that require sustainability expertise.

Indicator review and selection are done through several sub-steps allowing to gradually select the most relevant indicators for each relevant scope (e.g., addressing key questions formulated for a combination of a CE strategy/ies and a business process) (defined in Step 1).

3.2.2. Activities

1 Sub-step 2.1. Establishing initial indicator set

In order to establish the initial indicator set, a combination of filters in the 'leading performance indicator database' need to be applied. Explicitly, the filtering is done by setting a 'selection' filter for a combination of CE strategies and business processes, which constitute the key question in focus. Filtering allows us to automatically reduce the number of indicators applicable to the selected combinations, thus removing unsuitable indicators for the scope that is in focus. For instance, a combination of CE strategy 'repair and maintenance' and a business process 'after-sales service' can be selected in the database to address the question 'how to measure how a repair strategy would affect considerations during after-sales service?' (discussed in Step 1). This selection would bring the initial set of indicators suitable for the selected combination and questions in focus.

2 Sub-step 2.2. Prioritizing sustainability aspects

Once the initial indicator set appears, it is further possible to refine it by setting a 'selection' filter for a sustainability aspect/s of higher interest or concern. Details of the selected CE initiative, industry type, product type, location of business are among factors that impact what sustainability aspects might be prioritized [42]. Furthermore, the key question from Step 1 should be considered to assist the selection of sustainability aspects of concern. For instance, if the selected CE initiative concerns offering products for shared use, cost aspects, product durability and lifetime and resource consumption for and by the product under its use might be considered. Similarly, if a company belongs to the textile sector and is planning to change the process of dyeing, it might prioritize environmental aspects of water consumption and dye consumption, and liquid waste generation [43]. A company producing electronics might prioritize social aspects of supplier and community relationships (e.g., associated with mineral extraction coming from conflict zones) [44] and environmental aspects of energy consumption [45]. Likewise, some of the aspects might be de-selected: if a company regulates social and ethical issues through its code of conduct regularly, social aspects related to employment conditions and supplier relationships can be de-selected. Although the significance of a balanced TBL inclusion, especially for a long-term strategy, it may be beneficial for a company to decide on one dimension (e.g., environmental) at a time [42] when selecting indicators for CE screening. When focusing on one dimension, it is recommended to have indicators covering a broad spectrum of aspects (for instance, energy/waste indicators for a process, material consumption and expected lifetime of a product). These considerations should be discussed in a team to encourage dialogue about sustainability aspects significant for the selected initiative and the company. A short description of each sustainability aspect and related issues are provided in the database to assist their interpretation, which can be very useful for the project team during indicator selection process, considering that most of the companies in EU are SME's [46] and may not have an environmental or sustainability engineer, whose expertise is essential in facilitating the selection of significant aspects and issues [47].

3 Sub-step 2.3. Reviewing and selecting suitable indicators

Once the initial indicator set is shown and sustainability aspects are prioritized, it is necessary to review the proposed set of indicators. The review and evaluation of indicators is a thorough process that requires operating with and iterating the details and key issues outlined in previous steps. The team should comprise sustainability or environmental managers and other project staff (e.g., product developers if the CE initiative involves product redesign). It is essential that the team has substantial knowledge of its own processes/products and the CE initiative. The involvement of the product and business development team can greatly impact to what extent the solution can be reached [42]. The team can consult the indicator database to understand how each indicator is measured and what data is needed. Furthermore, a set of guiding questions should be used to assist the review and indicator evaluation (with elaboration provided under each guiding question), as follows:

- How relevant is the indicator for your industry or company?

For instance, the environmental indicator available in the initial set for CE strategy 'Reduce, Restore and Avoid impacts in Raw material and Sourcing' and a business process 'product development', is 'Pesticide use'. While this indicator is irrelevant for a heavy machinery company, it may be highly relevant for a food producing company. Similarly, the indicator 'Ozone Depletion Substances in the Product' is irrelevant for the textile industry, while can be relevant for the industry producing foam blown with chlorofluorocarbons (CFCs) used for thermal protection (e.g., used in aerospace industry) and for industries producing electronic and photographic equipment (e.g., cleaning fluids containing CFCs) [48].

- How relevant is the indicator for the selected CE initiative?

For instance, two of the environmental indicators available in the initial set for the combination of CE strategy 'Reduce, Restore & Avoid impacts in Raw material and Sourcing', CE strategy 'Recycle' and a business process 'end of life operations', are 'Amount of Restricted Materials (REACH) in products' and 'Amount of Prohibited Materials (SVHC) in products'. While these indicators are very important for a company that considers open-loop recycling (i.e., recycling of one product type to obtain material to be used as an input for another), they may be not important to measure if the company intends to do closed-loop recycling (i.e., when recycling own product into the same or similar product), because this information might already be available and used to make a decision to implement a recycling strategy. Furthermore, the importance of this indicator can only be judged by an expert (for instance, environmental, product or production engineer) as opposed, for example, by a non-expert of hazardous substances, like sales or service manager.

- How much data is required to measure the indicator and how big is the uncertainty of data collection?
- Does data collection involve significant costs or time?

For instance, to measure the indicator 'First technological wear-out life' (i.e., the period, which the product can be used without an upgrade, and is based on external factors, such as technology infrastructure changes and attractiveness compared with competing products (in contrast to internal factors as physical degradation and failure)), the company might need to collect data from the users, which can be time-consuming and costly, especially in the 'business to consumer' model. On the other hand, the company may realize that the data is available because the company already collects it as a part of their business practice.

- Is the indicator easy-to-use and understand?
- Does the use of the indicator require experts?

It may be challenging for a service manager, for instance, to work with social indicators. This would require involving experts with the knowledge to evaluate the importance of a particular indicator and its application and interpretation.

4 Sub-step 2.4. Customizing and creating new indicators

Along the evaluation process, indicators may need to be customized or created [38] to better address particularities of (i) a prioritized CE initiative and its objectives, (ii) the sector, and (iii) own processes, products, and operations. For instance, the indicator 'Volume of chemicals and solvents used per product' can be customized to 'Volume and number of different chemicals used per product' to address the company's objective to understand what types of chemicals are used with the aim to remove them from the product. Furthermore, if the company's objective is to reduce the maintenance costs of a product, new indicators can be created to address it. Thus, the indicator 'Volume and number of different chemicals and solvents used for product maintenance' can be developed, being based on the existing indicator. To complement it, an economic indicator 'costs associated with the use of chemicals and solvents for product maintenance' can be formulated.

Sub-steps under Step 2 are iterative steps, which allow the reiteration of key considerations and issues related to a particular CE initiative and its details. Iterations encourage learning about own operations and products and what matters the most for the particular context.

3.3. Step 3: Composing the Final Indicator Set

Once the indicators are refined, customized and created, the final indicator set can be composed of what can be called key performance indicators for the selected scope. The final indicator set should, therefore, reflect the indicators that are prioritized for data collection. It is then important to check the TBL coverage to ensure a balanced indicator set unless the specific dimension has been de-selected on purpose (sub-step 2.2.). The final set should be practical to measure and consist of a manageable number of indicators, normally between 10 and 20, to provide a basis for actions [49]. The checklist below should be used to evaluate the final set on its comprehensiveness by addressing the following:

- Does the set consist of 10 to 20 indicators?
- Are all indicators relevant?
- Do indicators cover all TBL dimensions?
- Do indicators reflect life cycle thinking?

As the outcome of Step 3, a set of indicators is composed and an overview of the required data is prepared.

Implementing the Final Set of Indicators

In order to understand the performance of the selected CE initiative, it is important to implement the final set of indicators. Indicator application is the most extensive step since each final indicator would require tracking, collecting and managing data. The database provides formulas to compute each indicator, thus easing the task of identifying what data is needed. It is necessary to set a plan for data collection with a time period and responsible for data monitoring and registration. Sustainability or environmental managers, normally, already have an overview of what data the company might be routinely collecting as part of business practice. Moreover, knowledge of the indicators and necessary data allows them to identify the sources of specific data. Data collection processes, however, should ensure reliability, validity and verifiability, and requires a critical technical assessment [50]. Data quality can greatly influence the results of indicator application and compromise the decision-making process. Data can be collected from management, technical or procurement reports, existing management systems, stakeholder meetings, etc. [50]. Moreover, data needs to be collected for as many initiatives as set up in step 1 to ensure that the baseline 'as-is' system versus 'to-be' system, i.e., a new circular initiative, can be compared. Essentially, the initiatives must only be compared based on the same set of indicators, to enable understanding of sustainability performance of the proposed actions (i.e., decreasing or increasing trend). After comparison, it may be necessary to return to step 2 to select more indicators or to step 1 to refine details of the CE initiative.

4. Empirical Application in Case Study Settings

Research Step III aimed to test the procedure through case studies, which evaluated the extent to which the procedure could support the selection of suitable performance indicators. Three Nordic manufacturing companies have participated in the evaluation, varying in size (from less than 10 employees to 10000) and sector (company 1—furniture solutions for public and private spaces, company 2—manufacture and service of heavy industrial equipment, company 3—textile sector and home accessories). A detailed description of a procedure application is presented below using a case of Company 1, followed by a summary of learnings from all cases. A detailed description of the procedure application for Company 2 and Company 3 are provided in Appendix B. Condensed feedback from each company is presented in Appendix C in Table C1 with direct quotes and authors' interpretations.

Company 1 can be classified as a micro-enterprise (<10 employees) with headquarters in one of the Nordic countries. The company designs and provides furniture solutions for public and private spaces. Since its inception around 10 years ago, the corporate strategy and objectives have been formulated around designing furniture systems that are driven by sustainability and individuality principles. Furniture systems are designed with the user in mind, modular and customizable, so to give the users the possibility of building variations of furniture from the same components, thus allowing the user to 'design' their own space with no need to buy more. Their strategic vision is formulated around efficient, regenerative and responsible use of resources, enhanced co-operation with local stakeholders and customers, and improving the physical and aesthetic quality of furniture.

Two company representatives participated throughout the engagement workshops: first co-founder, with expertise in sustainable and environmentally conscious product design solutions, and second co-founder, specializing in interior and furniture design. During the initial exploration session, it became clear that the company is considering several circular economy solutions to be implemented. The circular solutions, required, among others, rethinking own business model, establishment of a new value chain partnership, setting a product take-back system. For the indicator selection process, however, the 'circular material' initiative, in which the focus was on using the recyclate as a feedstock for a product type A, has been prioritized (Step 1). This decision mirrors the corporate environmental objective of regenerative and responsible use of resources, in that, the 'circular material' is to be locally "produced" from collected waste. Another driver mentioned during the session was to create awareness of waste and the 'value' stored in it, inspire other industries and create a new market for waste as a resource.

Consequently, the 'circular material' initiative was chosen as the scope to proceed with for indicator selection (Step 2). The intention of the company was to see what sustainability considerations to make and what to measure in order to support the decision. Moreover, the company acknowledged that the focus should not be solely on materials, but also on the conversion process of the material, transport, and end of life. This was explained by closer cooperation of the case company with another company responsible for waste recycling and forming of recyclates into new components. Considering this view, the initial scope for indicator selection consisted of a combination of CE strategy 'reduce impact in raw material and sourcing' and a business process 'product development', with the key question formulated as 'what indicators to use to help understand sustainability performance of the CE initiative when designing a product with a recycled content instead of virgin material'. After applying the corresponding filters in the 'Leading performance indicator database', the initial indicator set comprised of 33 indicators. It was decided not to further refine indicators according to sustainability aspects, but to select the indicators one by one answering the guiding questions under sub-step 2.3. Furthermore, the information registered in the 'Leading performance indicator database' was used to understand each indicator and judge it against others. Specifically, the column, which described the importance of measuring an indicator, was found to be helpful in evaluating the importance of a particular indicator. For instance, for the indicator 'Laminated or compound materials' the purpose of indicator measurement and the significance of indicator value was stated as 'Laminated or compound materials have limited potential for recycling. Decrease amount of Laminated or Compound Materials in a product'. As a result of the review process, 8 indicators were selected (Figure 4). During the indicator selection process, the discussion of the team unfolded around the indicator 'embodied energy': the participants expressed their uncertainty in how to measure it or how to get the data for it, taking into consideration the novelty of the process of waste recycling and its formation into a desired recyclate.

In addition, as the company indicated their interest in understanding the implications of the waste collection and its recycling process, another round was set up to select more indicators addressing the conversion processes of waste. Consequently, a CE strategy 'reduce impact in raw material and sourcing' and CE strategy 'recycling' were combined with business process, 'end of life operations" to understand what should be measured, when recycling waste and converting them to a recyclate for subsequent use in a new product. As a result, the initial set comprised 19 indicators, which were then reviewed using the procedure, resulting in 3 indicators in the final set. Accordingly, the final set consisted of 11 indicators to be implemented for sustainability screening: 8 indicators covering environmental aspects, 2—social and 1 economic (Figure 4).

It can be pointed out, that these selections were performed in an iterative way, in that, the initial scope chosen by the company allowed to navigate the database and gradually (de)select suitable indicators. During the indicator screening process, however, the participants noticed that there is a lack of social indicators, especially under the 'product development' process. At the same time, however, the users were overwhelmed by the number of indicators originally available in the database, referring to a challenge that a user might have if working in the database prior to defining the scope. The outcome of a case study was the application of the selected indicators and comparison of the proposed CE solution with the 'as-is' system. The company expressed the concern that major data was missing due to the unestablished process (i.e., conversion of waste to the feedstock material), therefore, in order to calculate the selected indicators, the company had either to contact entities, which were performing similar type of recycling and forming process or to collect data from literature. At the end of workshop B, the evaluation session focused on identifying the usefulness of the selection process and selected indicators for decision–making as well as receiving general feedback on how to improve the procedure and usability of the tools. All the comments were consolidated and used to improve the selection procedure, and the database layout.

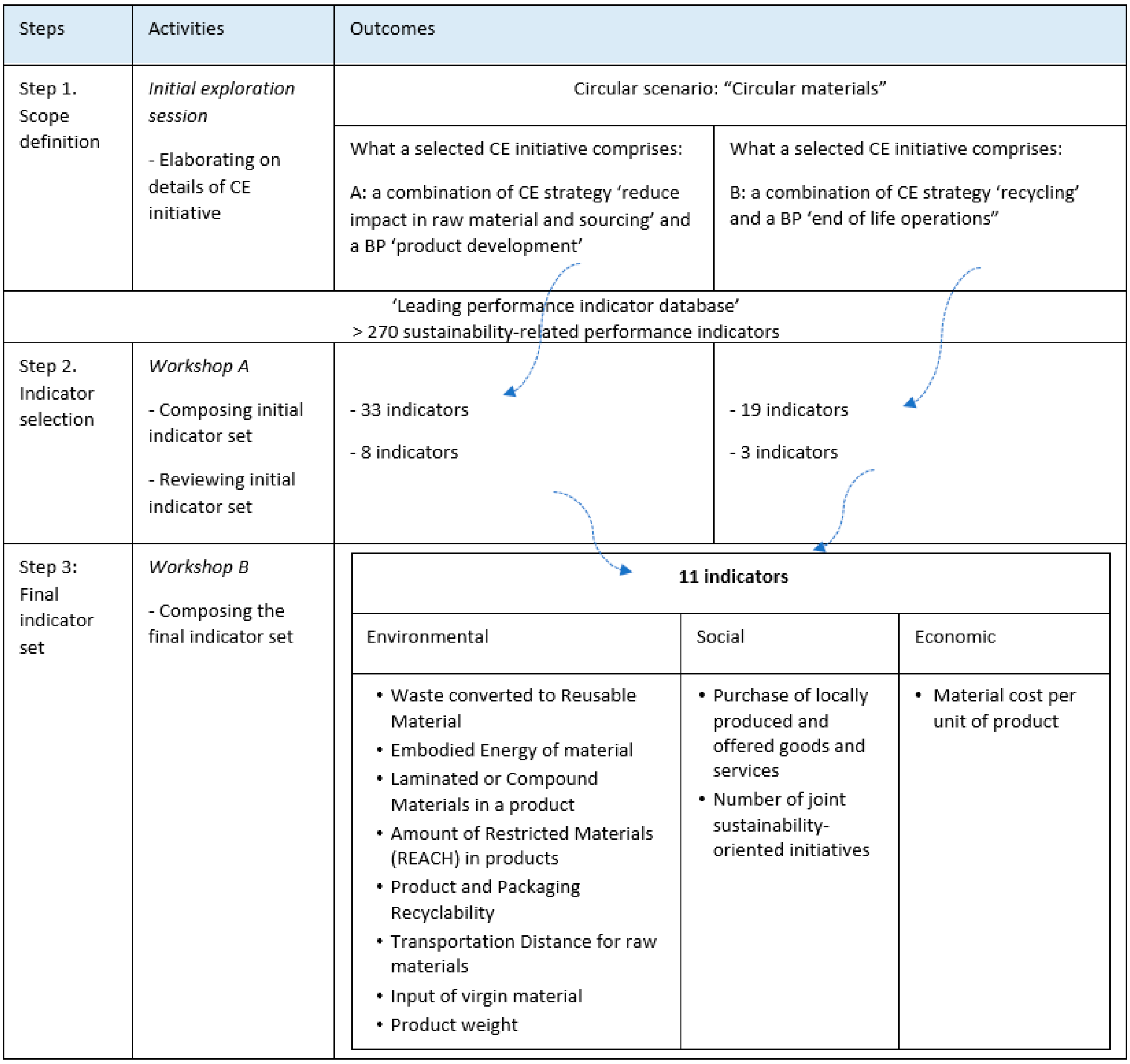

Figure 4. Overview of activities and outcomes of the procedure application in Company 1.

Some specifics in relation to the first case study application can be pointed out. Firstly, the majority of the selected indicators are product-oriented. This selection can be attributed, firstly, to the selected scope, and secondly, to the expertise, the users from the company had, i.e., expertise in product design. It can be expected that more 'operational' indicators, specifically concerning the process of waste recycling, would be selected if people with suitable expertise participated. Nevertheless, the company expressed an interest in engaging value chain partners in the selection process to capture more sustainability aspects. Secondly, since little concrete details and data were available for the circular solution in focus, it was difficult to simulate the results of indicator application to be able to compare the circular and 'as-is' scenarios. From the application experience, the users suggested that the procedure for selection should emphasize the importance of corporate sustainability vision, so the final set of indicators can be reflected back onto it. As one of the participants suggested: "The process of indicator selection should start with aligning or defining the organizational sustainability vision and objectives. It is very important to make a company aware of why the selection of indicators is important and what the indicators can be used for. It is important to connect the final set of indicators to the corporate values". Another suggestion was to adapt the database to smaller companies, with one user commenting: "Make the tool user-friendly for those, who may not have an expertise in sustainability assessments, but have a passion to work with indicators to make improvements", complementing that "… the procedure requires the facilitator with sustainability expertise to facilitate the team and aid the interpretation of each indicator", thus making it challenging for (smaller) companies to use the database and select the 'right' indicators. On the other hand, the participants highlighted the importance for the user to see and evaluate the initial indicator set, stating: "It is good to have gradual steps in the database to obtain the initial set of indicators and then to select the most suitable indicators for the final set using the guiding questions. It gives a good overview of the whole process of the indicator selection, as well as tracks what indicators have been removed from the final set, but initially comprised the initial set". The participants also emphasized the usefulness of the list of guiding questions, stating that "… they are very helpful because they "force" the user to think of every single indicator and reflect on it. Also, the indicator evaluation helped to understand the internal processes and what matters the most and what are the gaps". It was added that, despite the presence of assisting formulas and purpose of measurement for each indicator, the process of indicator selection can be a time-consuming activity, especially for a small company with no sustainability expert that could potentially facilitate the evaluation process.

Summary of Insights from the Case Studies

The outcome of the procedure application in all the cases was the final set of indicators ready to be used for measuring the potential sustainability performance of the selected CE initiatives and the comparison of different alternatives. While the application procedure has been identified in all the cases, some differences could be observed. Firstly, Company 1 expressed the need to have a support step to assist in the formulation of sustainability strategy and objectives. "As a small company, we think that establishing and being clear about own sustainability goals and strategies is very crucial, also in terms of understanding why working with indicators at all". Secondly, the participants emphasized the importance of having a facilitator with relevant expertise for the indicator selection procedure. Despite the fact that the participants selected suitable indicators for the final set, the lack of expertise of 'broader' sustainability created a challenge along the process, making it more time consuming, when navigating prioritization of significant sustainability aspects. It was suggested to provide more information about each TBL aspect found in the database to assist SMEs in prioritization.

Company 2, on the contrary, was very determined in limiting the scope for the screening as well as in their decision on what type of indicators to focus on. This can be ascribed to the competence and experience within sustainability the participants possessed as well as to the 'insider-like' (i.e., internal manufacturing) CE scope selected. Furthermore, the participants, knowledgeable of other sustainability assessment techniques, e.g., LCA, highlighted the importance of addressing trade-offs during indicator selection and, consequently, the decision-making process. Key remarks from Company 2 concerned the usefulness of the database and the procedure in selecting a set of key indicators for each project the company initiates. As emphasized, the key indicator sets can be used across projects to identify improvements and monitor changes. One of the key suggestions was to guide the users in the possibility of limiting the scope to certain key sustainability aspects, to reduce the complexity of operating with too many indicators simultaneously. It was also suggested to state the recommended number of indicators for the final set, so as to assist the user in defining when 'enough is enough'.

Company 3 recognized the suitability of indicators for the scope selected, however, pointed out the importance of 'allocating' indicators to the specific users, who have the competence to evaluate and validate every single indicator. In that, the participants stressed the need to engage experts from several corporate departments, where the sustainability manager would be responsible for identifying the key experts based on the type of CE initiative in focus. Moreover, the participants commented on the usefulness of applying filters to de-select certain sustainability dimensions and aspects. As pointed out, going from a smaller to a larger set by gradually adding more indicators can reduce the complexity of decision-making, when evaluating the importance of each indicator. In addition, key recommendations concerned the conditions of working with the selection procedure, in that, it is critical to define the scope for which the indicators will be selected as well as the baseline, which the new initiative will be compared against. All the comments were consolidated and used to improve the selection procedure, and the database layout and content. Table C1 in Appendix C provides quotes from discussions in case companies. Table 2 presents a summary of key improvement opportunities, labeled as recommendations, which have been identified through the empirical evaluation and incorporated in the final version of the procedure as presented in Section 3.

Table 2. Summary of the key recommendations to improve the procedure based on the empirical application.

Recommendations	Case company			Explanation	Adopted feature
	C1	C2	C3		
Strategic consideration	√			Ensure alignment of lower level performance indicators with corporate sustainability objectives	*Not adopted in the current procedure*
Scope definition	√		√	Ensure the scope is defined before proceeding to the indicator selection	Introduction to the procedure highlights the importance of having a defined CE initiative prior indicator selection process. Furthermore, practical examples on how to construct CE configurations for selected CE initiatives are given in Step 1
Baseline identification	√	√	√	Ensure identification and explanation of a baseline scenario	The recommendation to define the baseline scenario in order to encourage scenario comparison on the basis of the selected indicators is given is Step 1
Multidisciplinary team	√		√	Ensure the experts with relevant expertise are involved in the indicator selection and evaluation process	Introduction to the procedure highlights involvement of actors with relevant expertise for indicator selection, evaluation and customization process
Triple bottom line aspect navigation	√	√	√	Support flexible (de)selection of relevant triple bottom line aspects to reduce complexity	The recommendation in Step 2 was introduced to allow for prioritization of sustainability aspects, thus reducing the complexity by simultaneously operating with too many indicators and sustainability aspects
Indicator number	√	√	√	Provide a recommendation about the number of indicators in the final set	Step 3 indicates *the recommended number* of indicators to be included in the final set
Account trade-offs		√	√	Provide a recommendation about how to address trade-offs between indicators	*Not adopted in the current procedure*

5. Discussion

The case study evaluation of the procedure and corresponding indicator database presented positive results, indicating their support to companies in the selection of suitable leading indicators to measure the performance of CE initiatives. Furthermore, the empirical settings allowed us to identify opportunities to improve the usefulness of the presented tools. Main learnings from the empirical investigation are as follows:

- it is essential to set the scope for indicator selection by outlining a CE initiative and elaborating on its details by explicating what corporate decisions it affects (e.g., business process orientation) and what specific CE focus it has (e.g., CE strategy view) prior indicator selection process,
- it is necessary to set a baseline scenario, upon which a CE initiative scenario can be compared,
- it is important to involve a multidisciplinary team to support the selection of suitable indicators, including a sustainability 'steward' to facilitate the interpretation of indicators and an expert team who is engaged in the development of the CE initiative into focus (e.g., product designers, after-sale managers),
- availability of indicator attributes, such as formulae, units and purpose of measurement, eases the interpretation of each indicator, which facilitates the selection process. This is important especially for SMEs, which might not have a sustainability manager to support indicator interpretation, similarly, availability of elaborations on sustainability aspects and what they entail facilitates their interpretation and prioritization,
- it can be beneficial to work with indicators from one sustainability dimension at a time, however, a final set should comprise a balanced number of TBL indicators,
- the iterative selection procedure seems to help in arriving at suitable indicators, the suitability of which is judged by the users who are to operate with indicators and relate to their results.

The learnings also highlight limitations. Firstly, the procedure and database were tested in a limited number of companies from specific sectors, thus limiting the evaluation of their usefulness for other contexts. Furthermore, testing in more companies could allow us to look into cases, where the scope for indicator selection is expanded to include more combinations of CE strategies and business processes, for instance including those requiring simultaneous changes in business models, product design and operational activities. Secondly, the procedure does not address how to resolve situations, when trade-offs between indicators arise, which is essential in providing assistance in the decision-making process. Therefore, future work should evolve around developing a support tool to guide decisions in trade-off situations. Thirdly, the 'Leading indicator database', used to retrieve indicators, contains non-sector-specific indicators. The procedure accounts for this by providing examples of how to customize and create indicators, however, it may be a time-consuming process that could possibly hinder the easiness of the procedure application and indicator selection in the industry. Future research could address the development of indicators that are sector-specific or providing sector-specific guidance for indicator selection. Furthermore, future work could include analysis of relationships between the identified indicators and recognize the most common variables used to calculate the indicators. It would also be beneficial to consider aggregating indicators for simplicity and diffusion in the industry. However, some caution must be taken due to the potential drawbacks of using composite indicators or indices to measure complex phenomena, such as sustainability and CE [37]. It can be pointed out that the indicator database could be enhanced by developing more indicators to cover social aspects and indicators suitable for the business model development process, as discussed in the study by [24].

To indicate the contribution of this study to the context of CE development and indicator-based sustainability assessments, we identify several criteria to provide its comparison against other works. We selected several works that satisfy the following criteria: (i) they provide examples or propose indicators for assessment, (ii) they provide a reasonable categorization of indicators, and (iii) they focus on the early stages of decision-making. The identified works include recent studies on employing indicators to support the development of sustainability-oriented strategies, CE being one of them, and discussed by [38,51[52][52][52]–53] as presented in Table 3.

Table 3. Comparison of present research with similar works based on a range of criteria.

Reference	Considers all dimensions of sustainability	Considers a variety of circular economy strategies	Considers a variety of business processes	Considers a life cycle perspective	Encourages a dynamic indicator selection process	Presents a practical application in industry
Present research	√	√	√	-*	√	√
[51]	- Only environmental	√	- Only product development	-	-	√
[52]	√	- Limited to recycling	- Only end of life process	-	-	-
[38][38][38][38]	- Only environmental	-	- Only product development	√	√	√
[53]	√	-	- Only product development and manufacturing process	√	-	√

Particularly, [51] propose environmental and functional indicators to measure the performance of a product family, considering a wide range of CE strategies. The authors aggregate a set of indicators into several 'prescribed' indices to evaluate the circularity of proposed product designs. [52] propose a methodology for designing a sustainable recycling process supported by indicator-based measurements. Their approach is limited to recycling only, although with a three-dimensional sustainability consideration, where four indicators for each dimension are prescribed. Work by [38] provides a procedure to select product-oriented indicators, based on the life cycle orientation and environmental aspect(s) of main concern under the product development process. [53] provide a set of three-dimensional indicators classified according to life cycle stages to be used during product development and manufacturing to evaluate the sustainability performance of products and processes. Whilst they refer to several resource-efficient strategies (e.g., remanufacture), the indicators are not accordingly classified.

Summarizing the above-mentioned studies, it is evident that more research is needed to account for the myriad of perspectives when it comes to the application of leading sustainability performance indicators to support the development of CE solutions. In this sense, current research presents a significant contribution by the fact that it takes into account all dimensions of sustainability, a comprehensive selection of circular economy strategies and a holistic set of business processes (from business modeling, through product development, to end-of-life operations) (Table 3, present research) to allow filtering and pre-selection of classified indicators, to support the development of several CE solutions simultaneously, whilst considering their sustainability performance. Although the study does not have a distinct classification of indicators according to life cycle stages, it takes this perspective into account, when, for instance, presenting indicators selected under the product development process (follow the web address as presented in Section 2.2.). Importantly, the procedure encourages a dynamic selection of indicators, to avoid the prescription of indicators that may be irrelevant for some business contexts. Noteworthy, the approaches that 'prescribe' indicators imply that some criteria are more relevant than the others, which seems counterintuitive in such complex and multi-faceted concepts as sustainability and CE [54,55].

A few implications of this study exist. From the theoretical view, firstly, despite a very high level of details provided about each indicator and related sustainability aspect, there is still an assumption that users of the indicators in the industry can interpret indicators and relate them to potential sustainability impacts. To address this, prospective research could focus on establishing a link between leading indicators and related sustainability impacts. Secondly, the database and the procedure do not support supplementary use of CE-specific indicators, i.e., the ones measuring the rate of resource recirculation. The research could advance by developing a procedure to support complementary use of sustainability performance indicators for CE and CE-specific indicators, so as to explicate the link between the implemented CE solutions and the achieved TBL performance, which is currently quantitatively unreported in by industries [56]. From the empirical perspective, the procedure requires a CE initiative to be already planned, thus providing no support on how to approach ideation and development of a specific initiative relevant for a specific corporate context.

6. Conclusions

This research aimed to develop, evaluate and enhance a procedure for a systematic indicator selection to measure the performance of CE strategies from a TBL perspective. The procedure provides guidance for industrial practitioners in selecting a suitable set of performance indicators for measuring the potential sustainability performance of CE strategies prior to their implementation. The procedure was tested with the help of case studies, contributing to its enhancement and consolidation into the final version as presented in previous chapters. The main contribution of this study is the procedure for a systematic indicator selection that is based on the rationale of stipulating a dynamic and flexible selection process. This is to ensure that the selection process accounts for the diversity of CE perspectives and applications and the context they are positioned in (e.g., product, process, sector). The construct of the 'Leading performance indicator database', which is used as a tool to extract the indicators from, eliminates the complexity in searching for indicators and making judgments of their suitability for the assessment. In that sense, the classification of indicators according to a variety of CE strategies, business processes and TBL dimensions allows us to retrieve an initial indicator set for each possible CE initiative. The initial indicator set is not prescriptive, however, but rather indicative, with procedure encouraging the user to evaluate each indicator, and customize or create new if needed. Although this process might seem challenging, the advantage is to induce learning and engage more profoundly with sustainability considerations during the CE initiative development process, as one of the case participants commented: "Also, the indicator evaluation helped to understand the internal processes and what matters the most and what the gaps are". From a practical point of view, the procedure intends to reduce the complexity and uncertainty of a decision-making process in companies, which arises from a complex interplay of CE and sustainability domains. Consequently, this minimizes the challenge of operating with too many or too irrelevant performance indicators, contributing to a more structured and informed performance measurement using leading indicators. The procedure should be used in the early stages of CE planning and development, to ensure industrial practitioners use the 'best' knowledge of potential sustainability outcomes of their initiatives to make the decisions.

From a theoretical point of view, our aim is to advance theory on CE development support using leading sustainability-related performance indicators. So far, the literature has either proposed newly developed indicators for CE, which mostly measure the intrinsic performance by accounting for the rate of resource recirculation[21] or focus on impact assessments. While being useful, the former do not account for a wide range of aspects related to sustainability (social implications, land use, etc.) [21], while the latter, despite well established and robust methodologies, either cannot assess dematerialized or performance-based CE strategies or provide results that are easily understood by industrial decision-makers [57]. The advantage of leading TBL indicators is in their ability to be understood, hence used, by industries, and to give early warning about potential sustainability impact of CE solutions. The practical contribution of the study is in its support for industrial practitioners in finding boundaries of what sustainability aspects should be considered and in structuring the process of selecting relevant indicators for sustainability performance measurement of CE initiatives.

Supplementary Materials: The following are available online at http://www.mdpi.com/ . Appendix A: Figure A1. Case study set up: main activities and actors involved. Appendix B: Application of Indicator Selection Procedure in Company 2 and Company 3: Figure B1. Overview of activities and outcomes of the procedure application in Company 2. Figure B2. Overview of activities and outcomes of the procedure application in Company 3. Appendix C: Table C1. Consolidation of key discussion points at the case companies.

Author Contributions: Conceptualization, M.K., D.C.A.P. and T.C.M.; expert review, D.C.A.P. and T.C.M.; case study investigation, analysis and data interpretation, M.K.; validation, M.K., D.C.A.P. and T.C.M.; writing first manuscript, M.K.; review and improvement suggestions for first manuscript, D.C.A.P. and T.C.M.; supervision, D.C.A.P. and T.C.M.; funding acquisition and resources, D.C.A.P. and T.C.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by NordForsk, Nordic Energy Research, and Nordic Innovation under the Nordic Green Growth Research and Innovation Programme, grant number 83144.

Acknowledgments: This article is one of the outcomes of the research project CIRCit (Circular Economy Integration in the Nordic Industry for Enhanced Sustainability and Competitiveness). The authors would like to thank the CIRCit consortium—Research Institutes of Sweden (RISE), Technology Industries Finland, Innovation Center Iceland, Norwegian University of Science and Technology (NTNU) and colleagues from the Technical University of Denmark—for facilitating the engagement with companies and participating in enriching discussions about Circular Economy. Special acknowledgments go to the participating companies and their engaged participation.

Conflicts of Interest: The aforementioned funding institutions had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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3.2.2. Evaluation of the indicator selection procedure and the corresponding leading indicator database

The case studies provided evaluation of the usefulness of the indicator selection procedure and the leading indicator database. Additionally, the evaluation pointed out at the strengths and weaknesses of both types of support, which helped to improve them and support the development of the User guide, with key findings highlighted next. All recommendations were coded as comment ID # and summarized in Appendix II, indicating which recommendations were taken into account to guide the improvements. In particular, the following strengths were indicated: Step 1 and the corresponding guidance on elaborating activities under a proposed CE initiative as well as formulation of key questions was evaluated as helpful for creating a common thread between the objective of the selection process and the indicators considered relevant. This made the sustainability screening "meaningful", as indicated by the practitioners. The prioritization in Step 2 was found useful for reducing complexity of reviewing too broad spectrum of indicators, while the guiding questions in sub-step 2.3. were evaluated as very helpful, because "… they "force" the user to think of each single indicator and reflect on it" (comment #23). The indicator information such as indicator description and the purpose of measurement were found particularly helpful for supporting indicator interpretation (comment #16, #23). The guidance on the number of indicators in the final set was helpful to reduce the uncertainty of how many indicators would be sufficient, and the checklist for the final indicator set was useful to ensure only relevant indicators were considered (comments #29 - #32). In summary, the evaluation indicated that the procedure and the corresponding indicator database provide a satisfactory support in guiding the selection of relevant indicators, as few citations below indicate:

> *"All in all, the database consists of some very useful indicators that can help a company to focus on certain areas to define possible impacts on sustainability. Again, the advantage can be that those indicators are operational, therefore, help companies to focus on measurements and monitor changes" – C1*

> *"Indicators found in the database are very helpful to internally manage processes and make decision on the improvements". "The overall alignment is that the indicators' [scope] [in the leading indicator database] is broader than an LCA, meaning that it can be used to evaluate (also screen) the initiatives on their sustainability impact based on [on hand] indicators' calculations (LCA requires a software and extensive data)" – C2*

> *"The advantage of having an overview of different sustainability aspects and related indicators is in pointing to the questions we should be asking our suppliers. It can help us being more systematic about what to ask" – C5*

> *"We consider sustainability in everything we do, and the indicators [in leading indicators database], help to structure the process and bring an understanding of what to take into account, when planning and evaluating any sustainability-oriented initiative, including a circular" – C6*

Specifically, the support was found useful on three main aspects: i) supporting the measurements on both, a CE initiative and a baseline system; ii) supporting the measurements from a holistic TBL perspective; iii) supporting a structured approach to aligning relevant sustainability aspects with key performance indicators.

Additionally, several weaknesses could be pointed out: firstly, the challenges with CE terminology were prominent. When looking at the list of CE strategies in the database, some companies ascribed different meaning to certain CE strategies, which was very apparent for a medical (following strict regulations and standards) and bio sector companies. This could also be related to the confusion between miscellaneous definitions of CE due to the lack of a standardized terminology as highlighted by the literature (Kirchherr, Reike and Hekkert, 2017) and supported by comments #48 and #49. Secondly, several industrial practitioners experienced challenges in understanding sustainability dimensions and related aspects, which is still a common challenge in industry (Nilsson and Lindahl, 2016; Sihvonen and Partanen, 2017). This has resulted in the evaluation of usability of the support in terms of the 'Effort of application' as 'high', which was associated with the time that was needed for the practitioners to understand sustainability aspects and sustainability indicators and provide argumentations during the indicator review process. The company from the bio sector pointed out the lack of indicators suitable for bio products, which is related to the limitations of the indicator database. Moreover, several concerns were raised in relation to indicator application, such as the uncertainty in the quality and sources of data acquisition as well as uncertainty in dealing with trade-offs. These concerns align with the challenges reported in the literature (Abbasi and Nilsson, 2016; Dekoninck *et al.*, 2016; Stindt, 2017).

3.2.3. A user guide and an interactive database to support manufacturing industry in a systematic sustainability screening of CE initiatives

The case studies provided a qualitative evaluation of the procedure and the corresponding indicator database, leading to their improvements and integration into the final version of the user guide (referred as Guide). Several limitations highlighted in previous chapter were addressed. The user guide is therefore, seen as another contribution to RQ.3: How to support a systematic selection of relevant sustainability performance indicators for early stage sustainability screening of CE initiatives?, with the aim to support manufacturing actors in the deployment of the procedure and the leading indicator database.

The Guide incorporates the description of the target audience, expected time to complete each step, inputs and expected outputs for each step, following the criteria for the support development directed by DRM, as shown in Table 7. This information provides details about the 'use context' of the Guide.

Table 7. Use context as embedded in the user guide for sustainability screening

Criteria #1 - purpose	**Criteria #2 – target company**	**Criteria #3 – potential application**	**Criteria #4 – key users**	**Criteria #5 – input data**	**Criteria #6 – output data**
- to support selection of relevant sustainability indicators to guide early stages of design and	- to be used to support decision-making in manufacturing industry responsible	- to support design and development of any initiative or project	- managers and engineers involved in the design, development and implementation of a circular economy initiative (e.g.	- details about a circular economy initiative - contextual knowledge, i.e.	- a set of relevant performance indicators

development of CE initiatives	for design and manufacturing of secondary goods (from techno- and bio-sector)	- secondary: selection of indicators for internal management systems or supply chain measurements	business managers, product developers, production engineers, sustainability engineers, etc.)	organizational strategy and vision, products, actors, processes	- data for indicator calculation - comparison of alternative initiatives

Background information about the sustainability screening relying on leading performance indicators was incorporated in the Guide. Additionally, each step of the procedure for indicator selection (as presented in Chapter 3.2.1.) was described and accompanied by help boxes with practical examples, following the recommendations from the case study evaluations, as summarized in Appendix II. For the selection procedure, few additional sub-steps were added under Step 1 and Step 3 to assist their operationalization (Figure 9).

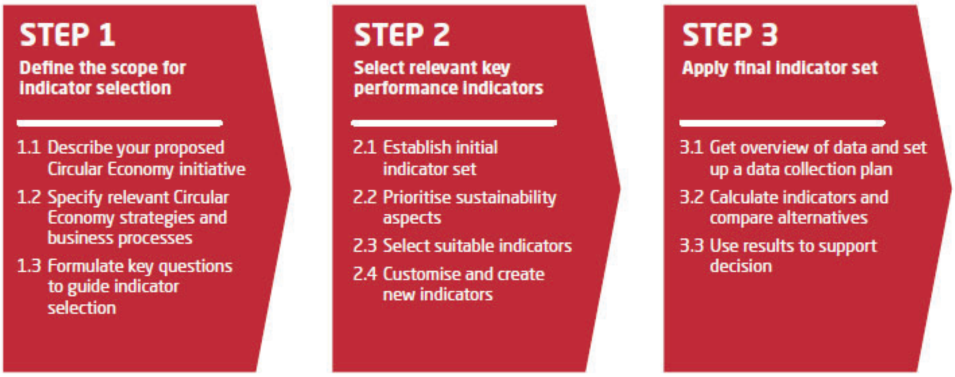

Figure 10. Procedural steps and sub-steps for indicator selection and application as described in the Guide (as in Kravchenko et al., 2020)

The recommendations also led to the development of an interactive database built in Excel, which comprised the leading indicator database and additional interactive sheets to support the activities according to the procedural steps. Moreover, the recommendations helped to improve the coherence and clarity of the terminology and language used in the Guide, in the procedure and in the interactive database. To address key recommendations and challenges indicated through evaluation, the following enhancements were introduced in the Guide and the interactive database; firstly, the Guide and the interactive database guided identification of the 'right' CE strategies for the proposed CE initiative in Step 1, supported by the checklists in the interactive database. This was necessary to address the challenge the industrial practitioners experience in navigating miscellaneous definitions of CE and related strategies. To assist understanding of the sustainability aspects under TBL dimensions, a complementary worksheet 'sustainability aspects' was created, providing definitions, examples and references for each aspect considered in the database. This was done to account for the challenges especially SME's or companies without a sustainability manager might experience when operating with sustainability-related terminology. To support indicator prioritization, review, customization and creation, a series of help boxes were introduced, which provide practical recommendations and examples of 'how to'. To encourage selection of relevant indicators and avoid 'biased' selection towards the 'costly' indicators, few recommendations were given in the guide. To visualize a TBL balance of the selected indicators in the final set, a visualization worksheet was added to the interactive database. To assist the indicator application from the final set in Step 3, several sub-steps were elaborated in the Guide. This was done by providing an example of a data collection plan, a list of potential data sources with the data quality assessment table, and a guidance for indicator result interpretation. An exemplary case was added in the Guide to demonstrate the process of the sustainability screening of CE initiatives.

Reflection on the contribution

The user guide and the interactive database aim at providing support to industrial practitioners in facilitating sustainability screening of CE initiatives based on the leading performance indicators. This support provides a guidance for how and when it is beneficial to use it, what input information is needed and what outputs are expected. In this way, it helps the industrial practitioners overcome one of the challenges of selecting a sustainability support associated with the uncertainty in what methods and tools to select and when (Schulte and Hallstedt, 2017; Held *et al.*, 2018). Additionally, the support can be characterized by a technical simplicity, i.e. not relying on a special software (Brambila-Macias, Sakao and Lindahl, 2018), which facilitates the screening of sustainability performance in hand (supported by evaluation in Appendix II). The support facilitates a structured decision process, which may reinforce the importance of the selected indicators and support organizational learning (Gibson, 2010).

The final version of the user guide was integrated in the CIRCit Workbook 1 (the cover page of the CIRCit workbook 1 is shown in Figure 10) and referenced as Paper C in this thesis. The interactive Excel database was made open access and can be accessed via the web link available in the Guide and at (M. Kravchenko, Pigosso and McAloone, 2020b)

Figure 11. CIRCit Workbook 1 cover page: with integrated User Guide and reference to the interactive database

3.3. Results for Study C: A trade-off navigation framework for decision support

3.3.1. Criteria for a trade-off navigation framework

A selective literature review in descriptive study I-C provided several results; firstly, it helped identifying examples of typical trade-offs within and between sustainability criteria considered during product development, supply chain and logistics, and business model development. Secondly, it provided a summary of the gaps associated with trade-off identification and analysis; and, thirdly, it helped identifying the criteria that could guide the development of a trade-off decision support. The aim of the literature review was not to provide a precise and exhaustive list of criteria, but to orient the research process towards a certain direction (Biolchini *et al.*, 2005).

In summary, four criteria were collected, as following:

- Criterion #1: it is fundamental to enable elicitation of sustainability objectives and use relevant tools to reveal trade-offs

The criterion highlights the challenges associated with sustainability-related trade-offs, which might be 'hidden' during the decision-making process because of the lack of inclusion of sustainability criteria in the decision process along other, 'traditional', criteria (Gibson *et al.*, 2005; Bovea and Pérez-Belis, 2012). Additionally, integration of the environmental and social criteria along the economic would often lead to trade-offs (Gibson *et al.*, 2005), and defining the objectives for these criteria could strengthen their prioritization in the decision process (Schulte and Hallstedt, 2017).

- Criterion #2: it is important to provide several prioritization principles in conjunction to assist trade-offs understanding and management

A sustainability-related trade-off analysis is often seen as a 'discussion support' rather than merely a decision support (Moreira and Tjahjono, 2016). A trade-off analysis, therefore, should provide a better understanding of the factors that influence the inclusion of and prioritization between sustainability criteria in the decision process (Driessen and Hillebrand, 2013). The prioritization principles should be linked to the contextual settings (Watz and Hallstedt, 2018). A structured and transparent dialogue about the contextual settings and their influence on the priority areas minimizes the risk of ad hoc decisions (i.e. based on past experiences) (ibid.) and allows reframing assumptions and expectations about the proposed solutions (Gibson, 2010).

- Criterion #3: it is important to enable evaluation of trade-off acceptability

Trade-off acceptability evaluation should support the evaluation of whether and/or to what extent the trade-offs are acceptable. The analysis should be supported by a quantitative (performance measures and targets) and/or qualitative (i.e. desired or undesired trend) evaluation that should guide the judgments about trade-off acceptability or the need to consider new alternatives instead (Driessen and Hillebrand, 2013). The type of evaluation, the sequence of decisions and reframing of priorities need to be documented to ensure transparency and traceability of the decisions (Gibson, 2010).

- Criterion #4: it is important to develop tools and procedures that are relatively easy to be implemented by industrial practitioners

A decision-making process for sustainability should encourage dialogue between internal (cross functional) and external stakeholders and reinforce mutual learning about sustainability performance of the alternatives (Gibson *et al.*, 2005). This requires tools and procedures to be flexible to integrate knowledge of the decision makers from different functions and corporate levels in the decision analysis process rather than offer non-flexible computerized techniques, which might challenge practitioners in understanding the connection between the decisions and results of these techniques (Dekoninck *et al.*, 2016; Zarte, Pechmann and Nunes, 2019).

Reflection on the contribution

This study brings attention to the importance of supporting analysis of decisions involving sustainability-related trade-off situations. According to the reviewed literature, integration of sustainability criteria into decision process will likely involve trade-offs, hence there is a need to support trade-off analysis for a structured and informed decision making process. The four criteria are intended to stimulate future research in the following directions: i) how to incorporate the trade-off considerations into existing tools, techniques and approaches for the integration of sustainability in business processes; ii) how to develop guidelines to support trade-off prioritization and acceptability; iii) how to link trade-off prioritization and acceptability judgement to the sustainability maturity of a company. In this thesis, the four criteria served as a cornerstone for developing a trade-off navigation framework, presented in Chapter 3.3.2.

The results of this Study were documented in Paper 3, embedded next. The paper provides elaboration on the criteria and examples of sustainability trade-offs across business processes.

Paper 3: *Kravchenko, M., Pigosso, D. C. A., & McAloone, T. C. (2020)*

Developing a tool to support decisions in sustainability-related trade-off situations: understanding needs and criteria.

Proceedings of the Design Society: DESIGN Conference, 1, 265-274
https://doi.org/10.1017/dsd.2020.137

INTERNATIONAL DESIGN CONFERENCE – DESIGN 2020
https://doi.org/10.1017/dsd.2020.137

DEVELOPING A TOOL TO SUPPORT DECISIONS IN SUSTAINABILITY-RELATED TRADE-OFF SITUATIONS: UNDERSTANDING NEEDS AND CRITERIA

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Abstract

Early integration of sustainability considerations into decision making is seen as a key enabler for companies to understand the potential implications of their decisions on the triple bottom line aspects. Lack of the tools to support decisions when trade-off between sustainability aspects occur, however, may lead to uninformed decision-making and undesired outcomes. By consolidating the learnings from empirical work together with literature recommendations, we propose key criteria to be considered when developing decision support tools to manage sustainability-related trade-off situations.

Keywords: sustainability, decision making, design support system

1. Introduction

Early integration of sustainability considerations into decision making during various business processes is seen as a key enabler for companies to understand the potential implications of their decisions on the triple bottom line aspects (Korhonen et al., 2018) and introduce improvements early in the design and development processes (McAloone and Pigosso, 2018). This can support development of more sustainable products, services, processes and systems (Gagnon et al., 2012).

Various methods and tools have been proposed to assess the sustainability impact of products, services and processes, such as environmental LCA (ISO 14044, n.d.), cost-benefit analyses (Hoogmartens et al., 2014), Social LCA (Fontes et al., 2016). While the impact assessment methods can be deployed to understand the consequences of a project implementation (McAloone and Pigosso, 2018), their use in early stages to assist decision making is limited due to lack of information to feed the tools (Bengtsson, 2001). This creates several paradoxes: if information is lacking, the tools have limited applicability during the early stages of design to support decision making, thus making it harder to understand the sustainability performance in advance and introduce improvements; if the tools are used later in the process, firstly, the improvements may be harder to introduce, and secondly, the impacts may be impossible to trace back to the decisions that have been made during the process. To address this challenge, several tools have been proposed to be specifically employed early in the design and development processes, such as a streamlined LCA for early vehicle development by Arena et al. (2013), qualitative sustainability compliance index for early product development by Hallstedt (2017), leading sustainability indicators for circular economy screening by Kravchenko et al. (2019). These tools as well as many others aim to provide decision support in different business processes by integrating environmental, economic, social or three-dimensional sustainability considerations. While, indeed, these

tools provide a structured support in identifying relevant sustainability criteria and the logic for assessing the potential sustainability performance (e.g. of products, services or processes), the research calls for more work on integrating decision support techniques after the assessment is done (Stindt, 2017). Unambiguously this concerns development of structured procedures to support decision making in trade-off situations (Haffar and Searcy, 2017), which are inherent in sustainability-oriented decision making because of the complexity of considered criteria and uncertainty about sustainability outcomes (Siew, 2008; Simonovic et al., 1997). Earlier works (Byggeth and Hochschorner, 2006), as well as more recent (de Koeijer et al., 2017; Wu and Pagell, 2011) discuss the lack of support provided to the decision makers in industry in navigating complex decisions in sustainability trade-off situations. Decision support is needed to ensure the adequate information is used to enable practitioners making informed decisions by explicitly taking into account sustainability considerations and reinforcing knowledge about potential risks and opportunities behind their choices. Consequently, it may support selection of the 'best' alternative during design and development of sustainable products, services and processes.
This paper explores this issue by consolidating the learnings from empirical investigations and literature review to understand the criteria to be considered for the development of a decision-support tool to assist decisions in trade-off situations. Before that, we provide theory and examples of sustainability-related trade-offs to bring understanding when trade-off situations occur and when they are difficult. Subsequently, we provide examples of few studies that explored decision support techniques and the extent to which they enable practical management of trade-offs. Based on the findings, we identify gaps and opportunities for future research.

2. Research approach

The need for guidance in a trade-off situation emerged as part of the empirical work involving company case studies in a large Nordic research project on circular economy implementaiton. During the workshop activities, which aimed at assessing potential sustainability performance of a specific circular economy solution using leading sustainability indicators (Kravchenko et al., 2019), it became evident that the trade-offs were present. The trade-offs were made explicit after the selected indicators (measuring selected environmental, economic and social aspects), were calculated and used to compare two alternatives: the 'current' and the 'circular economy' solutions. This led to the investigation of the need to support decisions when trade-off between sustainability aspects occur.
Design Research Methodology (DRM) was used as a main framework to support the investigation (Blessing and Chakrabarti, 2009). While the DRM consists of four main and iterative stages, we followed first two to search for evidence to support our initial assumption and then to understand the advances in the current research and obtain information for the effective development of a design support later, as the research proceeded. In the first stage, Research Clarification, the intention was to clarify the need and understand the gaps in research related to trade-offs. As a result of this stage, the need to support practitioners in their decisions under trade-off conditions was made evident, in that:

- there is a need for providing a direct support to practitioners in a trade-off situation within and between sustainability aspects (Byggeth and Hochschorner, 2006; Haffar and Searcy, 2017);
- there is a need to develop decision support tools that are 'easily' integrated into decision processes and are understood by practitioners (Zetterlund et al., 2016).

The second stage, Descriptive Study, was then followed during which a literature review process has been conducted to attain an understanding of what criteria to consider when developing a decision support tool. This stage generated insights about the key aspects to be considered to fill the identified gaps and fulfil the needs (Blessing and Chakrabarti, 2009). The main contribution of this research is to complement current sustainability assessment research by initiating a discussion about how to guide the development of appropriate tools to support designers and project planners in navigating sustainability trade-off situations.

3. Research clarification: Sustainability-related trade-offs

Sustainability assessment can be simply defined as any process that directs decision-making towards sustainability (Morrison-Saunders and Pope, 2013). Being a process, decision-making occurs over period of time, often under complex and dynamic circumstances involving multiple objectives through participation of stakeholders often eliciting conflicting interests. Integration of sustainability issues further complicates the decision-making process, where the complexity lies not only in defining sustainability criteria and how they can be measured, but to what extent need sustainability considerations be as important as 'traditional' criteria (Gibson et al., 2005; Simonovic et al., 1997). Criteria are used by decision-makers to plan and guide the decision-making process to support taking a certain decision. It is widely acknowledged that the 'importance' of criteria is driven by a variety of values, which reflect fundamental (e.g. corporate or project) objectives (Retief et al., 2013). For instance, for a new product development project, such 'traditional' criteria would be: strategic fit; customer requirements; limited commercial risk and market responsiveness; conformity to law and regulations (Bovea and Pérez-Belis, 2012), while sustainability-related criteria could be: presence of toxic substances; energy efficiency; etc.

3.1. Trade-off types and occurrences

Trade-offs can be described as tensions in the decision-making process to favour some criteria that lead to certain desired outcomes over others. Byggeth and Hochschorner (2006) define trade-offs as *"situations when a sacrifice is made in one area to obtain benefits in another …* [whereby] *it is usually impossible to optimize them, all at once"* (p. 1420). For instance, during a packaging selection process, the tensions can arise between the 'traditional' criteria, such as cost of material, technical performance and supplier proximity, and sustainability criteria, such as recyclability or recycled content (de Koeijer et al., 2017). It has been reported that corporate trade-offs can arise on different levels, such as strategic (macro level), tactical and operational (micro level) (Hahn et al., 2010; Prendeville et al., 2017). Macro level trade-offs concern the question of *whether* (whether a company should engage in sustainability projects) with trade-offs related to sustainability dimensions, time considerations and stakeholder demands (Haffar and Searcy, 2017). Micro level trade-offs concern the questions of *which* (which areas to engage in sustainability) and *how* (how to engage in them, i.e. how to act and what principles to apply) (Byggeth and Hochschorner, 2006; Prendeville et al., 2017). Table 1 provides examples of trade-offs as identified by the literature. Interestingly, Haffar and Searcy (2017) note that trade-offs encountered on micro levels are influenced by those encountered on macro level, or put similarly, earlier choices influence (facilitate or delimit) further ones, making the decisions sequential (Wu and Pagell, 2011). Unambiguously, the sustainability-related trade-offs on macro level will occur as a result of corporate decisions only when the decision-makers are 'aware' of sustainability-related problems and can understand what opportunities exist (Haffar and Searcy, 2017), thus implicitly or explicitly establishing principles or rules according to which decisions at tactical and operational levels will be made. For instance, a corporate decision to become a producer of one of the most eco-friendly and energy-efficient insulation systems will signal about the corporate awareness of energy preservation needs and the environmental and health impact of insulation materials, while also influencing the principles product designer will follow and the criteria according to which the product's performance will be evaluated. While such criteria as presence of toxic materials and superior thermal properties (good insulator) could play a key role in product design, and can be considered as 'non-negotiable' (i.e. strategically set), consideration of other criteria such as material use, material cost and water usage can potentially lead to the identification of trade-off situations, i.e. more material needs to be used to satisfy the superior insulation requirement, thus increasing costs, or the process of producing the insulation material is very water intensive. These trade-offs, however, can only be identified if the decision makers (in this case product developers) use relevant sustainability assessment tools to identify other criteria to be included in the decision making process. This brings back the discussion in the introduction part about the importance of developing and providing relevant sustainability-related decision support tools to the practitioners to enable them to: i) set decision boundaries and reduce uncertainty of what criteria are important for sustainability-related decision-making (Gagnon et al., 2012); ii) enable a dynamic decision process, where the information selected is meaningful for the information users (Bengtsson, 2001; Zetterlund et al., 2016); iii) evaluate alternatives, uncover trade-off situations and use guidelines and rules to navigate trade-offs in an explicit way (Gibson et al., 2005); iv) make decisions in a rationale way and track every decision that has been made, reflect on it and iterate (i.e. select other criteria or select different alternatives for evaluation) whenever necessary (Waas et al., 2014; Watz and Hallstedt, 2018).

Table 1. Trade-off examples from sustainability literature

Reference	Research domain	Trade-off classification	Trade-off example
Byggeth and Hochschorner, (2006)	Eco-design and product development	According to sustainability aspect: a) in one environmental aspect b) between different environmental aspects c) between different sustainability aspects	a) Material weight vs material toxicity (e.g. small amounts of a toxic material and more weight of a less toxic material) b) More material vs less energy (e.g. more material for insulation to save energy in use) c) Material and cost (e.g. lightweight material that is more expensive)
Prendeville et al. (2017)	Eco-design and product development	According to decision levels: a) strategic b) tactical c) operational	a) Higher recyclable material costs due to supplier transportation costs b) Material substitution (recycled form of the virgin material is only offered by one supplier) c) Two parts are to be moulded together that affects cost-efficiency of disassembly
Björklund and Forslund (2019)	Sustainable logistics	No distinctive classification	- Social considerations vs investment - Uniform performance indicators for all logistic providers vs provider specific indicator and right balance of indicators across sustainability dimensions
Driessen and Hillebrand, (2013)	New product development	No distinctive classification, but based on stakeholder value prioritization	- Organic and locally grown ingredients: if no local suppliers offered organic options, the trade-off is between organic but international supply vs non-organic and local - Reduction of VOC content in chemicals complicates the use of the chemical by the user
Wu and Pagell (2011)	Sustainable supply chain management	No distinctive classification	- Support locally grown [organic] produce vs reliability of supply in terms of variability and volumes
de Koeijer et al. (2017)	Sustainable packaging development	No distinctive classification	- Material selection: 'known' less sustainable material vs 'unknown' more sustainable material (*unknown was linked to the newness of the material on the market and doubts about its long-term success)
Holt and Watson (2008)	Corporate social responsibility	No distinctive classification	- local vs international sourcing and carbon footprint: supporting local (often vulnerable) communities internationally (e.g. Fairtrade procurement) vs carbon footprint related to transport
Amaral and Guerreiro (2014)	Logistics planning	No distinctive classification, but based on time response and cost	- Transport mode: air shipping is costly but provides timely responses vs rail mode is cheaper but provides less timely responses; - Centralization of warehouses: centralized location increases outbound transport cost but lowers the inbound costs while the decentralized has the opposite effects plus increased warehouse cost per warehouse

3.2. Management of trade-offs and trade-off support techniques

From the theory presented above and the trade-off examples provided in Table 1, it is clear that understanding trade-offs, their occurrence and management is a complex task.

To understand how the literature has proposed to manage trade-offs and support decisions, we present summaries of several works that reviewed to what extent different tools support decisions in sustainability-related trade-off situations. These works provided reviews of tools from two different, but sustainability-related strategies, such as Eco-design and Sustainable supply chain management.

Byggeth and Hochschorner (2006) analysed 15 Eco-design tools to understand to what extent do they provide decision support in trade-off situations during product development process. Their conclusion was that while nine of the tools included valuation (i.e. implicit rating of importance of criteria or strategies), their support of decision was not sufficient. The authors indicate that valuation should concern not only the identification of trade-offs, but provide guidance for decisions when trade-offs are revealed. Several gaps in relation to the tools and their suitability for trade-off decision support are highlighted, such as: i) they may be too simple and do not address complex issues of sustainability; ii) some of the guidance needs to be supported only by using more comprehensive tools, such as life cycle assessment (for instance, 'dematerialization' strategy needs to be only prioritized when the whole life cycle is considered as opposed only to 'material consumption' aspect, to avoid sub optimization); iii) they do not give direct guidance on managing trade-offs concerning various aspects of sustainability, provided other 'traditional' criteria are satisfied. The latter one is especially relevant to address since few eco-design methods have been proposed to provide support in early design stages considering environmental and functional requirements of a product (e.g. the Green Quality Function Deployment by Bovea and Wang in (Bovea and Pérez-Belis, 2012). Despite the findings by Byggeth and Hochschorner (2006) in early 2000s, there is still a gap in the literature to support decisions in sustainability-related trade-off situations (Haffar and Searcy, 2017; de Koeijer et al., 2017).

Taticchi et al. (2015) analysed decision support tools for managing sustainable supply chain. The authors specifically focused on understanding to what extent performance measurements are supported by decision tools to guide supply chains design and operation. The conclusion was that while various methods and tools have been used to support performance measurements in sustainable supply chain, they rarely supported decisions to address conflicting objectives incorporating triple bottom line approach; furthermore, while mathematical modelling (such as multicriteria decision analysis and agent based modelling) that aims at optimizing solutions may be a practical manner to identify the most suitable option, it can lead to oversight of some trade-offs and impede alternative solution generation as a consequence of the trade-off management (de Magalhães et al., 2019).

To complement the literature, we acknowledge the importance of any sustainability assessment technique to include a decision support procedure to assist decision-making in a trade-off situation. This paper tries to investigate what criteria are necessary for the development of decision support tools. We specifically look at the literature concerning trade-offs that occur at tactical and operational levels, i.e. relate to decisions in business processes (as opposed to strategic processes), e.g. product development or manufacturing processes. Moreover, we are specifically interested in understanding techniques to address trade-offs within and between sustainability criteria, assuming all the other criteria fulfil the requirements of the project.

4. Outcomes of the descriptive study: Criteria for the development of a decision-support tool to assist decisions in trade-off situations

Due to the complexity of the trade-off situations and the lack of a generic tool to support sustainability-related trade-off decisions, we have consolidated few criteria that should be considered for the development of a decision-support tool to assist decisions in sustainability trade-off situations. This consolidation is based on the recommendations extracted from the above-cited works as well as on the results of internal discussions in the research group. These criteria are not exhaustive and serve to facilitate the discussion focused on trade-off management for sustainability aspects, as opposed to, for instance, trade-offs between functional requirements in a product development process.

Criterion #1: it is fundamental to enable elicitation of sustainability objectives and use relevant tools to reveal trade-offs

As discussed before, trade-offs are inherent in sustainability-related projects. However, not all the tools can reveal trade-offs, thus falling short on making them explicit for the decision-makers. Gibson et al. (2005) argue that a 'good' sustainability-oriented assessment should reveal trade-offs, because making the trade-offs explicit helps to address any major critical aspects of sustainability concern that can emerge as part of the decision process (Eakin et al., 2009). It is, therefore, essential to ensure that the decision-makers elicit their sustainability objectives before the assessment. For the objective elicitation, it is crucial to focus on 'fundamental' objectives as opposed to 'means' objectives to avoid too narrow focus (Hammond and Keeney, 1999). A fundamental objective can be to 'reduce overall environmental impact of a product X', rather than stating 'increase recyclability of a product X', which can be a means objective to potentially achieve the fundamental objective. After the objectives have been defined, it is important to select appropriate assessment tools and techniques (e.g. sustainability performance indicators) to understand to what extent the objectives can be achieved by different alternatives. Consequently, a tool that incorporates various sustainability aspects from the three-dimensional perspective should be prioritized (Byggeth and Hochschorner, 2006). Additionally, a tool should enable an assessment from a life cycle perspective (Byggeth and Hochschorner, 2006) and include a guideline or processes for identifying case and context-specific factors (Gibson et al., 2005). This can be linked to the main concerns of the sector, the company or a product can be classified according to (Kravchenko et al., in review): for instance, the packaging use and waste generation along the value chain should be considered as key issues if a company belongs to the food sector. Such guidelines can be very useful for the decision makers during the process, considering that most of the companies in EU are SME's (EC, 2019) and may not have an environmental or sustainability engineer, whose expertise is essential in facilitating the selection of key issues (McAloone, 1998). Furthermore, this process can also serve as a 'checklist' for environmental experts, who would often use heuristics to justify their choice, while being useful, however, may lead to systematic errors if not supported by additional tools (Bakker et al., 2012).

Criterion #2: it is important to provide several prioritization principles in conjunction to assist trade-offs understanding and management

Once the trade-offs have been revealed, it may be necessary to use several prioritization tools to provide a better understanding of the factors that influence and are influenced in the decision process (Driessen and Hillebrand, 2013). Those prioritization principles may be of qualitative and/or qualitative nature. One of the prioritization techniques can be to use strategic requirements to understand whether they can support or confront the intended decisions (Byggeth and Hochschorner, 2006; Hahn et al., 2010). For instance, the corporate commitment to offer a 10 year warranty can be a driving factor for adding more material (material use aspect) to increase durability. Another factor can be a brand image or customer requirement, which will, for instance, make a specific part or feature of a product 'preserved' from changes, e.g. white surface for medical appliances. For medical appliances, again, the safety criterion and legal requirements can be driving factors to replace some durable parts in a refurbished appliance to guarantee the conformity (i.e. more new parts will be used in a refurbished appliance even though the used parts were quality-tested and could serve another use cycle). To facilitate the preference-setting, those different factors or requirements can be classified as 'negotiable' and 'non-negotiable', thus delineating what can be accepted in design decisions (Morrison-Saunders and Pope, 2013). While it is mandatory to comply with minimum requirements of legislation and standards (Byggeth and Hochschorner, 2006) (i.e. non-negotiable criteria), companies can set their own minimum or maximum requirements. For instance, a minimum requirement for a cosmetics company is to never use parabens as preservatives in their products, which may require finding more expensive alternatives (cost aspect) or adding protective packaging to prevent mould formation (material use aspect). While EU regulates what forms of parabens are banned, and what maximum concentrations of specific parabens are allowed (Andersen and Larsen, 2013), it is still a higher priority for a company to use their own, 'non-negotiable' requirements. These 'non-negotiable' requirements can be set by a company to 'stay ahead' as a respond to a variety of changes, such as

legislative, social, technological, that might fore come as a consequence of the upcoming megatrends (KPMG International, 2014).
Another prioritization technique to use could be a relatively simple prioritization matrix, which could allocate all important criteria. The prioritization is done by a pair-wise comparison of the criteria and assigning a score to each. After several rounds of prioritizations, it may become obvious what criteria are negotiable, what are not, and what are the likely trade-offs to be 'accepted'.

Criterion #3: it is important to enable evaluation of trade-off acceptability

Different prioritization techniques enable the explication of the most important criteria and their relative importance to each other and to the main objectives. This creates visibility of the rationale about the trade-offs that are potentially to be accepted. However, before the final trade-off acceptance, it is important to evaluate the trade-offs. Gibson et al. (2005) have formulated several rules to be used during the process of argumentation for trade-offs. These rules can be used as a base to develop guidelines or checklists to be followed during the decision process. The following rules should apply for the evaluation of trade-off acceptability:

a) any acceptable trade-off must deliver net sustainability gains (over the long-term);
b) no trade-off involving significant adverse effect is acceptable unless all alternatives are worse;
c) no displacement of significant adverse impact from present to future can be justified unless all alternatives are worse;

To address the evaluation for the rule a), a set of guiding questions or a decision tree can be developed to assist understanding of the net sustainability gains. For instance, such questions as 'can you achieve a balance across objectives that cover all dimensions of sustainability?' can be used to understand if the selected alternative can be adjusted. If only two objectives can be balanced, another guiding question could address whether the 'sacrifice' of the third objective can be managed in the longer term (e.g. increased cost which is expected to decrease with time because of, for instance, maturity of the process or technology) or 'offset' by other projects. If no balance can be achieved between the objectives, the guidance could be to understand if other alternatives exist, otherwise the solution has to be rejected. For instance, if the product redesign can not guarantee achievement of the objective to reduce GHG emissions, the project can be suspended, however the strategic management can take a decision to reduce volume of produced and sold products, so to achieve the objective in an alternative way. In this way, it is essential that the designer team has the right tools to understand the trade-offs and communicate them upwards to have a decision taken. To address rules b) and c), a matrix can be used to understand the importance of trade-offs evaluated by e.g.: severity, probability, scale, duration, frequency of the adverse impact, for instance, using scales and colour schemes as in risk or environmental impact assessment matrices. To understand the severity and probability, it may be necessarily to consult experts from the field related to a trade-off. For instance, if application of a fiberglass material in a product is accepted despite the recyclability aspect being negative, experts from the field may indicate the latest advances in the recycling technology, which can help justify the trade-off acceptability. The expertise in the networks of suppliers, partners and customers can be advantageous to get knowledge about materials, products and processes (McAloone, 1998), which can reinforce sustainability learning and potentially lead to resolving the trade-off (Brennan and Tennant, 2018).

Criterion #4: it is important to develop tools and procedures that are relatively easy to be implemented by industrial practitioners

As previously discussed, a sustainability-oriented decision-making process should not be merely a computational process, but a process that facilitates dialogue between different stakeholders, reinforces learning and creates transparency of the decisions made during the process. Therefore, for a successful integration of sustainability considerations into conventional design and development processes, sustainability assessment and decision support tools need to be relatively simple, so the internal and external decision makers can be involved throughout the whole process, from objective setting, to modelling and assessment and then in interpretation and decision taking.

Interplay of the four criteria in the decision-making process

Taking into account the arguments put forward earlier, we discuss the importance of the above-mentioned criteria in influencing the outcomes of the decision process. Figure 1 visualizes different ‘spaces’ of the decision process, such as the space of objective and goal setting and decision taking, trade-off space and decision support space. We can argue that if criterion #1 is not satisfied, the trade-offs may not be revealed, which negates the inherent value of *decision-making* as a process, making practitioners resort to taking fast, simple and myopic decisions. If criteria #2 and #3 are not satisfied, likewise, the practitioners may use ad hoc approaches to selecting the ‘best’ alternative while accepting some trade-offs being unaware of potential risks this acceptability brings. This can consequently influence the ability of decision-makers in taking actions to improve performance of the selected alternative or mitigate the accepted trade-offs. Same outcome can also occur when criterion #4 is not satisfied, making it harder for decision-makers interpret the results and meaningfully utilize them.

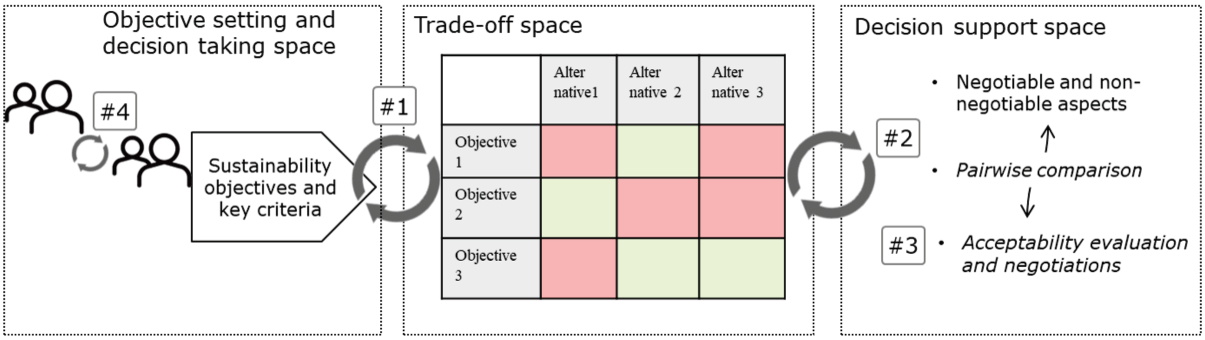

Figure 1. Relationships between different spaces of the decision-making process when the four criteria are considered

5. Concluding remarks

Based on the learnings from the empirical investigation and a literature review, this paper has explored the criteria for the development of a decision-support method to assist decisions in trade-off situations. The empirical work led to the identification of the need, which was then supported by the literature. Furthermore, the literature review provided an understanding of the types of trade-offs related to sustainability aspects and the gap related to the lack of the tool to guide decisions in a sustainability-related trade-off situations, provided all the other important criteria are satisfied. As a result, we elaborate on four criteria that are important to consider when developing a decision support tool. In summary, the key findings are following:

1. the four consolidated criteria seem to be generic to help resolving trade-offs during decision-making during various business processes; however there may be more criteria to consider
2. the four criteria can be used to develop an approach to trade-off management in the process of design and development of sustainable products and services
3. there are no apparent approaches focusing on trade-off management of this type, namely within and between sustainability aspects

Therefore, this paper is intended to inspire a discussion about what should be taken into account when developing a sustainability-related trade-off decision support tool. The main limitations of this study are related to the techniques employed to identify the criteria. Therefore, more research is needed to investigate how to complement the consolidated criteria and understand the approach to the development of the support tool. Future work should proceed by developing the support and testing it in empirical settings.

Acknowledgement

This article is one of the outcomes of the research project CIRCit (Circular Economy Integration in the Nordic Industry for Enhanced Sustainability and Competitiveness), which is part of the Nordic Green Growth Research and Innovation Programme (grant number: 83144), jointly supported by NordForsk, Nordic Energy Research, and Nordic Innovation. The authors would like to thank the CIRCit consortium partners for enriching discussions about CE and sustainability.

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3.3.2. A trade-off navigation framework support

The criteria consolidated from the literature review served as a foundation for proposing a trade-off navigation framework (TONF). Based on the selected criteria (as presented Chapter 3.3.1.), the TONF was operationalized, as summarized in Table 6 in Chapter 2.5.2. As a result, the proposal of the TONF contributes to answering RQ.4: How to support decision-making when trade-offs arise between sustainability performance indicators?

The TONF relies on Input data and a structured guidance (Figure 11), with the twofold objective to: i) help making trade-offs explicit, and ii) provide a structured approach to support trade-off analysis and acceptability in a transparent manner.

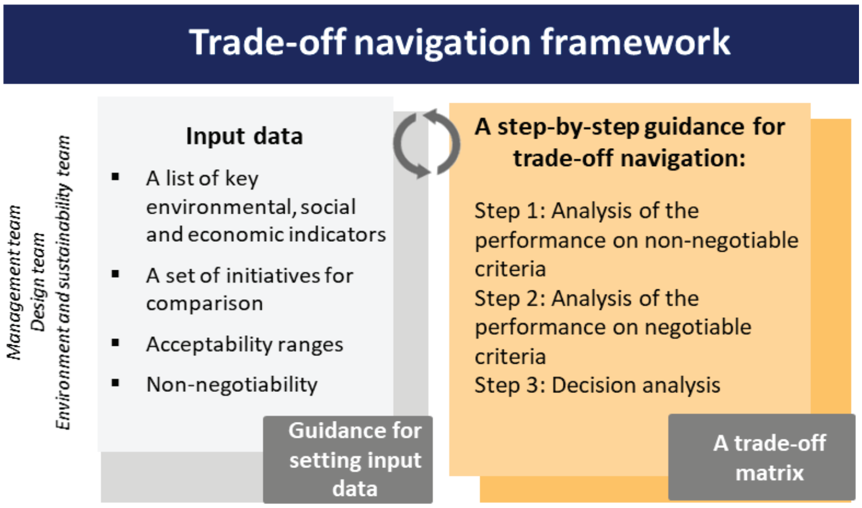

Figure 12. A trade-off navigation framework and its constituent elements: the Input data and the step-by-step guidance

'Input data' element acts as a pre-condition to reveal trade-offs and provide visibility of the decision framing to the decision-makers. Input data consists of a list of key environmental, economic and social indicators (or criteria), a set of initiatives that are considered in the decision-making process, definition of the acceptability ranges for the selected indicators and the level of their negotiability (Figure 11). To assist collection of input data, a guidance was proposed. Notably, a multifunctional team needs to be engaged for the provision of input data and handling trade-offs following a step-by-step guidance for trade-off navigation.

A step-by-step guidance for trade-off navigation consists of three steps, each aiming at supporting a dynamic and transparent dialogue about priority criteria, existing trade-offs, and initiative prioritization and re-evaluation in light of the revealed trade-offs. A trade-off matrix was developed in Excel to assist registration of input data and decisions. Step 1 focuses on the analysis of initiatives performance based on defined non-negotiable criteria. The advantage of this step lies in supporting a dialogue about defined acceptability ranges and why they are considered as non-negotiable. As opposed to weighting, it facilitates discussions and could trigger decision-makers to seek new or validate old information.

Step 1: Analysis of the performance on non-negotiable criteria

A. If *two or more alternatives* satisfy *all* the non-negotiable criteria, proceed to Step 2.
B. If *only one alternative* satisfies *all* the non-negotiable criteria, proceed to Step 3.
C. If *none of the alternatives* satisfy *all* the non-negotiable criteria, i.e. either some alternatives deliver the acceptable performance on some criteria but not the others, or neither of the alternatives deliver the acceptable performance, then all the alternatives should be rejected, unless:
    a. The non-negotiability of the criteria, hence the acceptable ranges, can be re-evaluated, supported by the questions:

- *Are the acceptability ranges too narrow or too broad?*
- *Can they be adjusted and how much?*
- *What is the aim of the defined acceptability ranges/target? (Does it show a problem/risks or an opportunity? Can it be seen as an approach to balance the objectives? Does it reflect means to achieving a specific goal?)*
- *Can we re-evaluate the ranges/target in a dialogue with stakeholders or management?*

This step requires returning to the Input data and re-evaluating: i) acceptability ranges; ii) number of considered alternatives; iii) number and type of key criteria for decision-making.

As a result of this dialogue, some ranges can be adjusted and the evaluation should proceed as follows:

D. If none of the alternatives satisfies all (adjusted) non-negotiable criteria, none can be accepted as is, requiring improvement or development of a new set of alternatives.
E. If two or more alternatives satisfy all the non-negotiable criteria, the analysis should proceed to Step 2.
F. If only one alternative satisfies all the non-negotiable criteria, the analysis should proceed to Step 3.

Step 2 focuses on the analysis or validate of initiatives performance based on defined negotiable criteria. Here, a pairwise comparison and ranking is suggested to support prioritization of the criteria explicitly.

Step 2: Analysis of the performance on negotiable criteria

In this step, the focus is done on the negotiable criteria. The analysis should only be performed for the selected alternatives from Step 1.

A. Select only the criteria for which none of the alternatives meets the performance within the acceptable ranges (e.g. if one criterion is satisfied by all the considered alternatives, it should be excluded from the analysis to simplify the weighting). For the selected criteria, weights should be assigned to them. A weight indicates the importance of one criterion relative to the other under consideration, i.e. a pairwise comparison. It is important to agree on the ranking scale and use it consistently to support the weighting process. A Likert scale from 'much more important' to 'much less important' could be used to assign priority weights. After weighting, a ranking of alternatives is performed based on their performance and the degree they satisfy the acceptable ranges. Similarly, a ranking scale should be defined, such as 1 to 3, i.e. from unsatisfactory (1), to some extent satisfactory (2), to satisfactory (3). As a result, the weighting score and the ranking score will be combined to show the alternative/s with the most satisfactory scores.
B. Following the results of the weighting and ranking process, a dialogue about the scores and whether they can help providing judgements for the prioritization of one alternative over others is encouraged. Proceed to Step 3.

Step 3 focuses on decision analysis considering the selected initiatives (e.g. which qualified Step 1 and were prioritized in Step 2), to allow decision analysis to be performed in light of potential trade-offs between all the criteria considered (Retief *et al.*, 2013). To make a decision, it is necessary to consider all the argumentations and justifications provided during the process.

Step 3: Decision analysis In this step, it is necessary to reflect back on the selected alternative(s) based on the results in Step 1 and 2. All the criteria, negotiable and non-negotiable, should be considered. To make a decision it is necessary to consider all the argumentations and justifications provided during the process. Following deliberations could occur: if the alternative X is accepted - can its performance on the non-negotiable criteria and high priority negotiable criteria compensate for the trade-offs that are accepted? If yes, does it reflect our goals and provide a new opportunity and minimizes risks? can alternative solutions be set up to compensate for the accepted trade-offs?

The TONF intends to encourage dialogue and provide a structured and transparent approach for analysing decisions and decision context, and not to provide a ready solution for such conflicts. In this way, it allows the decision-makers to "play" with scenarios, as to where different acceptability limits lie and how acceptable the considered alternatives are in light of those.

Reflection on the contribution

By using the TONF and following the guidance, manufacturing actors should be able to re-evaluate the priority criteria and proposed initiatives in light of the revealed trade-offs. By indicating how to frame a decision (input data element) and what relevant questions should be asked along prioritization and selection, the TONF ensures that adequate information is used to enable practitioners making informed decisions. This could reinforce knowledge about proposed initiatives, potential risks and opportunities behind their acceptance. Consequently, it may also serve as a feedback loop to manage conflicting criteria and introduce continuous improvements.

Motivated by the lack of support to manage sustainability trade-offs, the contribution of this study lies in the following: i) advancing the discussion about the importance of supporting sustainability-related trade-off situations; while there are various approaches to support balancing and management of trade-offs between traditional criteria (e.g. cost, technical performance), there is a lack of attention to sustainability trade-offs; ii) focusing on the importance of making trade-offs transparent; iii) proposing a hands on approach, which does not require modelling skills, hence can be used in the early stages of decision making.

Paper 4, which is embedded next, provides a detailed overview of the TONF development and evaluation. The paper puts forward: i) the summaries of literature reviews that supported understanding of the trade-off challenge among other manufacturing specific challenges; ii) the process of the TONF conceptualization and evaluation with experts; and iii) key learnings, contributions and limitations.

Additionally, a user guide and a trade-off matrix were developed to support operationalization of the TONF by practitioners. The user guide and corresponding matrix are made open access and available at (M. Kravchenko, Pigosso and McAloone, 2020a).

Paper 4: *Kravchenko, M., Pigosso, D. C. A., & McAloone, T. C.*
(In Review)

A trade-off navigation framework as a decision support for conflicting sustainability indicators within circular economy implementation in the manufacturing industry.

A trade-off navigation framework as a decision support for conflicting sustainability indicators within circular economy implementation in the manufacturing industry

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Abstract

Integration of sustainability criteria from a triple bottom line perspective is considered a challenge for manufacturing actors, who are engaged in developing sustainability-oriented initiatives. The earlier in the development process the criteria are integrated and sustainability potential is evaluated, the more opportunities exist to introduce improvements and select an initiative with a highest sustainability potential. The challenge does not only lie in understanding what sustainability criteria to use to assess sustainability performance, but in managing conflicting results, known as trade-offs. Trade-offs are situations characterized by conflicts between the desired objectives, where it is impossible to satisfy all criteria simultaneously. Although sustainability trade-offs are common, there is a gap in the existing approaches for sustainability measurements to support trade-off dialogue and decision-making. If trade-offs are not acknowledged, there is a risk of accepting an initiative leading to sub-optimizations or higher impacts. Therefore, this study proposes a framework to support trade-off analysis in the early development stages of sustainability-oriented initiatives. The trade-off navigation framework relies on Input data and a structured guidance, with the twofold objective to: i) help making trade-offs explicit, and ii) provide a structured approach to support trade-off analysis and acceptability in a transparent manner. The purpose is to encourage a dynamic decision process and reinforce the knowledge of decision-makers about potential risks and opportunities behind their choices. Using a case of CE initiative development, this paper discusses how a trade-off navigation framework was applied and evaluated by industrial and academic experts, leading to its improvement and identification of strengths and limitations.

Keywords: circular economy; sustainability indicators; triple bottom line; trade-offs; decision support; early development stages; business process

1. Introduction

In today's competitive and unpredictable markets, manufacturing companies are seeking innovative ways to transform their businesses to satisfy customer needs while sustaining long-term financial advantages and reducing environmental impact (Lacy, Long and Spinder, 2020), ultimately striving to contribute to sustainable development. Transition to circular economy (CE) is seen as one of the most powerful ways for business to innovate to achieve competitive advantage by building environmentally and socially resilient systems (EMF, 2013). CE implies a systems perspective, where production and consumption systems both need to be redesigned to function in a circular way, which aims at eliminating waste, minimizing pollution and retaining value of goods in the system for longer (Kirchherr, Reike and Hekkert, 2017). For the manufacturing industry, accordingly, it requires simultaneously engaging multiple business processes, including business models, product and service design, forward and reverse logistics, manufacturing, and others, to develop and implement a CE initiative (Lieder and Rashid, 2016).

For a CE initiative to contribute positively to sustainability, triple bottom line (TBL) considerations (i.e. economic, environmental and social aspects as elements of operational sustainability) should be embedded in early stages of its development (Korhonen, Honkasalo and Seppälä, 2018). A variety of new metrics and approaches to measure CE has been proposed (Saidani *et al.*, 2019): some focus on measuring economic value of recirculated products and materials (Linder, Sarasini and van Loon, 2017), others focus on measuring virgin material input as a degree of product's circularity (EMF, 2015). Although new methods and indicators to measure CE are being increasingly proposed (Lindgreen, Salomone and Reyes, 2020), it is questionable to what extent they can be used to understand environmental and economic potential of proposed CE initiatives (Harris, Martin and Diener, 2021). Lonca *et al.* (2018) report that the use of re-treaded tyres, while increasing the degree of product's circularity, increases fuel consumption of a vehicle, hence does not contribute to overall resource savings. Similarly, Cooper and Gutowski (2017) argue that reuse strategy might not always be more environmentally friendly for electric and electronic goods due to rapid advancements in energy efficiency. Despite there are studies that highlight economic and environmental benefits of CE initiatives compared to non-CE ones (Kaddoura *et al.*, 2019; Warmington-Lundström and Laurenti, 2020), a case by case assessment is needed (Schaubroeck, 2020). Questioning the applicability of CE-oriented metrics and approaches for the assessment of environmental and economic benefits of CE, the applicability of existing environmental and economic assessment methodologies was investigated (Elia, Gnoni and Tornese, 2017; Sassanelli *et al.*, 2019). In summary, several challenges exist: firstly, none of the analysed methodologies, including a life cycle assessment (LCA), seem to assess the impacts of CE initiatives that concern redesign of business models for a shared or access-based product use or service provision (Elia, Gnoni and Tornese, 2017); secondly, many methodologies do not go beyond the assessment of material and energy parameters (Sassanelli *et al.*, 2019); thirdly, the lack of assessment from a social perspective is missing (Kristensen and Mosgaard, 2020), yet alone the assessment from a holistic triple bottom line perspective (Kalmykova, Sadagopan and Rosado, 2017). The holistic TBL assessment is not only needed to document the impact of CE implementations (Korhonen, Honkasalo and Seppälä, 2018), but to support the development stages of CE initiatives for early assessment of CE potential and possibilities of introducing improvements (Kravchenko, Pigosso and McAloone, 2020). Indeed, business model and product development are seen as driving processes to enable CE development (Bocken *et al.*, 2016); additionally, other operational business processes might need to be considered to support CE implementation (Blomsma and Brennan, 2017).

To ensure a holistic sustainability consideration during CE initiative development and avoid sub-optimizations (or even more severe sustainability impacts), high importance economic, social and environmental criteria of the TBL approach need to be integrated early in business processes along the key CE and traditional criteria (Korhonen, Honkasalo and Seppälä, 2018). The inclusion of TBL criteria increases complexity during decision-making, and while techniques based on qualitative or quantitative indicators to support their measurement exist (Bovea and Pérez-Belis, 2012), they lack to provide support for conflicting TBL indicators, known as trade-offs (Buchert, Halstenberg and Stark, 2017; de Koeijer, de Lange and Wever, 2017). This gap highlights the lack of attention to trade-offs between TBL indicators, despite the evidence that integration of the TBL perspective as a sustainability-oriented decision support would always involve trade-offs (Gibson *et al.*, 2005), either between or within the TBL dimensions (Byggeth and Hochschorner, 2006). Decision support is needed to ensure that adequate information is used to enable practitioners making informed decisions by explicitly analysing the existing trade-offs in light of contextual settings (Zarte, Pechmann and Nunes, 2019). This could reinforce knowledge about proposed initiatives, potential risks and opportunities behind their acceptance (de Magalhães, Danilevicz and Palazzo, 2019).

In light of the presented, this paper brings forward the need to address a sustainability trade-off challenge, which industrial actors experience when integrating TBL indicators for sustainability measurement of the proposed initiatives, including CE initiatives. Consequently, this study proposes a trade-off navigation framework (TONF) to support decision-making between conflicting sustainability indicators in a structured and transparent manner. The framework seeks to fill the identified gap by considering multiple sustainability indicators and prioritization principles based on acceptability ranges and their negotiability. The framework incorporates a step-by-step guidance to support industrial practitioners in carrying out the decision analysis between conflicting sustainability indicators. Additionally, it integrates a trade-off matrix to visualize the required input data and record changes along decision process. The main aim of the TONF is to create transparency about sustainability trade-offs and support dialogue about the opportunities and challenges of the considered initiatives in light of the revealed trade-offs.

2. Research design and methods

The research process followed a step-by-step approach, depicted in Figure 1. Accordingly, the research commenced by developing an *understanding* whether and when sustainability trade-offs are a challenge, and whether a trade-off support is provided by the existing decision support techniques (Step 1). As the gaps were discovered, Step 2 was set for the identification of the key criteria that could drive the development of a trade-off decision support. A hypothetical-deductive approach was followed throughout Steps 3 to 5 with the aim to propose a trade-off navigation framework (TONF) following the initial set of criteria from Step 2 and evaluate the framework to introduce improvements and test its usefulness (Minnameier, 2010). The TONF was developed with the twofold objective to: i) help making trade-offs explicit, and ii) provide a structured approach to support trade-off analysis and acceptability in a transparent manner. Overall, the objective was to inform and support decisions during early integration of sustainability indicators in business processes engaged in CE initiative development.

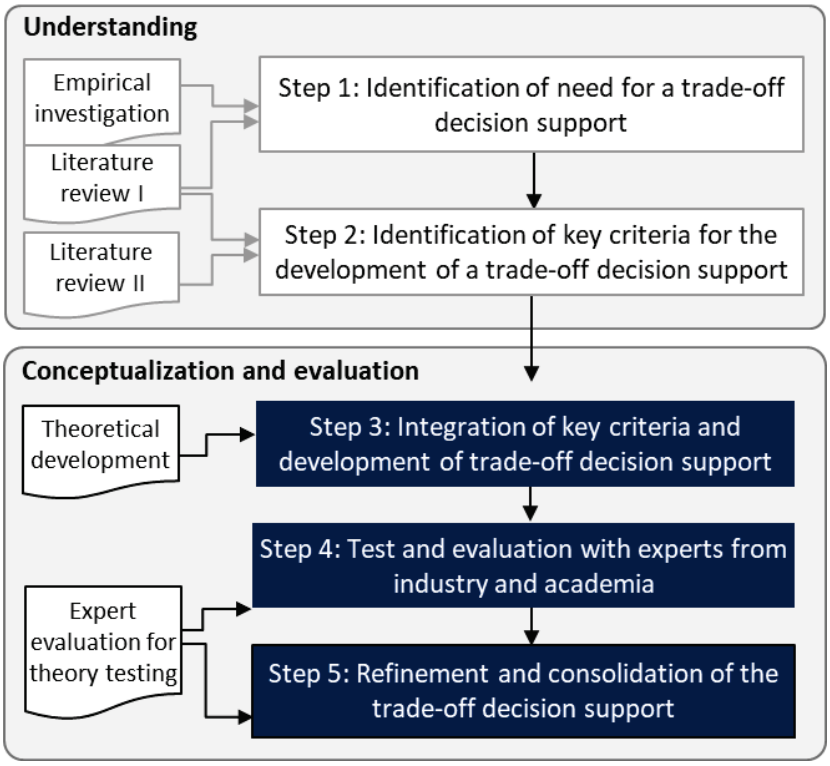


Figure 1. Overview of the research process with corresponding methods

To attain the objective, a number of research methods were employed in a following way:

Step 1 focused on the identification of a need for a trade-off decision support. Initially, the challenge regarding trade-offs became distinctive during the empirical work conducted in the preceding research that focused on the selection and application of relevant sustainability indicators to support development of CE initiatives. Subsequently, a literature review was performed with the aim of exploring whether the challenge of sustainability-related trade-offs, when implementing sustainability considerations during business processes, is a common challenge in the experience of manufacturing companies. Literature review I, a selective review (Yin, 2011), was performed because it is particularly useful to frame the research problem and clarify research assumptions (Rocco and Plakhotnik, 2009). The review focused on the studies from the fields of eco-design, sustainable business modelling, sustainable supply chain management and manufacturing to identify challenges relevant for a number of related business processes, such as business modelling (BM), product development (PD) and product-service system design (PSS), supply chain and manufacturing (SC&M). The review focused on the challenges related to the integration of sustainability criteria to support evaluation of a sustainability potential during early stages of decision process. Therefore, the generic challenges (e.g. time and cost of sustainability evaluation) (Dekoninck *et al.*, 2016) or challenges related to knowledge generation about sustainability issues and how to transform them into sustainability strategy or objectives (Schulte and Hallstedt, 2017; Stindt, 2017) were not taken into account. As a result, a trade-off challenge was identified as one of the most prominent challenges (as summarized in Section 3 in Table 2). Despite the result, the literature highlighted the gap in the existing tools to support decisions in sustainability-related trade-off situations (Molina-Besch and Pålsson, 2016; Buchert, Halstenberg and Stark, 2017).

Step 2, therefore, aimed at consolidating key criteria to assist the development of the TONF. A selective literature review II, similarly to literature review I, was performed with the aim to identify several criteria to act as building blocks for the TONF development rather than provide an exhaustive list of the criteria. The criteria were extracted from the literature from the field of eco-design (Byggeth and Hochschorner, 2006; Prendeville *et al.*, 2017) and sustainable supply chain management (Wu and Pagell, 2011; Björklund and Forslund, 2019), as well as normative works on sustainability assessment (Gibson *et al.*, 2005; Morrison-Saunders and Pope, 2013). The criteria are summarized in Section 4 in Table 4.

In Step 3, the criteria were operationalized into a first version of the TONF, incorporating Input data and structured guidelines as main elements of the TONF. The guidelines for a trade-off navigation are built based on some features of multicriteria decision-making analysis and psychology field.

In Step 4, the proposed TONF was tested and evaluated by two different expert groups: twelve experts from academia and eight experts from industry with mixed expertise (Table 1). A combination of interviews and a questionnaire was used for evaluation, as they are considered a common resource for gathering data about the outcomes of a theory testing (Blessing and Chakrabarti, 2009). The following hypothesis was formulated to guide the evaluation: 'the trade-off navigation can support manufacturing companies in making trade-offs transparent and supporting argumentations for trade-off justification and acceptability'.

The experts from industry were selected based on the following criteria: i) engaged currently or in the past in sustainability-related projects, either as an industrial practitioner or as a consult for industry. The experts from academia expressed their interest in participating in a workshop dedicated to trade-off navigation support. With industry experts, interviews were conducted with the selected participants individually. Each interview lasted for approximately one hour and followed the corresponding steps: i) presentation of the TONF; ii) presentation by the respondent about their background and challenge related to trade-offs; iii) demonstration of the TONF using an exemplary case; iv) semi-structured interview focused on the evaluation of the TONF attributes and general feedback. After each interview, the participants individually applied the TONF and subsequently filled in an evaluation questionnaire, consisting of 20 questions. The questionnaire served to collect information about respondents' knowledge area, familiarity with any sustainability-related decision support, followed by feedback on various attributes of the TONF that they had just trialled. The questions were varied, so as to both include closed-ended evaluation, relying on a three- and four-point Likert scales such as "to a larger extent", "to some extent", "no support" and "not satisfactory", "needs improvement", "satisfactory" and "very satisfactory", and an open-ended evaluation, in order to gather improvement suggestions. For the academic experts, the workshop was designed to compare two decision processes – one without- and one with the proposed TONF – using a simplified exemplary case, followed by the evaluation using the same evaluation questionnaire as for the industry experts. In Step 5, the TONF was refined, following the improvement suggestions from the combined evaluation by the industrial and academic experts. The final version of the TONF is presented in details in Section 4.

Table 1. TONF evaluation experts: industrial experts and academic experts

Expert ID	Area of expertise	Level of experience
Industrial experts (IE)		
IA#1	Product design, LCA modelling	>5 years
IA#2	Product design, manufacturing efficiency, circular economy design	>5 years
IA#3	Product design, circular economy design	>2 years
IA#4	Mechanical and environmental engineering	>25 years
IA#5	Health, quality and safety management, risk management	>2 years
IA#6	Product design, LCA modelling	>5 years
IA#7	LCA modelling, sustainability consulting	>10 years
IA#8	Environmental management, sustainable supply chain management	>10 years
Academic experts (AE) – collective		
AE#1-12	Product design, eco-design, LCA modelling	Mixed

3. Presentation of common challenges in implementation of TBL criteria in business processes and the prominence of trade-offs

Integration of sustainability into decision-making during business processes depends on a variety of so-called success factors, such as top and middle management support and commitment (Nilsson-Lindén *et al.*, 2018), allocation of time and resources (Short *et al.*, 2012), knowledge about sustainability issues (Abbasi and Nilsson, 2016) and ways of translating them into specific requirements (Schulte and Hallstedt, 2017), availability of tools (Dekoninck *et al.*, 2016), among others. Despite many businesses in Europe have defined their sustainability agenda at the strategic level (Short *et al.*, 2012), integration of sustainability into tactical and operational levels is still a challenge, for both large companies, as well as small & medium sized enterprises (SME's) (Paulson and Sundin, 2019; Watz and Hallstedt, 2020). This can be related to the complexity of criteria that decision makers at tactical and operational levels are dealing with – adding high relevancy environmental, economic and social criteria along key business, technical, functional, legal and customer requirements (Bovea and Pérez-Belis, 2012). Within the TBL criteria, several challenges exist and are prominent for a number of operational business processes. These challenges were consolidated through Literature review I in Step 1, as presented in Table 2.

Table 2. Challenges associated with implementation of sustainability criteria and the prominence of trade-offs: Note: fr[1] – frequency – number of publications; list of references is provided in Appendix I).

Nr	Challenge	Fr[1]	Example	Business process		
				BM	PD&PSS	SC&M
1	Prioritizing key sustainability issues and related criteria (e.g 'must' vs 'nice to have')	6	Deciding whether to focus on minimizing CO2 emissions and energy use or on water scarcity and water use	√	√	√

2	Balancing sustainability and other (technical, customer) criteria	9	Deciding whether to reduce VOC content in a chemical product which will complicate use of the chemical by the user	√	√	√
3	Finding a logic of selecting relevant sustainability indicators or measurement methods to quantify sustainability criteria	11	Deciding whether to use generic indicators or (customer, supplier, process) specific indicators; use absolute or relative indicators; find a right balance of indicators across sustainability dimensions	√	√	√
4	Uncertainty in what data to use for sustainability measurements and data quality	4	Understanding how toxicity is measured; understanding social issues are measured	-	√	√
5	Interpreting sustainability measurement results to guide decision-making process (e.g. to introduce improvements or show achievement of targets)	9	Understanding whether to focus on reducing the total number of chemical substances in a product or eliminating one chemical	√	√	√
6	Navigating conflicting sustainability criteria, indicators and measurement results	11	How to choose: increased durability compromises recyclability; sourcing of a recycled material increases transportation fuel use and costs	√	√	√

Challenge nr. 1. describes the difficulty of prioritizing key sustainability issues and related criteria (Hallstedt and Thompson, 2011; Battistella *et al.*, 2018; Paulson and Sundin, 2019), which can be associated with the lack of knowledge about interconnectedness of sustainability issues (e.g. waste generation) and related criteria (e.g. use of reinforced or mixed materials that are often hard to recycle) or the lack of procedures to support identification of significant issues and aspects (Issa *et al.*, 2015). The challenge of balancing sustainability and other (technical, customer) criteria (challenge nr. 2.) arises when optimizing the solution to satisfy both sustainability and other criteria is not possible (Abbasi and Nilsson, 2016; Dekoninck et al., 2016; Schulte and Hallstedt, 2017; Kennedy and Bocken, 2020). One example of such a conflict a manufacturer might experience is a potential to reduce VOC (volatile organic compound) content in their chemical product, however not doing so because such reduction complicates the use of the chemical by the user, which might affect user satisfaction (Driessen and Hillebrand, 2013). This challenge exemplifies a conflict between sustainability criteria and customer criteria. Another challenge is related to understanding how to select relevant sustainability indicators (nr. 3.) (Chou, Chen and Conley, 2015; Zarte, Pechmann and Nunes, 2019) or measurement methods to quantify sustainability (Abbasi and Nilsson, 2012; Stindt, 2017), which could signal about either the lack of support available in industries to systematically select relevant sustainability indicators among hundreds of potentially applicable (Kravchenko, Pigosso and McAloone, 2020) or uncertainty about suitability of some methods for sustainability measurement in the early stages (e.g. diametrically opposite views on suitability of LCA for BM measurement as in Evans *et al.*, 2017 and Manninen *et al.*, 2018; or for PD as in Schulte and Hallstedt, 2017 and Schöggl, Baumgartner and Hofer, 2017, or for logistics planning as discussed in Abbasi and Nilsson, 2012). Application of sustainability indicators requires setting up a procedure to collect relevant data. However, there is a challenge related to the uncertainty of understanding what data to use for sustainability measurements and how to verify data quality and reliability (nr. 4.) (Stindt, 2017; Paulson and Sundin, 2019). Firstly, this issue can be attributed to the challenge of finding a relevant indicator or a measurement tool (challenge nr. 3), secondly, to the issues of adding social criteria, which are often qualitative, along more tangible environmental and economic (Bhamra, Lilley and Tang, 2011). Thirdly, the challenge (nr. 4) can relate to the issue of time and cost associated with data collection and verification – use of generic data from databases is commonly a faster and cheaper way of data acquisition, however acquiring data from own operations, suppliers and users is regarded as more accurate and reliable (Fontes, 2016), although costly and time demanding.

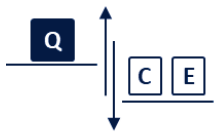
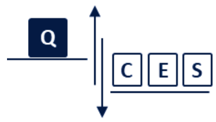
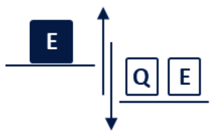
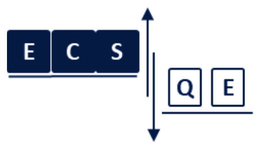
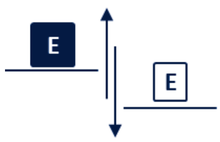
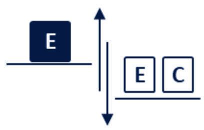
The ability of decision-makers to generate knowledge about relevant sustainability issues and use this knowledge as a feedback loop to guide decision-making implies that they can interpret the results of sustainability measurements; however this is frequently reported as a challenge (nr. 5.) (Chou, Chen and Conley, 2015; Dekoninck et al., 2016; Silvius et al., 2017; Held et al., 2018). Few possible reasons for a difficulty in result interpretation could be provided; firstly, it can be related to the unstructured process of sustainability integration, where the measurement (or assessment) is done without the explicit link to (what should precede the actual measurement) identification and selection of relevant sustainability issues and criteria, thus creating ‘fuzziness’ in sense-making process leading to devaluing sustainability assessment results (Shields, Šolar and Martin, 2002; Watz and Hallstedt, 2020). Secondly, because of the complexity of the results generated by certain mathematical tools or software, which are not easily pointing out at the improvement opportunities (or rather who should be using the result to indicate improvement opportunities) (Held et al., 2018) or requiring an analytical expert to clarify the results (Bengtsson, 2001), which can further be exacerbated by the lack of knowledge of sustainability issues by decision-makers who are the direct users of the results.

Additionally, practitioners experience challenges, when navigating conflicting results, i.e. trade-offs (nr. 6.). Trade-offs are situations characterized by conflicts between the desired objectives (Byggeth and Hochschorner, 2006), where it is impossible to satisfy all criteria simultaneously (Dutta et al., 2016). Trade-offs complicate the decision process, when a decision making team encounters difficulties in either balancing the key triple bottom line criteria or prioritizing some criteria at the expense of others (ibid.).

To prioritize and balance sustainability criteria, weighting and rating techniques are used, however, often under uncertainty(Matschewsky, Lindahl and Sakao, 2015; Dekoninck *et al.*, 2016; Buchert, Halstenberg and Stark, 2017). Uncertainty results from an unstructured process of working with sustainability criteria, i.e. the missing logic of selecting relevant criteria, as well as not utilizing results of the assessment to support weighting and ranking (Bengtsson, 2001). Uncertainty also causes decision-makers to resort to simple procedures in decision-making and use *ad hoc* tactics, e.g. selection of the same criteria used in previous projects or as a result of subjective preferences of the team without strategic, tactical and stakeholder perspective (Watz and Hallstedt, 2018). This tactic may compromise the decision-makers' ability to understand trade-offs and manage them along the initiative implementation (Wu and Pagell, 2011).

Table 4 presents some of the trade-offs that might arise during the development of a CE initiative. Due to a CE being rooted in existing concepts such as industrial ecology, sharing economy and eco-design (Geissdoerfer *et al.*, 2017), the trade-offs for CE development are common. Table 4 shows that trade-offs can arise: i) between sustainability-related and other (e.g. technical, quality) criteria; ii) between sustainability criteria, for instance, between economic aspect of cost and environmental aspect of selecting a non-toxic material; iii) as well as within the dimensions either between different aspects, such as selecting a more lightweight durable material, however not recyclable, or within aspects, such as selecting a lightweight material, however containing toxic substances (Byggeth and Hochschorner, 2006).

Table 4. Examples of trade-offs between CE criteria and sustainability criteria during development of CE initiatives.

Development of a CE initiative	**Challenges and potential trade-offs between the CE criteria (E – environmental, Q – quality, C – cost)**		**Challenges and potential trade-offs with added triple bottom criteria (E – environmental, Q – quality, C – cost, S – social)**	
Offering a leasing scheme for a product (limited time allows to control returns of used products; reduced cost of 'ownership' for the customer) (Agrawal *et al.*, 2012)	Might require adding/substituting material to increase durability of a product (or parts) leading to increase in development costs and higher (or other type of) resource use		Might require selecting a material supplier who has not documented material origin	
Introduction of recycled content (to reduce reliance on virgin materials) (Hahladakis and Iacovidou, 2019)	Might reduce product/part aesthetic quality (leading to customer dissatisfaction) and physical durability (leading to shorter lifetime)		Recycled material might be offered by local recycler at reduced costs	
Elimination of toxic substances (e.g. from impregnation process) (to reduce contamination of potential recycling flows) (Pieroni, McAloone and Pigosso, 2019)	Might compromise durability of the product leading to its premature obsolescence and waste generation		Might require additional cost from the user to maintain the product	

While translating sustainability requirements into 'traditional' design and development requirements helps concretizing sustainability criteria (e.g. relating "reduce fuel usage" to "lower car weight" in product design) (Romli *et al.*, 2015) and ensuring they will be included in the decision making process, not all sustainability criteria can be directly translated into such specifications (Watz and Hallstedt, 2018), which requires a list of additional sustainability criteria to be added as key criteria in the decision process. It can be pointed out that implementation and trade-off challenges arise as a result of a more thorough work with sustainability during initiative development stages, which in turn could signal about a relatively high maturity of design process to jointly consider sustainability issues to strengthen decision-making processes (Pigosso, Rozenfeld and McAloone, 2013).

The review shows that most challenges are very prominent for all business processes; additionally, it also shows that trade-offs could arise not only when comparing initiatives on the basis of sustainability indicators, but also when prioritizing sustainability indicators. The review also highlighted the gap related to the availability of a trade-off support - whereas sustainability-related trade-offs can be considered inherent in any sustainability-oriented decision-making process (Gibson et al., 2005), existing tools and techniques do not provide support to decision-makers at tactical and operational levels in navigating complex decisions in sustainability trade-off situations (Buchert, Halstenberg and Stark, 2017; de Koeijer, de Lange and Wever, 2017).

As a result, this study proposes a trade-off navigation framework (TONF) to support decision-making in trade-off situations between sustainability criteria. Due to the challenge reported for a number of business processes, the TONF aims to be rather generic and understandable by practitioners from different business functions. This particularity is essential, when considering that the majority of CE initiatives require involvement of a range of business processes to contribute to its design and implementation (Bocken *et al.*, 2016), therefore it can be expected that the decision support is understood and applied across functions.

4. Presentation of the TONF

4.1. Criteria for the development TONF

In order to support the TONF development, literature review II was conducted with the aim to identify several criteria. Table 5 presents the consolidated criteria, elaborations on them and how the criteria were operationalized in the TONF. As seen from Table 5, the criteria were embedded in the TONF by establishing requirements for Input data and developing a steb-by-step guidance to support decision analysis using the input data. The TONF is presented afterwards with detailed descriptions of the use context, requirements to the Input data and the steps in the guidance.

Table 5. Criteria for the development of a TONF based on key findings from literature

Criteria #	Elaboration	Criteria embedded in the TONF
Pre-condition		
#1 – Reveal trade-offs between and within sustainability dimensions (Gibson *et al.*, 2005); (Byggeth and Hochschorner, 2006);	- To reveal trade-offs, a sustainability assessment or performance measurement should be employed, providing results about performance from a three-dimensional perspective	**Input data:** - indicators (or criteria) to cover a holistic TBL perspective (cross and within dimensions)

(Abbasi and Nilsson, 2016); (Watz and Hallstedt, 2020)		- information about corporate and initiative-specific objectives and targets - multifunctional team of decision-makers
Decision analysis		
#2 – Provide several prioritization techniques to encourage open dialogue (Driessen and Hillebrand, 2013); (Morrison-Saunders and Pope, 2013); (Stindt, 2017)	- Prioritization techniques should encourage open dialogue about negotiable and non-negotiable criteria and facilitate ranking of alternatives - Prioritization techniques should encourage result interpretation and allow for deliberations of potential risks and opportunities of the proposed alternative initiatives	**A step-by-step guidance:** - guidance for setting acceptability ranges - guidance for setting non-negotiable and negotiable criteria - guidance for prioritization and dialogue on trade-off acceptability - guidance for a pairwise comparison and ranking
#3 – Provide rules to evaluate trade-off acceptability (Gibson *et al.*, 2005)	- Rules should encourage evaluation of trade-off acceptability	
#4 – Easy to use (Matschewsky, Lindahl and Sakao, 2015); (Zetterlund, Hallstedt and Broman, 2016); (Buchert, Halstenberg and Stark, 2017)	- Should be easily integrated in the decision process and applied directly by an industrial practitioner in daily routines (i.e. without support of a third party expert)	N/A - the TONF does not require utilizing programming techniques and requires direct involvement of a practitioners/decision-makers - practical examples to support each step of the guidance
#5 – Flexible for different business processes (own criteria based on the summary of challenges in Table 2)	- Should be rather flexible to accommodate needs of decision-makers in different business processes	N/A - practical examples to support each step of the guidance

4.2. Presentation of a TO navigation framework – required inputs and detailed guidance

The TONF consists of two elements, the Input data and a step-by-step guidance for trade-off navigation using the Input data and a supporting trade-off matrix developed in Excel (Figure 2). Use context is defined as following:

- Early stages of sustainability-oriented initiative development (e.g. conceptualization stages of business modelling and product development)
- Multifunctional teams (e.g. management, product designers, sustainability managers)

4.2.1. Input data

Input data are required as it acts as a pre-condition to reveal trade-offs and provide visibility of the decision framing to the decision-makers, therefore, are necessary to include in the decision making process and support trade-off analysis. Input data show what information is required to frame a decision, supported by the corresponding guidance for where to obtain it. Due to the decision-making being a collaborative process, characterized by the complex nature of decisions that are interdependent (Hansen and Andreasen, 2004), the information gathering would require time, iterations and involvement of several decision-makers, such as project leaders and management team, designers and engineers, and environmental or sustainability professionals (Figure 2). The iterations are necessary because decision-making is a process, during which 'tentative' decisions, based on the available information, are made until new information emerges to help verify the decision (ibid.). Therefore, the information required would need to be updated anytime a new type of information is available, and the guidance for trade-off navigation facilitates this.

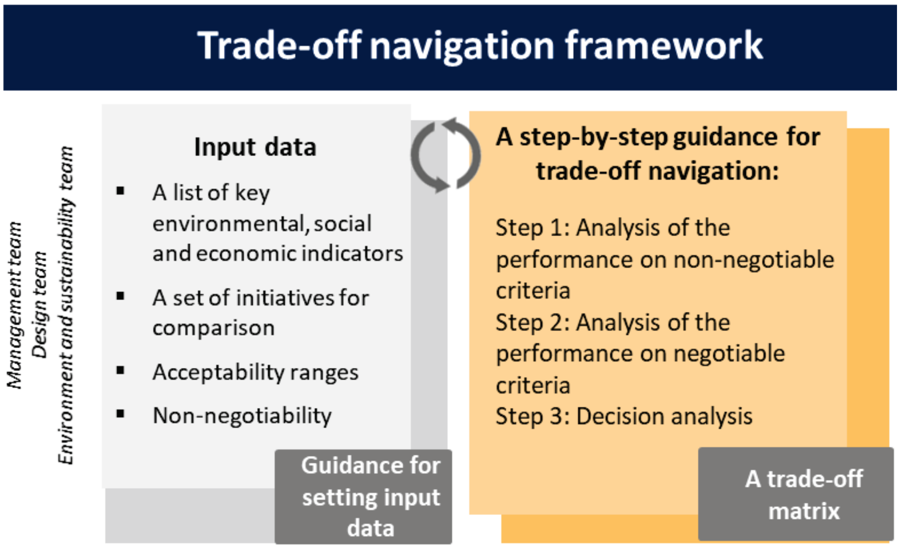


Figure 2. A trade-off navigation framework and its constituent elements: the Input data and the step-by-step guidance.

A. A list of key indicators for a set of initiatives for comparison

The 'success' of manufacturing industry in investigating and advancing sustainability initiatives to achieve competitive advantage is directly linked to *the contextual settings*, i.e. the ability of the industrial actors to exploit internal capabilities and external resources during business processes (Ray, Barney and Muhanna, 2004). In other words, identifying, managing, and leveraging *contextual sustainability* criteria during business processes, such as business modelling or product development, are critical in ensuring the alternative initiatives are proposed to solve particular sustainability problems. Sustainability objectives can be understood as statements for what specific problems have to be solved and to what extent and indicate a direction of preference (Shields, Šolar and Martin, 2002). Driven by the corporate strategic vision and corporate objective (DaSilva and Trkman, 2014), the sustainability objectives should be formulated: while the sustainability objectives on a strategic level can be generic (e.g. minimize environmental impact), they should be translated into *specific objectives and then into specific criteria* to provide guidance and serve as requirements for decisions and actions at tactical and operational levels (Hallstedt, 2017). *Economic, social and environmental criteria* should then be considered during the decision making process, i.e. during development of alternatives. These criteria can often be expressed as either qualitative or quantitative indicators (Table 6), which serve as decision criteria to guide evaluation of the 'best' initiative, i.e. the solution with the highest potential, or performance, of fulfilling the stated objectives (ibid.). Importantly, the criteria and/or indicators need to be (formulated) aligned with the information and terminology used by the actors, who are to be involved in the decision making (Bengtsson, 2001), because uncertainty about the meaning of criteria and their values can lead to 'under prioritization' of the unknown (less known) criteria (Retief *et al.*, 2013).

Table 6. Relationships between objectives, criteria and indicators (based on Shields, Šolar and Martin, 2002)

Corporate values and strategy - approach to sustainability			
control	**Objective** ***(as a direction)***	**Criteria** ***(as a concrete aspect)***	**Indicator** ***(as a measurable support)*** *information*
Decisions and actions	- increase product safety OR - eliminate toxic substances	Toxicity of a product	Measured by e.g. type and amount of toxic materials in a product (%)
	- increase work safety	Safety at working stations	Measured by e.g. noise levels; physical load index; etc.
	- increase share of products that can be recycled	Product recyclability	Measured by % of recyclable material in a total mass of product
			Consequences/Impact assessment

In sustainability-related assessments, complementary use of quantitative and qualitative indicators and measures is advisable (Waas *et al.*, 2014), which provides a basis to assess, compare and reveal a difference between proposed alternatives. The assessment can concern: i) comparison between several alternative (design) solutions proposed to reach a particular objective, e.g. comparison of a 'traditional' sale-based business model with an 'access-based' business model; ii) evaluation of the degree of improvement between design options for a product, e.g. 'traditional' product design versus design following circular economy principles (e.g. bio-based materials) (Kjaer *et al.*, 2018); and iii) evaluation of performance to drive the objective setting (Retief *et al.*, 2013). Therefore, the goal of employing a sustainability assessment early in the design stages is to ensure that performance indicators and measurements could provide early warning and indicate areas to support improvements or point out the 'best' alternative, which delivers desired performance on the selected criteria.

B. Guidance for indicator selection

It is necessary to establish a set of key criteria or indicators to cover economic, social and environmental dimensions. Ideally, a number of criteria should be around 7 and max 10, with more criteria complicating the decision process (Retief *et al.*, 2013). Selection of the key criteria should be based on the contextual settings (Watz and Hallstedt, 2018), i.e. aligned with company's strategy and objective, corporate approach to sustainability, specifics of the products and processes, or driven by the results of past impact assessments (Arena *et al.*, 2009). Sustainability criteria can selected from the existing frameworks, such as sustainability criteria and sustainability compliance index for product development by Hallstedt (2017). As highlighted before, the criteria might need to be expressed as indicators, which allow for more granularity to measure performance on the criteria: criteria 'resource use' can be expressed by indicators measuring material use, material sourcing origin or material toxicity. Several procedures are available to support such evaluation, such as quantitative evaluation of business model concepts for circular economy by Pieroni, McAloone and Pigosso (2019), sustainable manufacturing indicators by OECD (OECD, 2003) and leading performance indicators for sustainability screening of CE initiatives by Kravchenko, Pigosso and McAloone (2020). Ideally, 10 to 15 indicators ought to be used (ibid.), covering either multiple criteria (aspects) from the same sustainability dimension (e.g. energy and material aspects of the environmental dimension) or multiple criteria from different dimensions (e.g. cost, toxicity, user safety, number of different type of material in a product). While it is important to include criteria for economic, social and environmental dimensions for a holistic sustainability coverage (Gibson *et al.*, 2005), in some cases only one dimension can be considered, however represented by diverse criteria (e.g. material efficiency, energy efficiency, toxicity) (Arena *et al.*, 2009). To frame a decision, several sets of criteria might be established, however the criteria within one set should belong to one level, i.e. either strategic, tactical or operational, to support decision framing and prioritization. Number of alternatives for comparison should be limited to a maximum of 7 (Retief *et al.*, 2013), however, fewer alternatives are desirable if the alternatives are very different (e.g. alternatives to reach a particular objective as opposed to alternatives for a (design) parameter change).

C. Acceptability ranges and their non-negotiability

Acceptability ranges is another input required to support decision framing. In that, this requires information which acts as a support for the evaluation of whether and/or to what extent the proposed initiative is acceptable, whether trade-offs exist and how significant they are and whether they have to be accepted or new alternatives should be designed instead (Driessen and Hillebrand, 2013). Negotiable criteria are the type of criteria the acceptable ranges and targets for which are flexible to be adjusted along the decision making process. Similarly, non-negotiable criteria can be understood as a boundary condition which 'locks in' the acceptable ranges and targets, thus helping to rank these criteria as an important priority.

D. Guidance for setting acceptability ranges and non-negotiability

For each indicator (or criterion), acceptable ranges should be specified. Acceptable ranges might consist of a minimum and maximum value that sets lower or higher limits for acceptable performance on the key indicators. Acceptable ranges should be defined considering internal and external sources for sustainability requirements that should guide the decision. A following list of the internal and external sources was created to assist definition of acceptable ranges as follows(Bovea and Pérez-Belis, 2012):

- Strategic vision, goals or project objectives set by the decision-making group (e.g. influenced by past performance impact assessments, trends analysis, dialogues from sectorial associations, market position, etc.)
- Customer and/or stakeholder requirements
- Technical (and performance) requirements
- Legal requirements (incl. health and safety, quality) and legal thresholds

Depending on these requirements, there might only be a lower value, a higher value or both. Depending on the number of the indicators, sustainability maturity of the company or the early stage of the decision process with limited information, qualitative statements can be used instead of quantitative values (Watz and Hallstedt, 2018). Examples of acceptability ranges for different contextual settings are shown in Table

7. Not all the acceptability ranges might be available at the point of the decision-making, therefore, it might be necessary to involve different stakeholders (internal and external) to create the inputs for the ranges, or discuss the ranges inside the project team itself.

Table 7. Examples of acceptability ranges for different contextual settings

<table>
<tr><td colspan="3">Examples of different acceptability ranges considering contextual settings:
for the criteria 'product toxicity' (measured by both type of toxic substances and their concentration) there might be different limits set by two companies.</td></tr>
<tr><td rowspan="2">Criterion</td><td>Company A</td><td>Company B</td></tr>
<tr><td>Acceptable ranges</td><td>Acceptable ranges</td></tr>
<tr><td>Toxicity of materials in a product</td><td>Acceptable limits:
the maximum and only acceptable limit is 0 for both type and concentration</td><td>Acceptable limits:
the lower value is set to 0 and higher value is set to 4% (of all types of substances, e.g. flame retardants) by total material weight following corporate goal to gradually phase out all toxic substances</td></tr>
</table>

Non-negotiable criteria can be defined following the sources used to define the acceptability ranges as presented earlier. For each criterion selected for the decision process, the classification is based following the logic: negotiable criteria would be defined as the ones with relatively flexible ranges; non-negotiable criteria would be defined as the ones with fixed acceptability ranges. Importantly, the classification of the criteria will not only differ from one company to another, but also within a company, from project to project, depending on the type of sustainability issue and the proposed solution (Retief *et al.*, 2013). Grounded in the importance of the contextual settings for prioritization, few questions were proposed to support reflection on the criteria classification, aiming at avoiding *ad hoc* prioritization (driven by past decisions or *a priori* values) (Watz and Hallstedt, 2018), such as: i) why is the criterion non-negotiable and what is the reference (source) for that; ii) how updated is this information? Examples of non-negotiable and negotiable criteria are given in Table 8.

Table 8. Examples of non-negotiable and negotiable criteria

<table>
<tr><td colspan="5">Examples of different acceptability ranges considering contextual settings:
for the criteria 'product toxicity' (measured by both type of toxic substances and their concentration) there might be different limits set by two companies.</td></tr>
<tr><td rowspan="2">Criterion</td><td colspan="2">Company A</td><td colspan="2">Company B</td></tr>
<tr><td>Acceptable ranges</td><td>Negotiability</td><td>Acceptable ranges</td><td>Negotiability</td></tr>
<tr><td>Toxicity of materials in a product</td><td>the maximum and only acceptable limit is 0 for both type and concentration, because it is a requirement of a customer</td><td>Non-negotiable criteria based on the customer requirements</td><td>the lower value is set to 0 and higher value is set to 4% (of all types of substances, e.g. flame retardants) by total material weight following corporate goal to gradually phase out all toxic substances</td><td>Non-negotiable criteria based on corporate objective</td></tr>
</table>

Recycled content in a product	the minimum and only value is 40 %	Non-negotiable based on the requirement of a customer	the minimum and only value is set to 25 %	Negotiable based on the corporate objective to replace virgin content by recycled whenever possible

4.2.2. A step-by-step guidance for a trade-off navigation

To start the decision analysis and record the decision process, all the information required by the Input data needs to be presented. A trade-off matrix was constructed in the Excel spreadsheet, allowing to register all the information. The coding in the matrix was done in a way to highlight which alternative and on what criteria does satisfy (highlighted in green) or does not (highlighted in red) the acceptability ranges. If one or more alternatives satisfy *all* the criteria, either of them can be selected to proceed for further development. If not all the criteria are satisfied, the analysis and a trade-off dialogue are encouraged following the proposed steps:

Step 1: Analysis of the performance on non-negotiable criteria

In this step, the focus is done on the non-negotiable criteria. All the alternatives should be compared based on their performance on non-negotiable criteria.

A. If *two or more alternatives* satisfy *all* the non-negotiable criteria, proceed to Step 2.
B. If *only one alternative* satisfies *all* the non-negotiable criteria, proceed to Step 3.
C. If *none of the alternatives* satisfy *all* the non-negotiable criteria, i.e. either some alternatives deliver the acceptable performance on some criteria but not the others, or neither of the alternatives deliver the acceptable performance, then all the alternatives should be rejected, unless:
    a. The non-negotiability of the criteria, hence the acceptable ranges, can be re-evaluated, supported by the questions:

- *Are the acceptability ranges too narrow or too broad?*
- *Can they be adjusted and how much?*
- *What is the aim of the defined acceptability ranges/target? (Does it show a problem/risks or an opportunity? Can it be seen as an approach to balance the objectives? Does it reflect means to achieving a specific goal?)*
- *Can we re-evaluate the ranges/target in a dialogue with stakeholders or management?*

This step requires returning back to the Input data and re-evaluating: i) acceptability ranges; ii) number of considered alternatives; iii) number and type of key criteria for decision-making (Figure 2).

Notably, while in most cases non-negotiable criteria are ‘locked in’, i.e. non-negotiable at the moment of decision making, their ‘non-negotiability’ can be revisited internally or externally, facilitated by the questions above. The dialogue facilitation is seen as a way to challenge the status quo and encourage information seeking and knowledge reinforcement (Retief *et al.*, 2013). For instance, alternative A may produce more noise than alternative B, but if the noise levels for both are within the acceptable ranges, they both qualify as potential alternatives to be accepted for further development. Similarly, alternative

A may produce more noise level than B, but also more than acceptable ranges permit. Then the evaluation should concern the analysis of the degree to which the noise level for alternative A is unacceptable and why. It has been shown that re-negotiations on the acceptability can happen with the involvement of internal or external stakeholders and managers, who will have an influence on the acceptability ranges and who might establish new initiatives to balance the accepted change (Epstein, Buhovac and Yuthas, 2015). As a result of this dialogue, some ranges can be adjusted and the evaluation should proceed as follows:

D. If none of the alternatives satisfies all (adjusted) non-negotiable criteria, none can be accepted as is, requiring improvement or development of a new set of alternatives.
E. If two or more alternatives satisfy all the non-negotiable criteria, the analysis should proceed to Step 2.
F. If only one alternative satisfies all the non-negotiable criteria, the analysis should proceed to Step 3.

Step 2: Analysis of the performance on negotiable criteria

In this step, the focus is done on the negotiable criteria. The analysis should only be performed for the selected alternatives from Step 1. To support this step, a weighting and ranking matrices were created in Excel sheet adjacent to the trade-off matrix.

A. Select only the criteria for which none of the alternatives meets the performance within the acceptable ranges (e.g. if one criterion is satisfied by all the considered alternatives, it should be excluded from the analysis to simplify the weighting). For the selected criteria, weights should be assigned to them. A weight indicates the importance of one criterion relative to the other under consideration, i.e. a pairwise comparison. It is important to agree on the ranking scale and use it consistently to support the weighting process. A Likert scale from 'much more important' to 'much less important' could be used to assign priority weights. In doing so, the weights will express levels of trade-offs between the criteria rather than in absolute terms (Retief *et al.*, 2013). After weighting, a ranking of alternatives is performed based on their performance and the degree they satisfy the acceptable ranges. Similarly, a ranking scale should be defined, such as 1 to 3, i.e. from unsatisfactory (1), to some extent satisfactory (2), to satisfactory (3). As a result, the weighting score and the ranking score will be combined to show the alternative/s with the most satisfactory scores.
B. Following the results of the weighting and ranking process, a dialogue about the scores and whether they can help providing judgements for the prioritization of one alternative over others is encouraged.
C. Proceed to Step 3.

Step 3: Decision analysis

In this step, it is necessary to reflect back on the selected alternative(s) based on the results in Step 1 and 2. All the criteria, negotiable and non-negotiable, should be considered, to allow decision analysis to be performed in light of potential trade-offs between all the criteria considered (Retief *et al.*, 2013). To make a decision it is necessary to consider all the argumentations and justifications provided during the process. Following deliberations could occur: if the alternative X is accepted - can its performance on the non-negotiable criteria and high priority negotiable criteria compensate for the trade-offs that are accepted? If yes, does it reflect our goals and provide a new opportunity and minimizes risks? can alternative solutions be set up to compensate for the accepted trade-offs?

5. Application of the TONF

In order to validate the proposed framework and evaluate its usefulness, eight industrial experts from manufacturing industry had the approach verified using a pre-defined exemplary case (example 1a and 1b). Evaluation with the academic experts only involved example 1a. Additionally, one industrial expert had own example through which the framework was tested (example 2). As a result, both examples, 1a and 2, are presented for the application of the TONF below, followed by the summary of the evaluation by the industrial experts and the experts from academia. To allow for a simplification of the decision process, Step 2 of the TONF guidance was omitted in the examples.

5.1. Example 1a: TONF application to support decision-making with 2 alternatives

5.1.1.Filling in the Input data

This example presents a small and medium sized company who would redesign a product to substitute the current material with the locally sourced recycled material. The objectives that drive the substitution are to increase reliance on local sourcing and create local jobs and to increase the share of the recycled material content in the product. These derive from the corporate intention to contribute positively to the community by creating jobs and converting waste to a valuable material, following some of the circular economy principles (Kirchherr, Reike and Hekkert, 2017). The company does not have a publicly available sustainability statement and belongs to the industry with no stringent environmental compliance, additionally, the product can be considered simple made of few parts. Following the guidance for setting the Input data, the trade-off matrix was filled in the Excel sheet (Figure 3). As shown in Figure 3, seven key criteria were selected to support sustainability performance measurement for two alternatives: Alternative 0 (A0), which represents the current design and Alternative 1 (A1), which represents the proposed design. All the required by the Input data information was made available: the performance was calculated for both alternatives and for all the criteria.

					Acceptable ranges			
Nr	Criterion/indicator	Units	A0 - a mix of recycled and virgin materials	A1 - recycled material A with reinforcement	Minimum pass value - lower limit for acceptance	Maximum pass value - higher limit for acceptance	Non-negotiable (if flexible -no, not flexible - yes)	Reference
1	Recyclability at the end of life	% of total product	0	0	40	50	No	corporate intention to increase recyclability
2	Lifetime of a product	ms	5	7	5	7	Yes	benchmark for a customer
3	Cost of materials	eur	300	1000	300	450	No	n/a
4	Energy intensity (use in production)	kwh	2000	100000	2000	4000	No	n/a
5	Local supply of materials	y=1; n=0	0	1	1	1	Yes	corporate intention
6	Toxicity of materials (hazardous substances)	y=1; n=0	1	1	0	0	No	corporate intention aligned with the recyclability intention
7	Waste recycled into material	kg/100 units	100	75	100	200	Yes	corporate intention

Figure 3. A trade-off matrix with Input data details and highlights of attended and not attended criteria.

The criteria were calculated as indicators using a database of the leading performance indicators for sustainability screening of CE initiatives proposed by Kravchenko, Pigosso and McAloone (2020). For some criteria the qualitative assessment was used: 'yes' and 'no' grading was done for the criterion 'local supply of materials' as well as for the 'toxicity of materials', which was marked for both alternatives as 'yes' to indicate that both are likely to contain hazardous substances according to the REACH regulation. The acceptability ranges were set: due to no established corporate goals or legal requirements, acceptability ranges for some of the criteria were defined following the results of the performance measurement for both alternatives. For instance, the minimum acceptability ranges for 'lifetime of a product' was set to match the current design in order to keep the current lifetime benchmark known to the customer, while the higher value was set to match to the new design, indicating that a slight increase would also be acceptable. Based on the corporate intentions outlined above, the criteria were classified as non- or negotiable (Figure 3, 'non-negotiable' criteria column with yellow highlights). After the trade-off matrix was filled, the proposed trade-off guidelines were employed step by step.

5.1.2.A step-by-step application

Step 1: Analysis of the performance on non-negotiable criteria

The analysis of the performance based on non-negotiable criteria shows that none of the proposed alternatives satisfy all non-negotiable criteria (Figure 4a). Specifically, the new alternative, A1, did not meet the minimum requirement of waste amount converted to recycled material established by the current alternative. The reason for that was lower efficiency of the recycling process due to poor quality of the waste collected locally. Following the guidelines, the list of questions was used to re-evaluate the acceptability ranges and their non-negotiability; particularly, the question "*What is the aim of the defined acceptability ranges"* was used to reflect on the desired ranges for the criteria 'waste recycled into material'. The waste was being collected from non-waste designated areas (i.e. beaches, green zones), which contributed to the overall intention of the company to restore local natural environment.

Therefore, the ranges were adjusted so the minimum acceptable value matched the new alternative, A1 (Figure 4b, with adjusted acceptability ranges for criterion 'waste recycled into material'). As a result, only one alternative, A1, satisfied all the non-negotiable criteria and was the only option that should be considered for further analysis. Therefore, Step 2 was omitted, as only one alternative satisfied Step 1.

					Acceptable ranges			
Nr	Criterion/indicator	Units	A0 - a mix of recycled and virgin materials	A1 - recycled material A with reinforceme	Minimum pass value - lower limit for acceptance	Maximum pass value - higher limit for acceptance	Non-negotiable (if flexible -no, not flexible - yes)	Reference
2	Lifetime of a product	ms	5	7	5	7	Yes	benchmark for a customer
5	Local supply of materials	y=1; n=0	0	1	1	1	Yes	corporate intention
7	Waste recycled into material	kg/100 units	100	75	100	200	Yes	corporate intention

					Acceptable ranges		
Nr	Criterion/indicator	Units	A0 - a mix of recycled and virgin materials	A1 - recycled material A with reinforceme	Minimum pass value - lower limit for acceptance	Maximum pass value - higher limit for acceptance	Non-negotiable (if flexible -no, not flexible - yes)
2	Lifetime of a product	ms	5	7	5	7	Yes
5	Local supply of materials	y=1; n=0	0	1	1	1	Yes
7	Waste recycled into material	kg/100 units	100	75	75	100	Yes

Figure 4a and 4b. The process of renegotiation in Step 1 – acceptable ranges for criterion 'waste recycled into material' were renegotiated.

Step 2: Not applicable

Step 3: Decision analysis

This step included the analysis of only one alternative, A1, involving all the criteria considered in the decision-making. Two criteria (nr. 1 and nr. 6) were excluded from the decision analysis (shaded areas in Figure 5), because they were not satisfied by either of the proposed alternatives. Based on the information in the trade-off matrix, accepting A1 would mean compromising performance on costs and energy intensity. Using A0 as a benchmark, accepting A1 would increase costs by three times and energy intensity by five times. The decision required a dialogue facilitated by the proposed questions in Step 3: if A1 is accepted, can its performance on the non-negotiable criteria compensate for the trade-offs that are accepted? Can alternative solutions be set up to compensate for the trade-offs? Several deliberations occurred during this dialogue, such as whether the cost of materials was primarily driven by the sorting of waste and its recycling process or by adding the reinforcement and forming a new material mix. If it was the latter, a new type of reinforcement could be considered, which would require making a new assessment with an additional alternative, A2, using the same performance criteria. Similarly, several experts proposed to investigate the energy source for the material processing facility and encourage the facility to switch to renewable energy. This could compensate for the high energy intensity of the process for A1.

					Acceptable ranges			
Nr	Criterion/indicator	Units	A0 - a mix of recycled and virgin materials	A1 - recycled material A with reinforcement	Minimum pass value - lower limit for acceptance	Maximum pass value - higher limit for acceptance	Non-negotiable (if flexible -no, not flexible - yes)	Reference
1	Recyclability at the end of life	% of total product	0	0	40	50	No	corporate intention to increase recyclability
2	Lifetime of a product	ms	5	7	5	7	Yes	benchmark for a customer
3	Cost of materials	eur	300	1000	300	450	No	n/a
4	Energy intensity (use in production)	kwh	2000	100000	2000	4000	No	n/a
5	Local supply of materials	y=1; n=0	0	1	1	1	Yes	corporate intention
6	Toxicity of materials (hazardous substances)	y=1; n=0	1	1	0	0	No	corporate intention aligned with the recyclability intention
7	Waste recycled into material	kg/100 units	100	75	75	100	Yes	corporate intention

Figure 5. Decision-making on the basis of all criteria: if A1 is accepted, what the trade-offs are?

5.2. Example 1b: TONF application to support decision-making with 3 alternatives

Using the same example, a third alternative, A2, was added, to illustrate how the decision analysis would develop if another option was introduced. Information about A3 was added to the trade-off matrix as shown in Figure 6. Following the guideline for Step 1 for non-negotiable criteria, it can be seen that A2 does not satisfy the 'lifetime of a product' criteria as well as 'waste recycled into material'. Therefore, it should be rejected unless the acceptability ranges for those criteria can be (again) re-negotiated. Starting with the 'lifetime of a product' criteria, the ranges cannot be adjusted based on the stated reference indicating that the benchmark of at least 5 years of lifetime should be sustained. The performance of A2 on the 'waste recycled into material' is beyond the established ranges, however the higher value could be seen as desirable justified by the corporate intention to follow circular economy principles. Despite the possibility of adjusting the ranges for this criterion, A2 does not satisfy the lifetime criterion, whose minimum range cannot be negotiated, therefore A2 could not be considered further in the decision-making.

						Acceptable ranges			
Nr	Criterion/indicator	Units	A0 - a mix of recycled and virgin materials	A1 - recycled material A with reinforcement	A2 - recycled material B	Minimum pass value - lower limit for acceptance	Maximum pass value - higher limit for acceptance	Non-negotiable (if flexible -no, not flexible - yes)	Reference
1	Recyclability at the end of life	% of total product	0	0	40	40	50	No	corporate intention to increase recyclability
2	Lifetime of a product	ms	5	7	2	5	7	Yes	benchmark for a customer
3	Cost of materials	eur	300	1000	340	300	450	No	n/a
4	Energy intensity (use in production)	kwh	2000	100000	3000	2000	4000	No	n/a
5	Local supply of materials	y=1; n=0	0	1	1	1	1	Yes	corporate intention
6	Toxicity of materials (hazardous substances)	y=1; n=0	1	1	0	0	0	No	corporate intention aligned with the recyclability intention
7	Waste recycled into material	kg/100 units	100	75	125	75	100	Yes	corporate intention

Figure 6. Decision-making with 3 alternatives – A2, despite better performance on most of the criteria, is likely to be NOT chosen due to its unsatisfactory performance on non-negotiable criteria 'lifetime of a product'

5.3. Example 2: TONF application to support decision-making with 3 alternatives

This example presents a large company who needs to design a customized product for a private customer. The company belongs to a highly regulated industry that needs to comply with safety legislation. Additionally, the product is complex, requires fuel to operate and consists of thousands of parts. The customization of a product (A1) was based on the customer requirement to increase comfort relatively to a previously owned product (A0), with the comfort defined as a 4 dB decrease of the interior noise level. Using this information, the trade-off matrix was filled in as shown in Figure 7. Initially, two criteria, noise levels and weight, were used by the company to assess how the performance of A1, the new design, would change compared to A0, the benchmark product. The 'noise levels' criterion was used a key criterion following the customer requirement, however the engineering team added 'weight' criterion to assess how addition of an insulating material would affect weight. Due to no requirements to either weight or price, no acceptable ranges were added. During the design process, the team has reached a prototype which delivered the 3.5 dB reduction of the required 4 dB. The noise reduction was below the required by the customer level, however the company decided to contact the customer and test the 'comfort' level delivered by the prototype. As a result, the noise level was evaluated as 'comfortable' and accepted by the customer, thus the decision was taken to proceed with A2. However, the following deliberations occurred after the project was delivered: firstly, had the engineers not considered the criteria of (insulating) material consumption and its impact on weight, the initial customer request would be satisfied without discussion. Similarly, more criteria could have been considered to understand how the initially desired alternative, i.e. A1, would perform in terms, for instance, its fuel consumption as well as impact the total cost of ownership. Had these criteria been used to show an increase in the total cost of ownership by 35% between A0 and A1 (fig. E2, criteria 3), the negotiations with the customer would have happened to understand to what extent the increase would be acceptable and provide more flexibility to introduce other alternatives. This example has strongly demonstrated the importance of negotiations, the TONF guidance for Steps 1, 2 and 3 relies on.

						Acceptable ranges				
Nr	Criterion/indicator	Units	A0	A1	A2	Minimum pass value - lower limit for acceptance	Maximum pass value - higher limit for acceptance	Non-negotiable (if flexible -no, not flexible - yes)	Reference	Notes *(e.g. indicate references for acceptable limits of the criteria; indicate eventual changes)*
1	**Noise levels**	dB, decrease by	0	4	3,5	4	4	Yes	customer requirement	adjusted after test and customer acceptance to 3,5 dB reduction
2	**Weight**	as % increase	0	24	12			No		
3	**Total cost of ownership**	as % increase	0	35	22			No		
4	**Fuel consumption in use**	as % increase	0	50	20			No		

Figure 7. Decision-making with more alternatives and criteria being added along the trade-off navigation

6. Evaluation of the results and discussion

These examples have shown how the TONF guidelines utilized Input data and the guidance to assist the discussions and provided transparency in trade-off navigation. In example 1a, the guidance for Step 1 supported reconsideration of the acceptable ranges for one criterion, which led to the prioritization of one alternative, A1, over another, A0, based on its acceptable performance on all the non-negotiable criteria. Step 3 allowed to evaluate A1 alternative in light of its potential trade-offs, i.e. whether the acceptable performance on non-negotiable criteria can justify the selection of A1 alternative, despite its compromised performance on several negotiable criteria. Supported by the questions in Step 3, some deliberations in relation to trade-offs occurred: the arguments were used to inquire more information to support a decision or setting new initiatives to mitigate trade-off consequences. Example 1b was set up to illustrate how an additional alternative, A2, despite delivering a better performance on all the criteria except for one, which could not be re-negotiated, could not be accepted, leading the decisions towards potentially accepting another alternative. Example 2 has shown the effectiveness of criteria negotiation with the customer, thus verifying usefulness of the guidelines in relation to encouraging discussion and reflection on the information used in the decision process and its sources.

Supported by the initial hypothesis posited in Section 2, the evaluation with experts indicated that the TONF framework is useful for: i) facilitating a dialogue about trade-offs acceptability and alternative prioritization, and ii) creating transparency and traceability of the decision process (Figure 8a-c). Accordingly, the Input data and their guidance provided a good overview of the information, required to frame the decision. For instance, the guidance about the number and type of criteria was found useful in "helping to broaden the focus and move away from 'single-criteria'-driven decisions".

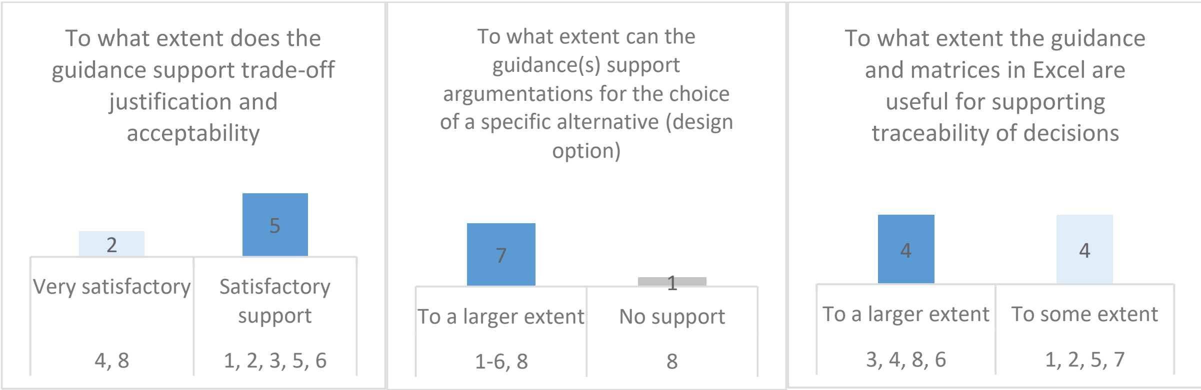


Figure 8a, b, c. Evaluation provided by the industrial actors (numbers coincide with experts ID from Table 1 in Section 2).

Usefulness of the guidance about the number of sustainability-related indicators and performance evaluation using both, qualitative and quantitative values, was also highlighted. The trade-off matrix in Excel was found useful in bringing all the information together and providing visualization of the decision process. The step-by-step guidance and corresponding questions were found useful in facilitating the dialogue about priorities, drive set up of the requirements and make the discussion explicit: "After going through these steps and questions - you know where the problem is. It helps to discuss (our) requirements for (our) concepts. It is a guidance for a conversation". Particularly, the following observations were made: first, decision analysis (Step 1) starting with non-negotiable criteria was found useful in terms of encouraging priority setting and reflection on it. Notably, for the analysis in Step 1, all the industrial experts preferred to operate with 'real' value instead of using a normalisation technique (i.e. transforming the original value into a dimensionless score based on how well it meets the acceptable range), as, for instance, Step 2 guides. Although normalization, presented as weighting, and ranking in Step 2 were useful for create a dialogue for reinforcing priorities between negotiable criteria (distinguishing between 'desirable' and 'nice' criteria to 'replace' or remove some of the 'nice' criteria to simplify the process), it was acknowledged that the final score should not be used as a sole factor to make a decision. Therefore, Step 3 could support the final analysis by combining results from Step 1 and Step 2.

Time-efficiency of the approach application was evaluated at low to medium provided all the required data could be obtained fast enough to support the decision. As one of the experts summarized this application: "the tool [TONF] is so great in its outcomes that, again, I believe it must be widely spread as support to organizational practice. Especially if applied in time (which is desirable)". The approach was also evaluated as generic to accommodate the needs of any level decision maker.

Several challenges, however, were also highlighted. First, a challenge of information acquisition was mentioned by all the participants. "You have to do your research and survey your customers and stakeholders", emphasizes one expert in relation to data collection to drive performance measurements and establish acceptability ranges. Data collection requires time, investment and knowledge, which are seen as generic challenges manufacturing companies experience when implementing sustainability in their business activities (Dekoninck *et al.*, 2016). Second, a challenge of selecting the advisable number of criteria or indicators was mentioned, which, if not supported to be contextually selected, can often lead to the *ad hoc prioritization*, often based on costs or CO_2 measurements as few of the widely known.

Considering the abovementioned, this approach to decision analysis and trade-off navigation can support early stages of decision making in situations with conflicting sustainability criteria. Importantly, it intends to encourage dialogue and provide a structured and transparent approach for analysing decisions and decision context, and not to provide a ready solution for such conflicts. In this way, it allows the decision-makers to “play” with scenarios, as to where different acceptability limits lie and how acceptable the considered alternatives are in light of those.

To indicate the contribution of this study to the domain of sustainability-oriented decision-making, it can be compared to several studies combining sustainability evaluation and decision support, including a trade-off analysis (Table 9). Ernawati *et al.*, (2015) propose a multicriteria decision-making approach to evaluate and select alternatives of a product design on the basis of four categories qualitatively measured by a number of criteria, such as customer satisfaction measured by ‘attractive design’, manufacturing utilization measured by ‘time needed to produce a product’, supply chain efficiency measured by ‘use of existing suppliers’, and environmental sustainability measured by ‘design for reuse, remanufacture and recycle’. The approach relies on weighting each criterion against another (pairwise comparison), multiplied by the ‘level of influence’ of the evaluator (e.g. expert from a decision-making team): the more criteria are under the evaluator’s control, the higher level of influence is assigned. By running a mathematical model, the design with a highest score is suggested. The approach by Ernawati *et al.* (2015), however, does not consider a range of criteria from the environmental dimension, nor the economic or social; additionally, no guidance is provided how to support qualitative evaluation of the criteria and how to interpret the final scores rather than solely relying on the highest score for design selection.

Table 9. Comparison of works for sustainability-related trade-off support and their fulfilment of research criteria. (note: – not fulfilled; ~ partially fulfilled; √ - fulfilled).

Reference	**Fulfilment of criteria for a trade-off decision support**				
	#1 – Reveal trade-offs between and within sustainability dimensions	**#2 – Provide several prioritization techniques to encourage open dialogue**	**#3 – Provide rules to evaluate trade-off acceptability**	**#4 – Easy to use (evaluated by practitioners)**	**#5 – Flexible for different business processes**
Present study	√	√	√	√	√
(Ernawati *et al.*, 2015)	–	~	–	–	–
(Rossi *et al.*, 2019)	~	√	–	√	~
(Hannouf and Assefa, 2018)	√	~	√	–	~

Rossi *et al.* (2019) propose and test a multi-criteria index to support eco-design implementation in manufacturing companies. Environmental impact measured by kg of CO_2, technical performance and costs both measured by monetary units (Euro), are the three product criteria considered for design evaluation. The authors propose a step-by-step approach, which considers internal and external drivers and their influence on the three criteria, which allows calculating weights for each criterion. The weights and measures for corresponding criteria are then calculated in a Product impact index, which is expressed in monetary units and used to compare product designs. A strength of this approach lies in the integration of economic and environmental criteria together with technical ones, as well as it encourages improvements based on the results (Rossi *et al.*, 2019); however, the weakness lies in the missing integration of the social criteria and aggregation of results into a monetary value, which might not be desirable to express environmental and social performance (Retief *et al.*, 2013). Hannouf and Assefa (2018) develop a Life Cycle Sustainability Assessment-based (LCSA) decision-analysis framework, which consists of two parts: i) application of a LCSA; and ii) decision-analysis with a five-phase approach. A LCSA is used to generate input data by providing results for economic, social and environmental impacts. Decision-analysis is then used to assist objective setting, a qualitative evaluation of each alternative's potential to achieve the defined objectives and rules for trade-off management. The trade-off management encourages balancing the overall environmental, economic and social objectives supported by acceptability and manageability tests, which assist decision-makers in a dialogue about potential adjustments and management (amelioration) of existent trade-offs. As a result, if no adjustments are possible and trade-offs can't be managed, the alternatives are rejected managed (Hannouf and Assefa, 2018). The advantage of this approach by Hannouf and Assefa (2018) is in the iterative nature of the LCSA decision-analysis framework, which encourages returning to a LCSA to adjust or add new input information and then repeat the phases. However, the LCSA decision-analysis framework approach lacks empirical evaluation.

7. Conclusion

This study presented the trade-off navigation framework (TONF) and its constituent elements: Input data and a step-by-step trade-off navigation guidance. The research followed a research process driven by understanding the needs and gaps in relation to trade-off challenges and their handling, consolidation of criteria for the development of a trade-off navigation, and a consequent conceptualization, testing and refinement of the TONF. Based on several literature reviews and expert evaluation for theory-testing, the TONF was refined to its final version and evaluated by experts as being a useful approach for trade-off navigation and dialogue in industry.

The TONF is proposed with the aim to assist decision-making between conflicting sustainability criteria and should be used during early development stages of sustainability-oriented initiatives, including CE ones. A first element, the Input data, provides a detailed overview and a guidance to the adequate information needed to frame a decision. A second element, a step-by-step guidance, guides decision-making by encouraging analysis of the considered initiatives in light of the defined Input data. The iterations are encouraged to allow adjustments of the Input data, including consideration of new alternatives or other key criteria to support decisions. The evaluation provided evidence that the TONF is useful to support argumentations for the choice of a specific alternative, reinforce understanding of priority areas, and create transparency and traceability of decisions. The improved procedural rationality may help practitioners make informed decisions by explicitly justifying selection and prioritization of particular sustainability criteria, thus reinforcing the knowledge about potential risks and opportunities behind their choices. Consequently, it may not only support selection of the 'most beneficial from a triple bottom line perspective' alternative during design and development of circular products, services and processes, but also serve as a feedback loop to manage conflicting criteria and continuous improvements.

The main academic contribution of this study can be summarized as:

- Advancing the discussion about the importance of supporting sustainability-related trade-offs after sustainability evaluation
- Consolidation of key challenges in manufacturing industry related to the integration of sustainability criteria in the early stages of business processes
- Identification of criteria to support trade-off navigation
- Proposition of a structured approach to trade-off navigation

From a practical perspective, following can be highlighted:

- Overview of the information required to frame a decision
- A practical and flexible approach to making trade-off explicit based on the contextual information
- A structure to support objectivity and traceability of decisions, including re-evaluation of sustainability implications of proposed CE and other initiatives

However, there are some limitations that need to be further explored in future research, such as: a) further practical application involving multifunctional teams of decision-makers, engaged in business model, product development, operational activities, supply chain; b) further practical application involving more than 3 alternatives; iii) automating the steps in the TONF guidance to retrieve and update Input data; iv) integrating a simple mathematical model to allow building scenarios based on the most desirable objective or goal; v) investigating the potential to integrate the TONF into existing methods used in business processes. Currently, this study aims at developing a user guide and improving the trade-off matrix in Excel to support easier operationalization of the TONF in industry.

Acknowledgments:

Appendix I: References for Table 2 in Section 3

Challenge number	**References**
1	(Hallstedt and Thompson, 2011; Abbasi and Nilsson, 2012; Matschewsky, Lindahl and Sakao, 2015; Battistella *et al.*, 2018; Nilsson, Sundin and Lindahl, 2018; Paulson and Sundin, 2019; Kennedy and Bocken, 2020)
2	(Hallstedt and Thompson, 2011; Abbasi and Nilsson, 2012, 2016; Dekoninck *et al.*, 2016; Schulte and Hallstedt, 2017; Nilsson, Sundin and Lindahl, 2018; Zarte, Pechmann and Nunes, 2019; Kennedy and Bocken, 2020; Watz and Hallstedt, 2020)

3	(Abbasi and Nilsson, 2012, 2016; Chou, Chen and Conley, 2015; Buchert, Halstenberg and Stark, 2017; Evans *et al.*, 2017; Stindt, 2017; Nilsson, Sundin and Lindahl, 2018; Zarte, Pechmann and Nunes, 2019; Paulson and Sundin, 2019; Baldassarre *et al.*, 2020; Watz and Hallstedt, 2020)
4	(Dekoninck *et al.*, 2016; Stindt, 2017; Paulson and Sundin, 2019; Watz and Hallstedt, 2020)
5	(Chou, Chen and Conley, 2015; Dekoninck *et al.*, 2016; Silvius *et al.*, 2017; Battistella *et al.*, 2018; Held *et al.*, 2018; Nilsson-Lindén *et al.*, 2018; Zarte, Pechmann and Nunes, 2019; Kennedy and Bocken, 2020; Watz and Hallstedt, 2020)
6	(Abbasi and Nilsson, 2012, 2016; Chou, Chen and Conley, 2015; Matschewsky, Lindahl and Sakao, 2015; Dekoninck *et al.*, 2016; Buchert, Halstenberg and Stark, 2017; Evans *et al.*, 2017; Salari and Bhuiyan, 2018; Battistella *et al.*, 2018; Nilsson-Lindén *et al.*, 2018; Paulson and Sundin, 2019)

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3.3.3. Evaluation of the trade-off navigation

The evaluation of the trade-off navigation framework with constituent elements provided evidence of its usefulness in the following: i) facilitating a dialogue about trade-offs acceptability and alternative prioritization, and ii) creating transparency and traceability of the decision process. A summary of the qualitative evaluation by both, academic and industrial experts is provided in Appendix III. During the evaluation, the following benefits were emphasized: the Input data and their guidance provided a good overview of the information, required to frame the decision. Guidance on defining key criteria and indicators, their number and coverage of criteria between and across TBL dimensions was found useful in "helping to broaden the focus and move away from 'single-criteria'-driven decisions". At the same time, a challenge of acquiring information for the Input data was highlighted, which requires information gathering from internal and external sources. A step-based guidance for a trade-off navigation was found useful on the following aspects: firstly, it was helpful to focus separately on non-negotiable and negotiable criteria and discuss why they were set in the following way. Secondly, the questions in Step 1 and 3 could 'to a larger extent' support argumentations for the choice of a specific alternative. Additionally, the TONF was seen as a vehicle to improve communication of actors within and across business processes (i.e. communicating why certain decisions were taken or not taken as well as flexible to accommodate needs of any level decision maker (e.g. business developer, product designer, etc.).

> *"The beauty of the approach is that it is generic enough to capture a bunch of different types of decision-making processes"*
>
> *"The three steps make very much sense"*
>
> *"What I learned is how simple it can be presented. I think you have included the right things in there in probably the most time efficient manner"*
>
> *"Nice little technique to help us keep a track (both memory and justification) of our decisions around trade off prioritization"*
>
> *"Users should be properly informed of the high benefits that they might expect at the end of the session [TONF application], therefore making it worth learning how to use the tool. Especially if applied in time (which is desirable) the time to learn and catch up might be considerable. However, the tool is so great in its outcomes that, again, I believe it must be widely spread as support to organizational practice"*

Following the evaluations, it can be posited that the TONF has a potential to support sustainability trade-off consideration in manufacturing industry. However, as any approach, it has certain limitations, which were reported in Paper 4, embedded in the thesis.

4. Discussion

4.1. Sustainability screening framework for circular economy initiatives

By combining the findings from the theoretical and empirical investigations from Studies A, B and C, a framework is proposed, to aid the understanding and describe important elements of consideration, regarding how early stage sustainability screening of CE concepts can be deployed (Figure 12).

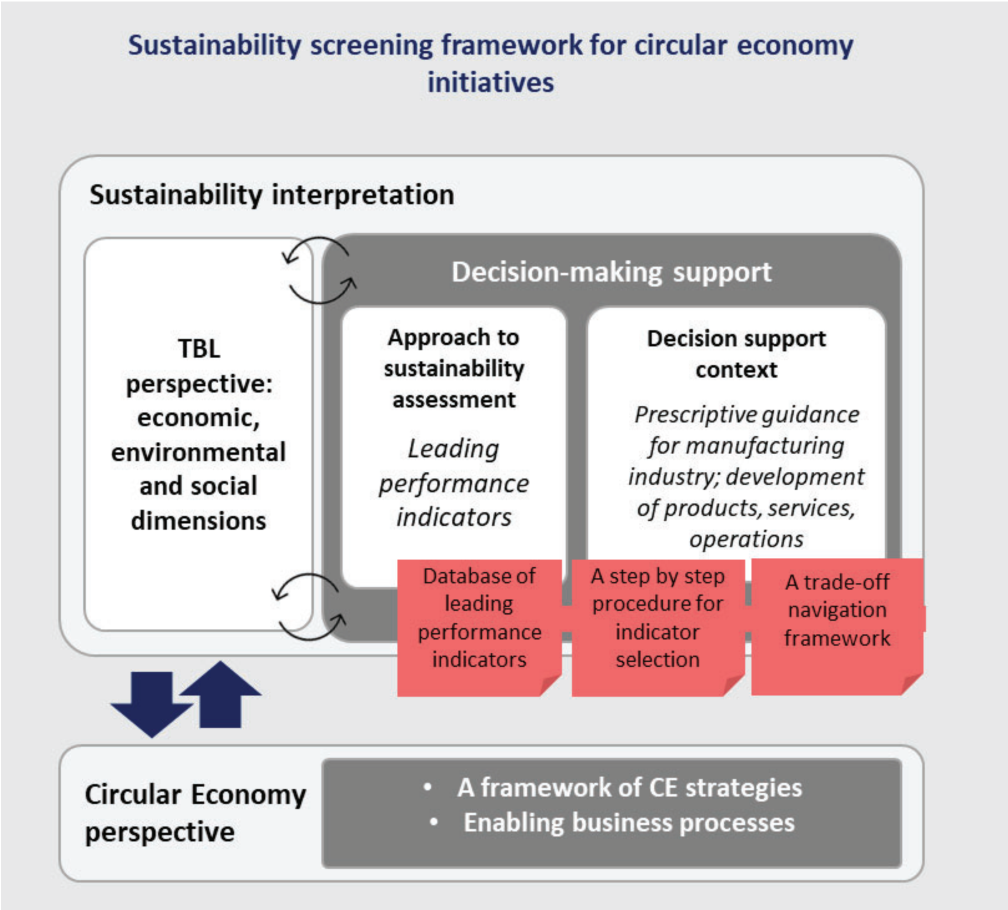

Figure 13. A sustainability screening framework for circular economy initiatives

Figure 12 illustrates the framework and highlights the main constituents of the decision-making support: from the sustainability perspective, a TBL interpretation was followed, which influenced selection of a leading indicator approach as a main approach to assess sustainability performance. To enable the assessment, a database of leading performance indicators was consolidated. Similarly, the TBL perspective combined with the particularities of the decision support context (e.g. manufacturing industry and focus on products, services and operations) influenced the prescriptive nature of the support – a step by step procedure for indicator selection and a trade-off navigation framework provide guidance for selecting and applying relevant information with the purpose of supporting a dynamic decision process and reinforcing the knowledge about sustainability implications of proposed initiatives. From a CE perspective, CE initiatives were defined as a one or several CE strategies that are possible to realize through operational business processes. This perspective, again, was aligned with the decision support context, i.e. supporting development of products, services and processes.

As a result, the framework brings together several the key concepts, approaches and methods to support sustainability screening of CE initiatives in the early development stages. In that, it does not only indicate the '*whats*', but also the '*hows*' of the screening, by providing guidance for the key steps to take and methods to employ. It is not the intention to claim that the framework covers all possible elements at a procedural or methodical level related to both, sustainability and CE context; instead, the framework provides a visualization of an approach to combining established theories and results, derived from empirical data to synthesize the key concepts being studied. The purpose of the framework is to advance measurements of the sustainability performance of alternative CE initiatives in their early development stages, thus allowing for the adjustment of a candidate initiative to improve its performance, before detailing and implementation. Similarly, the framework intends to guide comparison of circular and non-circular initiatives and support selection and development of an alternative initiative with the highest sustainability potential.

4.2. Reflection on the approach for framework development

To be able to arrive at the framework, several principles and approaches for and within sustainability assessment were followed, all in alignment with the sustainability interpretation followed in this research. It is important to acknowledge that the interpretation of sustainability and the choice of a methodological approach (when developing) for a sustainability assessment has a tremendous impact on the assessment outcomes and decision framing (Gasparatos and Scolobig, 2012). As a result, this Chapter brings forward the discussion about the rationale and decisions made in the development of the sustainability screening framework for circular economy in light of existing approaches to sustainability and sustainability assessment.

Does the sustainability interpretation and assessment approach matter?

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" is one of the most quoted definitions of sustainable development as stated by the Brundtland Commission in "Our Common Future" report from 1987 (Waas *et al.*, 2011). The definition followed the key principles of sustainability, such as equity, precaution, dynamism and global responsibility (Hugé et al., 2013). Broadness of the definition led to many interpretations, attempting to make the concept more tangible (Waas et al., 2011). As a result, various discourses within sustainability were proposed (Hugé *et al.*, 2013). Discourse refers to a structured way of representing ideas and concepts that enable particular types of actions (ibid.). In order words, how sustainability is framed guides selection of a methodological *approach to sustainability assessment*, whose primary purpose is inform actions to ensure positive contribution to sustainability (Ness *et al.*, 2007). An approach to sustainability assessment affects how sustainability is operationalized (what to measure and how), and how results are presented and used (guidance on who should use the results and how) (Sala, Ciuffo and Nijkamp, 2013).

One interpretation of sustainability is a *holistic sustainability*, in line with 'sustainable development as integration' discourse by Hugé *et al.* (2013). It represents sustainability as a multidimensional construct (a model) based on environmental, social and economic pillars, which are interdependent and mutually reinforcing (Waas *et al.*, 2011). The definition of sustainability within the dimensions had largely been influenced by the interpretations of what 'unsustainable' is (Hugé *et al.*, 2013); thus the economic dimension is linked to welfare, environmental - to resource preservation and environmental protection, social – to poverty and equity (Waas *et al.*, 2011). Due to a more tangible view on sustainability that brings together traditional disciplines, this three-dimensional (often, but also contested as in Waas *et al.* (2011)) representation has been popularised in science and in practice (ibid.), known as triple bottom line (TBL) approach (Elkington, 1998).

Another interpretation of sustainability is the 'sustainable development as limits' discourse (Hugé *et al.*, 2013). It situates human actions within the (dynamic) limits of ecosystems, with Planetary Boundaries approach (PBA) being one of the nominal examples (Rockstrom *et al.*, 2009). This approach emphasizes that the development should occur within the Earth's carrying capacity, because natural capital is limited and irreplaceable (e.g. resource scarcity and biodiversity loss) (Hugé *et al.*, 2013). The framework, as few others that adhere to the 'limits' discourse try to define the 'safe operational space' to ensure its maintained to prevent eco-systems collapse, which will lead to societal and economic collapse (Rockstrom *et al.*, 2009). Despite the defined boundaries, PBA does not provide a concrete guidance for actions in industry or organisations (ibid.). To operationalize the global PBA approach from the strategic point of view, a framework for strategic sustainable development (FSSD) was proposed by Robèrt, Broman and Basile (2013). The FSSD proposes a set of specific principles for sustainability and a multilevel framework to guide their application, including levels of system, purpose, strategic guidelines, actions and tools (ibid.). By guiding through the levels, the framework intends to help decision-makers asking the 'right questions' and prioritizing potential actions that comply with the set of sustainability principles.

Few other discourses can be pointed out, such as the 'sustainable development as change', which sees sustainability as a process of change rather than a fixed state, with focus on socio-economic transformation along the technological (Hugé *et al.*, 2013); and a multi-governmental framework of Sustainable Development goals (UN SDG's) with established indicators and targets (Sala, Ciuffo and Nijkamp, 2013).

The discourses presented is not a fixed typology, but an overview of diverse approaches to conceptualize sustainability and guide selection of a methodological approach for performing sustainability assessments (Hugé *et al.*, 2013). Ecologically dominant sustainability proposed by Montabon, Pagell and Wu (2016) is an example of a holistic triple bottom line interpretation of sustainability, however represented as a limited, nested, model, within which the economic dimension (third priority) is nested within social (second priority), which is then nested within environmental (first priority). The ecologically dominant model is a concept and no guidance how to operationalize it to guide actions exists. This examples emphasizes that each discourse is not homogeneous (Hugé *et al.*, 2013) and the selection of an assessment approach should consider a 'decision context': ''who participates,'' ''who decides,'' ''who uses,'' ''how complex is the decision", "what is the activity affected by decision", ''what values are involved", "what is the time horizon" (Sala, Ciuffo and Nijkamp, 2013).

In light of the presented, the three-dimensional representation of sustainability was followed in this research, which guided information selection and structuring to propose a sustainability screening (Figure 12, 'sustainability interpretation' box). Particularly, the TBL perspective guided identification and selection of indicators, development of the procedure and a trade-off navigation framework, which affected what indicators were identified, how they were structured in a database and how a guidance for indicator selection and trade-off analysis was developed. Accordingly, the guidance for indicator selection considered a balanced inclusion of indicators to measure TBL dimensions and aspects within them; it did not however emphasize one dimension over another (as, for instance, in the ecologically dominant model). This affected the prescriptive logic in this research, which provided information and guidance to support decision-making with a balanced consideration of TBL dimensions and a transparent trade-off analysis; however, leaving the final choice to the user in line with the corporate sustainability approach within natural- resource-based view. The prescriptive nature is aligned with pragmatism, which focuses on indicating how the decisions *can* be taken in light of the real world settings, which influence how corporate decision-makers would use information, provided in sustainability assessment, to make decisions. Therefore, the *prescriptive approach to decision-making* differs from a normative, which instructs how decisions *should* be made (McFall, 2015).

Following the 'decision context' logic, this research conceptualized sustainability screening through an *indicator-based approach to sustainability assessment*, which followed a holistic TBL perspective of sustainability (Figure 12). Conceptualization considered manufacturing actors and other industrial practitioners as main participants in, users of and decision-makers in the sustainability screening framework (Figure 12, 'decision support context' box). Additionally, the scope was limited to the technical perspective of operational business processes, i.e. how to develop (improve) products, services and operations. This led to the choice of *a leading performance indicator based assessment*, and assisted the development of the indicator database, the indicator selection procedure and the trade-off navigation, all with the rationale to support sustainability screening within that particular 'decision context'. Additionally, the balanced TBL perspective required acknowledgment of trade-offs (Waas *et al.*, 2011), leading to the proposal of the trade-off navigation. As posited by Sala, Ciuffo and Nijkamp, (2013), the researcher who adopts a balanced TBL perspective and a prescriptive guidance, allows making trade-offs (i.e. does not 'limit' them), and should take responsibility for making this transparent for sustainability assessment users and decision-makers. Although trade-offs can be considered inherent in sustainability (Gibson, 2006), it is possible to limit them following the 'sustainable development as limits' discourse, by instructing to what extent trade-offs are acceptable within the carrying capacity of the planet (Waas *et al.*, 2011). This brings this research to acknowledge that the perspective for and construct of the sustainability screening for circular economy would influence decision-makers' interpretation of sustainability and pose limits for what types of actions will follow based on the results of the screening. Had the sustainability screening aimed at another scope, e.g. assessing the whole production and consumption system or providing guidance for policy makers, the approach to sustainability and to sustainable assessment would have been different. Similarly, had the research followed the FSSD framework, the indicators would be classified differently; additionally, the guidance for the indicator selection, their application and result interpretation would consider the established 'limits', alike operationalized by Hallstedt (2017) through sustainability compliance index. Additionally, if FSSD framework was followed, the sustainability screening framework development could have been aligned with the levels of FSSD, engaging purpose and strategic guidelines levels.

The risk of assessing dimensions in 'isolated' manner, favouring economic before environmental and social is a common critique of a balanced TBL approach and indicator based assessment exists (Gibson *et al.*, 2005; Waas *et al.*, 2011). Despite the critique, none of the sustainability discourses and proposed approaches to sustainability assessment are bias-free due to the interpretational and operational limits of and to sustainability (de Olde, Bokkers and de Boer, 2017). Along indicators, ecological and water footprints, cost benefit analysis, emergy analysis, social and environmental LCA are few examples of methodological approaches for sustainability assessment (Sala, Ciuffo and Nijkamp, 2013). Ecological and water footprints focus on biophysical flows, hence eco-centric; cost benefit analysis focuses on monetary flows, and hence anthropocentric; life cycle assessment focuses on environmental impacts – being more comprehensive in scope than ecological footprint (Hoogmartens *et al.*, 2014), however these approaches (and many others) adopt a reductionist view in assessing sustainability (Gasparatos and Scolobig, 2012). Even if several methods are combined, the approach to sustainability assessment will likely be reductionist due to aggregation and normalization of results (ibid.) or due to simplifications made throughout the assessment (Beemsterboer, Baumann and Wallbaum, 2020).

In summary, sustainability can be seen as an essentially contested concept under umbrella of which several discourses exist, and performing sustainability assessment can be as complex and contestable (Hugé *et al.*, 2013). This does not only require more transparency in existing sustainability assessment approaches about what representation of sustainability was adopted, how it influenced the process and results of the assessment; this calls for integration of different methodologies and epistemologies to study interconnectedness of ecosystems, society and economy and to enable co-production of knowledge with other, non-academic, stakeholder groups (Sala, Ciuffo and Nijkamp, 2013). This is in line with ensuring the objective of transdisciplinarity of sustainability science.

How sustainable is circular economy?

The overview of diverse discourses of sustainability and approaches to sustainability assessment brings clarity regarding the differences of reported benefits of CE in terms of environmental and economic impacts – assessment scope and methodological approach have an important role to play. Additionally, how CE is conceptualized complicates comparison even further (Kirchherr, Reike and Hekkert, 2017; Kravchenko, McAloone and Pigosso, 2020), as this discussion aims to put forward. CE, as an umbrella concept, encapsulates several sub-concepts with a shared feature (Blomsma and Brennan, 2017), promoting resource preservation and economic gains for the production and consumption systems as the central notion of CE (Geissdoerfer *et al.*, 2017). Through this lens the CE concept appears "intuitively positive" (Harris, Martin and Diener, 2021, p.173), acknowledged by many academic, industry and governmental bodies as a major means towards sustainability (Van den Berg and Bakker, 2015; Stewart and Niero, 2018; EU Commission, 2020). A number of scientific articles attempt to compare CE and sustainability using the key principles, underlying concepts and expected outcomes: Sauvé, Bernard and Sloan (2016) assert that both, sustainable development (SD) and CE are anthropocentric, with a core concept of CE lying in economic objective, while a core objective of SD is society, in line with its key principle of intra- and intergenerational commitments. Geissdoerfer *et al.* (2017), on the other hand, see intra- and intergenerational commitments, cooperation of different stakeholders for innovation and non-economic only development as shared principles between SD and CE. In terms of outcomes, CE is expected to create new markets and new revenue channels, many employment opportunities, protection of natural resources, water, energy and minerals and reduction of greenhouse gas emissions, among others (EMF, 2019; Kumar *et al.*, 2019; Velenturf *et al.*, 2019). It is however notable that there is little coherence between how the principles of CE (if not matched with SD) could lead to the anticipated outcomes for SD (Korhonen, Honkasalo and Seppälä, 2018). Additionally, Sauvé, Bernard and Sloan (2016) note that because initiatives for SD have been developed within a linear economic model and did not result in major improvements (see absolute and relative decoupling discussion in Chapter 1.1.1.), some CE proponents distance CE solutions from long existed in a linear model SD solutions. This could explain the proposal of various methods to measure CE benefits: indicators and indexes focused on material recirculation and economic value aim at showing a progress towards a fully circular system (e.g. MCI indicates a score of 100% as the best), which at the same are used to demonstrate achieved environmental and economic benefits (Harris, Martin and Diener, 2021). While these measures could provide a very clear direction to target unlike open-ended progress towards sustainability (Sauvé, Bernard and Sloan, 2016), the concerns have been risen to question whether fully circular flows are (e.g. thermodynamically) possible (Skene, 2017) and whether the metrics could indeed be used as proxies for environmental and economic impacts (Kristensen and Mosgaard, 2020; Harris, Martin and Diener, 2021). Furthermore, a growing number of recent academic articles find little consistency between the metrics proposed to measure CE (Kristensen and Mosgaard, 2020; Lindgreen, Salomone and Reyes, 2020; Schöggl, Stumpf and Baumgartner, 2020), yet alone their ability to measure a broad spectrum of outcomes for the economic, environmental and social sustainability (Harris, Martin and Diener, 2021). This does not necessarily lead to a conclusion that the approaches and related metrics to measure CE do not have a right to exist; rather this highlights the importance of complementing the CE-oriented assessments by sustainability assessments for a holistic perspective.

To answer the question 'how sustainable circular economy is' requires transparency about how both, CE and sustainability, are conceptualized, what approach to sustainability assessment is to be followed and why and how the results should be interpreted. The CE strategies framework by Blomsma *et al.* (2019), followed in this research, helped to conceptualise CE in a tangible way, also addressing several gaps presented in Introduction. While not aiming to open a discussion about how many frameworks of CE exist, this research acknowledges that adopting any another CE perspective would have influenced the development of the sustainability screening framework. By bringing CE and sustainability together, it becomes evident that further advancements are needed regarding: i) standardization of CE principles and strategies; ii) clarification of the needs and purposes of CE-only assessment approaches; based on this, approaches could be proposed for an integrated CE and sustainability assessment; iii) wider knowledge c-creation between different stakeholders (organizations, business, communities, policy-makers).

With a New Circular Economy Action Plan adopted by the European Commission as one of the main blocks of the European Green Deal, CE is put at heart of the agenda for sustainable growth (EU Commission, 2020). While the key themes of the Plan might not be new, the way it emphasizes sustainable design, value chain collaboration, consumer engagement and ensures innovation funding and support for uptake of digital technologies, provides a powerful way to attract business community to work with CE towards sustainability. Therefore, it is of paramount importance to provide support to business actors (among many others) to ensure CE actually contributes towards sustainability. Sustainability screening for circular economy with focus on indicators for TBL performance measurement is one of the attempts to contribute to this support.

5. Concluding remarks

This chapter first summarizes the results in light of the developed research questions. Second, it brings forward the contributions of this research to the literature and practice, highlights several research limitations and provides suggestions for future research.

5.1. Fulfilling the research objective

This PhD research was motivated by the lack of an overall assessment framework, able to support the early stages of CE development, whilst simultaneously considering the holistic sustainability perspective. Considering the rapid uptake of circular economy by the manufacturing industry, it is essential to support the early stages of circular economy development by integrating sustainability in the decision-making process, facilitating selection and implementation of the initiative with the highest sustainability potential. Following the motivation, the research was driven by several gaps, primarily attributed to the conceptual framing of CE and shortcomings of the existing sustainability assessment and measurement frameworks, summarized such as:

- For CE - there is insufficient focus on CE strategies beyond recycling and on measurements beyond material aspect; additionally, synchronization of decisions across business processes, needed to develop CE, is not supported;
- For sustainability measurements – there is a lack of a holistic perspective on the three dimensions of sustainability simultaneously; moreover, the results generated from the assessments are often complex, which hinders their inclusion into early stages of decision-making. Considering the multifaceted nature of criteria and indicators in sustainability measurements, the decision support seldom goes beyond results generation to support decision analysis in trade-off situations.

Based on the gaps, three Studies – Study A, B and C – were designed with the main objective to contribute to the development of a framework for sustainability screening for circular economy initiatives, which aims to provide a decision support for the early stages of CE development. Each of the Studies contributed with the following results, which constituted main elements of the framework:

Study A	**i.** a database of >270 leading performance indicators classified according to TB dimensions and corresponding aspects, five business processes and thirteen CE strategies

This result directly answers **Research Question 1** *(RQ.1: What leading performance indicators exist, to measure economic, environmental and social aspects of sustainability?)* and **Research Question 2** *(RQ.2: How to categorize indicators to enable meaningful selection of indicators for early development stages of CE initiatives?).* Based on the shortcomings of the existing sustainability assessment and measurement frameworks, RQ.1 was driven by the theoretical lens of leading performance indicators, which offers a useful approach to measuring performance in the early stages. As a result, RQ.1 was addressed by performing a systematic literature review to investigate leading performance indicators suitable for measuring economic, environmental and social performance. The review provided a large number of indicators, which established a theoretical foundation for building a database of indicators suitable for measuring separate and combined CE strategies from a holistic TBL perspective. In order to operationalize the database, five business processes and thirteen CE strategies were considered for classification. By establishing a classification logic (outlined in Chapter 2.3.), the indicators were classified in a way to enable their meaningful selection for the corresponding CE initiatives. This answered RQ.2, thus addressing several gaps related to CE by expanding its measurements to TBL aspects beyond materials and costs, by considering a wide number of CE strategies, and by establishing a business process perspective, which could facilitate decision-making across business processes. Additionally, the database provides detailed information about each indicator, which facilitates its understanding and solves uncertainty of what data to use to measure the indicators.

Study B	**ii.** a step by step procedure for a systematic selection of relevant indicators for corresponding CE initiatives, for supporting their sustainability performance measurement

In order to ensure selection of only relevant indicators for corresponding CE initiatives, a step by step procedure was developed and evaluated, thus answering **Research Question 3** *(RQ.3: How to support a systematic selection of relevant sustainability performance indicators for early stage sustainability screening of CE initiatives?).* Additionally, RQ.2 intended to addresses numerous challenges of indicator-based assessment frameworks by providing a guidance for locating potentially relevant indicators, for enabling their contextual selection and for selecting a manageable number of indicators. The procedure therefore, provides a conceptual structure to systematically identify, prioritize, customize and create relevant indicators, to be used for sustainability screening for different CE initiatives, i.e. whenever different business process are involved and various single or combinative CE strategies are considered. Empirical evidence demonstrated the importance of the sustainability-related leading performance indicators and the selection procedure in the following: i) presence of indicators covering all TBL dimensions facilitates a more holistic measurement; ii) indicator selection procedure facilitates contextual selection of indicators, which promotes the likelihood of using them to guide decision-making process (e.g. introduce improvements or show achievement of objectives). In spite of several improvement opportunities, it is possible to assert that the procedure is useful to support selection of indicators for the early stages of CE development. Additionally, a user guide and an interactive database were proposed to assist implementation of the procedure and the indicators for sustainability screening of CE initiatives. This supports a more practical approach to the selection and application of indicators.

Study C	**iii.** a trade-off navigation framework to support structured and transparent decision making involving conflicting sustainability indicators

Multifaceted nature of the TBL indicators proposed for sustainability screening required additional support to assist decisions in conflicting sustainability situations, known as trade-offs. As a result, **Research Question 4** *(RQ.4: How to support decision-making when trade-offs arise between sustainability performance indicators?)* emerged, leading to a trade-off navigation framework. With the prevailing challenge in industry of how to deal with trade-offs between sustainability indicators (Dekoninck *et al.*, 2016; Held *et al.*, 2018), a trade-off navigation represents a first attempt towards providing a logic for addressing sustainability-related trade-offs, which are not addressed sufficiently in contrast to trade-offs between 'traditional' decision indicators (de Magalhães, Danilevicz and Palazzo, 2019). The trade-off navigation relies on several elements and a step-by-step guidance, which aim at making trade-offs explicit and clarifying the acceptability of proposed (design) alternatives and conflicts across desired indicators. Evaluation with industrial and academic experts showed that the framework facilitates a dialogue about (design) priorities, reinforces (design) considerations and creates transparency and traceability of the decision process. In this way, the trade-off navigation framework should act as a complementary decision support to sustainability performance indicators for sustainability screening of CE initiatives.

By bringing together the results from the Studies, a framework of sustainability screening of CE initiatives was proposed. This helps answering the main research question MRQ: How to provide decision-making support for manufacturing companies' in sustainability screening of circular economy initiatives in the early stages of development? The framework intends to guide selection and use of relevant information to assist comparison of circular and non-circular initiatives and support selection and development of an alternative initiative with the highest sustainability potential.

5.2. Contribution to the literature

From an academic perspective, this research has contributed to the literature in the domains of CE development, sustainability performance measurements from a TBL perspective and early stage decision-making by:

- Advancing the theoretical discussion on the use of leading performance indicators as an approach for supporting early stage sustainability performance assessment.
- Providing a consolidated database of leading performance indicators for economic, social and environmental performance measurement for five business processes and a wide range of CE strategies.
- Proposing a logic for indicator classification, which could be used to replicate studies for other sectors, such as construction, or for indicator classification on macro and meso levels and for various CE frameworks.
- Proposing a dynamic approach for a systemic indicator selection relying on contextual settings.
- Advancing the discussion about the need to incorporate the trade-off considerations into existing tools, techniques and approaches to support sustainability-oriented decision-making.
- Prescribing an approach for a trade-off analysis between conflicting sustainability indicators to support an informed decision process.
- Proposing a novel framework for supporting early stage sustainability screening for CE initiatives from a TBL perspective.

5.3. Contribution to the practice

From a practical perspective, this research has contributed by:

- Providing a consolidated database of leading performance indicators for economic, social and environmental performance measurement for five business processes and a wide range of CE strategies – a large repository of indicators with detailed information about descriptions, purpose of measurement, formulae and units.

- Providing a structured procedure to enable selection of relevant performance indicators for CE initiatives, consisting of either individual CE strategies or their combinations.

This provides an opportunity for industrial actors and other practitioners to locate useful indicators in a time-efficient manner. Additionally, it solves several challenges associated with the uncertainty how to transform sustainability issues and aspects into measurable indicators (Abbasi and Nilsson, 2012; Paulson and Sundin, 2019), as well as what data to use to measure sustainability aspects (Dekoninck *et al.*, 2016). This research shows that the generic nature of the indicators in the database could support building corporate management systems or be used across projects.

- Providing a structured approach to navigating trade-off situations between conflicting sustainability indicators.

While trade-offs, being inherent in most sustainability evaluations, complicate decision-making process, a structured approach to trade-off navigation creates visibility of the trade-offs and facilitates re-consideration of the design alternatives and criteria. In this way, the uncertainty, which leads to taking ad-hoc decisions, decreases, which helps exploring new (design) opportunities.

5.4. Research limitations

This research covers numerous aspects of sustainability-oriented decision support for early stage CE initiative development by means of sustainability screening. It provides initial findings and observations with the potential for extension, enhancement or confirmation through further research. Despite the contribution to the theory and practice, several key limitations could be highlighted, such as:

- Although the advantage of selecting a framework with thirteen CE strategies ranging from dematerialized offerings to recovery strategy for indicator classification, it still lacks granularity for some of the strategies. For instance, the CE strategy 'rethink value generation' implies the change to a corporate business model from product sale to offering product service, PSS, such as performance or access based models, sharing platforms, etc. Therefore, the classification could be done for different types of PSS (e.g. following the typology of Tukker (2004)) instead of an overarching classification according to the CE strategy 'rethink value generation' as it was done in this research. Similarly, the CE strategy 'recover' denotes recovery of energy and nutrients, for which a new classification could be done to distinguish between the two streams.

- Despite the adoption of a triple bottom line approach for indicator consolidation, more than a half of the indicators represent environmental dimension, while the social dimension is being underrepresented, particularly for the business model and product development processes.

- Most of the indicators are suitable to measure processes and products from a technological point of view, therefore, they might be insufficient to assist performance measurements of CE initiatives in bio economy sector (e.g. for organic products, nutrients, substances, molecular levels).
- The empirical studies were conducted in the context of the Nordic region, which is known for its high awareness of environmental issues (Short *et al.*, 2012) and where companies show a proactive approach with integrating sustainability into business activities driven by internal willingness and high benchmark standards (Salo, Suikkanen and Nissinen, 2019). Therefore, the research hypothesis should be tested with industries outside of the Nordic region with different, lower, level of sustainability maturity.
    - Similarly, the case studies on the selection of relevant leading performance indicators helped to test only a subset of the available indicators. More studies are needed to test all the indicators and propose new.
    - For a trade-off navigation framework, the evaluation did not involve multifunctional teams (which is preferred), neither the applicability of the framework to support trade-off situations in business model, manufacturing or supply chain process was tested.
- The proposed sustainability screening, particularly the leading indicators and the trade-off acceptability analysis rely on the details and data of the proposed CE initiatives; while the qualitative guidance is available, there is no data repository for fetching 'live' or generic data.
- The proposed sustainability screening relies on leading indicators for TBL performance measurement. It does not, therefore, account for measurements exclusively developed to measure CE, which might be useful to supplement the TBL metrics to show the alignment between the two.
- Missing classification of indicators according to life cycle stages. With the life cycle thinking and LCA being widely known (Beemsterboer, Baumann and Wallbaum, 2020), the indicator database could benefit from indicator classification according to life cycle stages.
- Large number of indicators consolidated in the database rely on operational metrics, which should be complimented by tactical and strategic metrics to balance the short and long term approach to sustainability measurement; accordingly, the research did not focus on providing support for defining sustainability strategy, vision and goals; nor the support was provided in defining relevant sustainability issues that could drive the proposal of new initiatives.

5.5. Suggestions for future research

Following the above-mentioned limitations, several recommendations could be given to extend, improve and confirm this research by:

- Developing new performance indicators to address:
    i. the environmental aspects of land use and soil pollution; aspects of the micro or nano-pollution (e.g. microplastics in virgin (Li *et al.*, 2020) and recycled materials (Roos, Arturin and Hanning, 2017);

ii. the environmental and social indicators suitable for business model and social and economic indicators suitable for product development processes, particularly focusing on stakeholder inclusiveness, i.e. user/customer and supplier perspective. For instance, supporting a) design for (sustainable and circular) behaviour (Ceschin and Gaziulusoy, 2016) (although should supported by ethical considerations (ibid.)); b) transition of roles, i.e. reduced ownership for consumers turning into users or 'prosumers' and suppliers (Xing, Wang and Qian, 2013), with social aspects of trust, empowerment, information security and more (with several indicators already proposed by Curtis *et al.*, 2020);

iii. the biological products, focusing on food, beverage, chemicals, fibres, nutrients, etc. This might be particularly useful for the cascaded use of bio-resources (Salvador *et al.*, 2021).

- Understanding and mapping the interconnectedness between the consolidated indicators: dependent and interdependent variables; positive, negative or neutral relationships; as well as developing 'live' formulas for immediate calculation and linking to 'live' data from internal corporate databases or generic databases.
- Supporting customization of indicators in light with sectorial differences.
- Developing an internet-based version of the User guide and the interactive database for the selection of relevant indicators, and the trade-off analysis to automatize the process and enable more interactive result visualization.
- Expanding the empirical investigation for the application of the User guide and the interactive database to support sustainability screening:
  - outside of the Nordic region;
  - for various CE scopes, i.e. for CE initiatives involving numerous CE strategies for simultaneous implementation;
  - evaluating the impacts of the support, i.e. whether the support is actually used (Blessing and Chakrabarti, 2009).
- Expanding the empirical investigation for the application of the trade-off navigation to support analysis of decisions between conflicting sustainability criteria or indicators:
  - to test the robustness of the proposed approach and improve it;
  - to evaluate the impacts of the support, i.e. whether the support is actually used.
- Proposing a guidance for the complementary use of sustainability screening for CE initiatives together with existing CE metrics
- Advancing the measurement approaches or developing indicators able to capture the sustainability potential beyond the triple bottom line approach. This suggestion goes in line with the few proposals to move away from a triple bottom line representation of corporate sustainability to 3R's: resilience, responsibility and regeneration (Elkington, 2020).

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Appendices

Appendix I – Business processes considered in the research: definitions and examples of decisions

Business process	Definition	Examples of typical decisions
Business model (BM) (modelling, development)	BM development involves exploring opportunities of value creation, capture and delivery for all its stakeholders through its entire value network (Wirtz et al., 2016)	· customer selection, location and position in value chain · differentiation of offerings: product type and/or service type · key operational activities, delivery channels, key partners and suppliers · revenue model and cost structure, configuration of resources (Massa and Tucci, 2013; Wirtz *et al.*, 2016)
Product development (PD)	PD process is a set of activities that a company employs to initiate, design and commercialize a product (Ulrich and Eppinger, 2012)	· identification of product's functions · selection of materials and suppliers · identification of product architecture and assembly scheme · identification of fabrication processes and tooling · consideration of the end of life scenario · estimation of costs · planning sales and service · product distribution channels (Rozenfeld, 2007; Ulrich and Eppinger, 2012)
Production and operations (P&O)	P&O are activities needed to produce/assemble products and services with help of operating equipment, incoming material and resources, employees and the outbound logistic actors (wholesalers, retailers) (Badurdeen et al., 2015)	· location, production capacity, technological processes · suppliers selection · procurement and delivery scheduling · number and location of logistics facilities · workforce · packaging (secondary, tertiary) (Ulrich and Eppinger, 2012; Badurdeen *et al.*, 2015)
After-sale service	After-sales service are the activities needed to maintain, during and after the delivery takes place, product quality and reliability in order to increase customer satisfaction (Tavakoli *et al.*, 2016)	· selecting stock location and inventory · procurement and delivery schedules · selecting sourcing and volumes of spare parts and materials, packaging needs · transportation mode and load · number and location of service stations · possible treatment activities · workforce training and capacity (Cohen and Lee, 1990; Tavakoli *et al.*, 2016)
End of life (EoL) operations	EoL operations are activities for managing a product, its parts and materials at the end of its use and lifecycle (Gehin, Zwolinski and Brissaud, 2008)	· selecting stock location and inventory · procurement and delivery schedules · selecting sourcing and volumes of spare parts and materials, packaging needs · transportation mode and load · number and location of EoL stations · possible treatment activities · workforce training and capacity (Gehin, Zwolinski and Brissaud, 2008; Lambert, Riopel and Abdul-kader, 2015; Tavakoli *et al.*, 2016)

Appendix II – Summary of the qualitative feedback from case studies performed in Study B

Comment ID	Case study	Attribute	Criteria	Original feedback	Adopted feature	Integrated into	Elaboration on the adopted feature
#1	C1	Generic	Broadness	It would be very beneficial if [this work] addressed how to translate results of the indicator calculation into business/marketing and branding strategy (i.e. communication and branding).	No	N/A	Outside the scope of this research
#2	C2	Generic	Broadness	This work [sustainability screening] needs to make more emphasis on organizational sustainability vision and objectives.	No	N/A	Outside the scope of this research
#3	C7	Generic	Clarity and simplicity	There are many words/phrases which are open to various interpretations and many of which seem to overlap. For example, in Step 1 the user is intended to select relevant 'scenarios', 'initiatives', 'BPs', and 'strategies' to get resulting 'configurations' and move to Step 2. Could these be made more concise? Are all of them necessary?	Yes	Interactive workbook; User guide Step 1	Step 1 was supported by Activity 1, 2 and 3 to help distinguishing between initiatives, strategies and business processes. Other terms were simplified or eliminated
#4	C6	Generic	Clarity and simplicity	There were some abbreviations that were unknown to me and that were not in the glossary. PSS for example. Possibly this is industry-dependent, of this i am not certain.	Yes	Interactive workbook	Provided full descriptions along abbreviations, whenever used
#5	C4, C6	Generic	Clarity and simplicity	4: We work with sectorial standards and some terminology might be different. We need to make sure we are selecting the right CE strategy. 6: I experienced some uncertainty in terminology where I had to pick between two things that in my world are similar, or where the initiative could count as both. For example, recycling versus nutrient use, for biological materials that are broken down and put back together again, this is hard to distinguish. Open loop versus closed loop are both recycling.	Yes	Interactive workbook; User guide Step 1	Activity 2 under Step 1 was introduced to support identification of activities under a proposed CE initiative rather than using direct names of CE strategies

#6	C1, C5	Generic	Clarity and simplicity	1: The language used to describe indicators is too academic, it can be challenging for companies to use the tool and understand what actually an indicator means 1: Make the tool user-friendly for those, who may not have an expertise in sustainability assessments, but have passion to work to make good 5: Requires time to learn the features and understand the selection logic.	Yes	Interactive workbook	The indicators were reviewed and their definitions simplified (whenever possible). Additionally, a column 'Purpose and significance of indicator value' was introduced under indicator information in Indicator database worksheet to ease indicator understanding. Also, a worksheet 'Sustainability aspects' was added to help understanding what each aspect means
#7	C3	Generic	Clarity and simplicity	Use screening/scanning, not the assessment so not to confuse with a LCA (life cycle impact assessment).	Yes	User guide	The tool has been renamed as a sustainability screening tool
#8	C6, C7	Generic	Ease of navigation and embedded features	6:I found the lack of auto-update somewhat problematic. 7: The guidance was helpful, but the tool itself did not seem to function as stated in the guidance. For example, the output of step 1 did not transfer into step 2. The reset filter button in Step 2 did not function and the step 2.4 slide states to 'Copy and paste the list of selected indicators' but it is not clear where and how to do this. The filters can be difficult to clear as well.	Partially	Interactive workbook; User guide Step 2.3	Auto-update was removed from 'Indicator database' and 'Step 3' worksheets. More guidance was introduced in the User guide in Step 2.3. indicating "When selecting a relevant indicator in the digital database, put an 'x' next to it to indicate it was selected. Use the 'Navigation' tab in the digital database to be guided through navigation features." Correspondingly, a new worksheet 'navigation' was introduced with visual guidance for navigation features.
#9	C3	Generic	Ease of navigation and embedded features	It would be nice to have a more interactive tool [i.e. web-based tool].	No		Not within the scope of this research project

#10	C3, C5	Generic	Relevance	3: Important to guide the user in understanding: “what are competencies the user should have in order to work in the database”, “when is appropriate to use the tool, i.e. in what part of the process do you use it” 5: Important to indicate who is a facilitator of a sustainability screening at a company or for a project. We need the 'owner' of the sustainability screening.	Yes	User guide, introduction	This is incorporated in the User guide, indicating the objective, when to use, key participants for a multidisciplinary team, time required to complete the selection and input and output data
#11	C2, C7	Selection procedure	Simplicity	2: The tool is “heavy”, maybe make it gradually more complex 7: Sometimes it is too many things to consider and the tool makes it even harder. It should simplify more.	Yes	User guide	Few sub-steps (e.g. 1.2 and 1.3; and 2.2) are introduced in the selection procedure to provide guidance on selecting relevant business process, CE strategies, and prioritization of sustainability aspects. Additionally, practical examples are given
#12	C1	Selection procedure	Simplicity	Indicator selection and screening process takes a lot of time, therefore, another session/workshop with more time is needed to judge the indicators against selection criteria.	Yes	User guide; Selection procedure, Step 2	Due to the scope of the indicators to cover the triple bottom line dimensions, the time is needed to understand indicators and carefully select them. To assist the selection process, sub-steps under Step 2 were detailed with guidance how to narrow down the indicator set by prioritizing sustainability aspects and how to select the indicators considering the contextual settings. Furthermore, a guidance on the number of indicators was given.
#13	C1, C2, C3, C4	Selection procedure	Relevance and coherence	1: The process of indicator selection should start with the aligning or defining the organizational sustainability vision and objectives. It is important to connect the final set of indicators to the corporate values. 2: It is important that the user (i.e. the team that uses the database) has a scenario (initiative) ready, to make filtering meaningful and to be able to further narrow down the set of selected indicators. 3: It is crucial that the user (the team) has the initiative outlined in details to be able to test it in	Yes	User guide; Selection procedure, Step 1.3; interactive workbook	Although not focusing on supporting the formulation of corporate objectives, Activity 3 under sub-step 1.3. was introduced, which recommends stating a set of objectives for the proposed CE initiative, thus guiding the indicator selection. In addition, the introduction in the User guide describes the objective, when to use, key participants for a multidisciplinary team, time

				the database. 1, 4: It is very important to make a company aware of why selection of indicators is important and what indicators can be used for.			required to complete the selection and input and output data.
#14	C5	Selection procedure	Relevance and coherence	5: One of the main challenges of working with these tools is that we do not have a defined circular model yet, as it has to start with business model and partner identification in the value chain.	Yes	User guide	This is incorporated in the User guide indicating when to use and what input data is needed
#15	C1	Selection procedure	Simplicity	.. the procedure requires the facilitator with sustainability expertise to facilitate the team and aid the interpretation of each indicator, thus it is challenging for (smaller) companies to use the database and select the ‘right’ indicators in a time-efficient manner.	Yes	Indicator database; User guide after Step 2	The 'Purpose and significance of indicator value' has been added to the indicator information in 'Indicator database'. Moreover, a new worksheet 'sustainability aspects' was introduced with definitions of each sustainability aspects the indicators measure. This was done to help understanding and work with sustainability screening. Moreover, few recommendations were introduced in the User guide such as: "It may be necessary to consult industry associations to understand the sustainability ‘areas of concern’ that are particular to your sector or material/substance you would like to use; this can facilitate selection of indicators that otherwise could be missed out"
#16	C1	Selection procedure	Completeness	“Purpose” column is useful to understand the indicator.	Yes	Interactive workbook	A column 'Purpose and significance of indicator value' was introduced under indicator information in Indicator database worksheet to ease indicator understanding. Also, a worksheet 'Sustainability aspects' was added to help understanding what each aspect means

#17	C1, C2	Selection procedure	Relevance and coherence	The feature “sustainability coverage” under Step 3 is a good visual aid to understand what dimension of sustainability is “winning” in the assessment.	Yes	User guide	In addition to the visual aid, the checklist in in Step 3 is introduced, which makes sure a TBL perspective is considered and the balance of indicators is achieved also within dimensions
#18	C3	Selection procedure	Relevance and coherence	It is confusing to have Business process and CE initiatives separated; the assessment is called assessment of CE after all.	No		Separation of business process and CE strategies was purposeful to enable a more flexible approach to selecting indicators for a range of CE initiatives
#19	C1, C2, C4	Selection procedure	Relevance and coherence	A way to guide the user better could be to set up examples for each Business process and a CE strategy, so the user can have a reference example that will ease the filtering of indicators. Each CE and Business process need more explanation (maybe more explicitly in the guide or directly in the excel workbook.	Yes	Excel workbook - Step 1 - Activity 1&2; User guide	Activities for each BP and CE strategies are described in Step 1 - Activity 2, which helps locating relevant BP and CE strategies. Furthermore, a practical example with application of steps was given in the User guide to help show how the steps can be operationalized
#20	C7	Selection procedure	Relevance and coherence	7: Step 1 seems clear, but moving from Step 1 to Step 2+3 was not clear even with the guidance slides. Perhaps there are too many fields to select variables and to many filters.	Yes	Excel workbook - Step 1 - Activity 1&2 and Step 1 - Activity 3	Sub-steps with Activities 1,2 and 3 were introduced to help working with few selections of business processes and CE strategies at a time
#21	C2	Selection procedure	Relevance and coherence	Importance of having boundaries during the indicator evaluation process, “so not to select too many, too few or too ‘biased’ indicators by trying to avoid trade-offs” and that “there might be ‘risks’ associated with operating with a ‘limited’ number of indicators or contradictory indicators.	Yes	User Guide; Step 2 and sub-steps	Due to the scope of the indicators to cover the triple bottom line dimensions, the time is needed to understand indicators and carefully select them. To assist the selection process, sub-steps under Step 2 were detailed with guidance how to narrow down the indicator set by prioritizing sustainability aspects and how to select the indicators considering the contextual settings. Furthermore, a guidance on the number of indicators was given.

#22	C1	Indicators & application	Relevance and broadness	The challenge can be that when selecting a specific business process to work with, or a certain CE strategy, we only get the filtered indicators according to the selected scope, however there might be other indicators that may bring more meaning to the company vision in general.	N/A		
#23	C1	Selection procedure	Relevance and coherence	.. [guiding questions] they are very helpful, because they "force" the user to think of each single indicator and reflect on it. In addition, the indicator review step helped to understand the internal processes and what matters the most and what are the gaps.	Yes	User guide; selection procedure	Prioritization of sustainability aspects is recommended to reduce complexity and improve focus on the scope rather than being generic. It is a part of Step 2, sub-step 2.2. Moreover, the guidance for the selection in step 2.3. provides examples of the contextual settings that influence the relevancy of indicators
#24	C2, C3	Selection procedure	Relevance and coherence	Some social indicators (e.g. human rights, labour, and code of conduct) are strategically set because they are a core value; therefore, we do not consider them [in this selection process]. However, some others, e.g. critical raw materials and sourcing, are important to consider for a particular scope.	Yes	Selection procedure, Step 2	Prioritization of sustainability aspects is recommended to reduce complexity and improve focus on the scope rather than being generic. It is a part of Step 2, sub-step 2.2. Prioritization of sustainability aspects, with elaborate guidance how to prioritize
#25	C1, C3	Selection procedure	Relevance and coherence	1, 3: Maybe some kind of a scale for each indicator can be introduced to show how good or bad the value of the calculated indicator is. In addition, a guidance can contain the list of "best" [important, mandatory] indicators within each dimension (social, economic, environmental). 6: Simplify the procedure by indicating 'mandatory' and 'optional' indicators.	Partially	Interactive workbook	A column 'Purpose and significance of indicator value' was introduced under indicator information in Indicator database worksheet to ease indicator understanding. Also, a worksheet 'Sustainability aspects' was added to help understanding what each aspect means. However, the classification according to 'mandatory' and 'optional' was not done based on the recommendations from the literature to facilitate a dynamic process of indicator selection. This means whether an indicator is 'mandatory' or 'optional' depends on the context used during sustainability screening

#26	C1	Selection procedure	Completeness	“Code of an indicator and Symbol” entries do not provide any importance for the indicator database.	Partially	Interactive workbook	The "symbol" has been removed, however the code is still present because it is seen as a feature that helps 'tracing' back the indicator when it has been customized or changed during the selection process
#27	C3, C6	Selection procedure	Relevance and coherence	3: We cannot review [did not choose] economic indicators as we do not have the right competencies. 6: Because I was not sure what would be relevant for my interest area, therefore I did not really use this [sub-step 2.2 - prioritization of sustainability aspects] option; however I was mostly after environmental indicators (because social are already added at the strategic level).	Yes	User guide, introduction	The user guide highlights the importance of bringing a multidisciplinary team to assist prioritization of relevant sustainability aspects and selection of indicators covering TBL perspective
#28	C3, C6	Selection procedure	Relevance and broadness	3: We need to customize few indicators to reflect our ambitions: e.g. instead of volume used, we more look into number of different chemicals used. We aim to remove a chemical than just reduce it. 6: Some indicators can be used to show the effectiveness of our CE solutions in terms of virgin material saved or waste minimized. It is our strategy to minimize resources use. 6: .. although I did find some indicators missing (e.g. for converting low grade biological products for a higher grade purpose (e.g. nutrients, bio-oils), I did not create any.	Yes	Selection procedure, Step 2; User guide	Support indicator customization to reflect the context; examples of customization and creation are provided in the Guide
#29	C1	Selection procedure	Relevance and coherence	It is good to have gradual steps in the database (different excel sheets) to obtain the initial set of indicators and then to select the most suitable indicators for the final set using the guiding questions. It gives a good overview of the whole process of the indicator selection, as well as tracks what indicators have been removed from the final set, but initially comprised the initial set.	Yes	Interactive workbook; Selection procedure	The selection procedure relies on a number of steps and sub-steps, allowing selecting relevant indicators. The procedure is iterative. The interactive workbook allows to register selected indicators and add/remove any other indicators when necessary

#30	C3, C4	Indicators & application	Relevance and broadness	3: Indicator calculation – data requirements: the data needed is extensive, therefore we need to see the value in indicators, because same data would be needed for an LCA; however the advantage of the indicators is that "we can use our own data, as opposed to an LCA, where a generic data is used". 4: Indicators are something we need to control; hence, we should be selecting them carefully.	Yes	Selection procedure, Step 2;	A column 'Purpose and significance of indicator value' was introduced under indicator information in Indicator database worksheet to ease indicator understanding.
#31	C6	Indicators & application	Relevance and broadness	Some indicators would involve significant costs over time or experts for most companies; however, they are very useful because they summarize well the initiative. Therefore, I am not certain how this should play into prioritization, as we do not have a sustainability manager.	Yes	User guide after Step 2	Few recommendations were given in the User guide; such as: "It may be necessary to create a 'parking lot' for indicators that are considered important, but require extra effort in data collection. Do not dismiss an indicator just because it is time consuming to calculate it"
#32	C2, C3, C5	Indicators & application	Simplicity	The biggest challenge is data acquisition; Data collection process is very resource demanding (often requiring contact to other departments within the company, but also supply chain, customers, etc.).	Yes	User guide	Step 3 in the User guide provides help with setting up a data collection plan and providing examples of data sources and data quality
#33	C6	Indicators & application	Relevance and broadness	Social indicators are very useful to add to other - already running - initiatives. However, social are generic, linked to the overall company strategy and hence, by default, to all CE and other strategies.	N/A		
#34	C6	Indicators & application	Completeness	I found particularly the initiatives lacking biological product options, and i had limitations finding good options for more optimal raw material usage or using low-grade products for a higher-grade purpose (e.g. going from waste to usage).	No		It is a limitation of an indicator database, where most indicators are on a product or production level and oriented towards technological products. Working with organic and biological materials might require other indicators focusing on nutrients, calorific values, etc. (findings are documented in Kravchenko et al., 2019)
#35	C1, C3, C5	Indicators & application	Relevance and broadness	1: Overall, the database consists of some very useful indicators that can help a company to focus on certain areas to define possible impacts on	N/A		

				sustainability. Again, the advantage can be that those indicators are operational, therefore, help companies to focus on measurements and monitor changes. 3: Some indicators are very relevant for our scope to start understanding our baseline and how we improve it (e.g. for internal recycling, we should ask suppliers about the defect rate % (environmental indicators of Defective products compared to manufactured products) and the quantity of waste generated when manufacturing the product). 5: The advantage of having an overview of different sustainability aspects and related indicators is in pointing to the questions we should be asking our suppliers. It can help us being more systematic about what to ask - innovation director. 5: The alignment between our (project) objectives and indicators help us ask the right questions - production manager & sustainability manager.			
#36	C2, C4, C5, C6	Indicators & application	Relevance and broadness	2: Indicators found in the database are very helpful to internally manage processes and make decision on the improvements 4: Selected indicators help understanding our products better and help returning for follow up activities 5: By looking at the final set, it can be that we already measure some indicators, again, which is beneficial to follow up on. However, some other indicators inspire us to ask other types of questions.	N/A		
#37	C2	Indicators & application	Relevance and broadness	The overall alignment is that the indicators [in the leading indicator] database is broader than an LCA, meaning that it can be used to evaluate (also screen) the initiatives on their sustainability impact based on [on hand] indicators calculations (LCA requires a software and extensive data).	N/A		
#38	C2	Indicators & application	Relevance and broadness	The database with indicators is very useful once the user learns how to operate and navigate in it. It is important that the user (i.e. the team that uses the database) has a scenario (initiative)	N/A		

				ready, to make filtering meaningful and to be able to further narrow down the set of selected indicators.			
#39	C6	Indicators & application	Relevance and broadness	We consider sustainability in everything we do, and the indicators [in leading indicators database], help to structure the process and bring an understanding of what to take into account, when planning and evaluating any sustainability-oriented initiative, including a circular.	N/A		
#40	C2, C4, C5	Indicators & application	Relevance and broadness	2: It would interesting to have a set of indicators for each project we initiate and run, e.g. project-related indicators. By having that, we can collect data that can be used across projects but also to monitor changes, trends and improvements over time. 4: Some indicators can be helpful to establish an environmental management system (EMS) or some eco-design requirements. Indicators can also to be used to construct some internal guidelines and rules to follow to make the decisions for sustainability easier and aligned between project stakeholders. 5: Indicators can be selected and used to improve our existing environmental management system (EMS), which is established by many of our factories.	N/A		
#41	C6	Indicators & application	Relevance and broadness	[The procedure and indicators can be used for other initiatives and internal activities], such as: initiative planning and follow up. General application, not necessarily circular. We are not a company that measures things on a daily basis, we are small, however indicators help us understanding what to take into account, it helps the planning.	N/A		
#42	C2	Indicators & application	Completeness	It is important to account for trade-offs - so not to select too many, too few or too 'biased' indicators by trying to avoid trade-offs and that there might be 'risks' associated with operating with a 'limited' number of indicators or contradictory indicators. We need to be asking: what are the acceptable boundaries for such sustainability screening? what if we are missing out something?	Yes		* A trade-off support is important and will be developed later in the project

#43	C3, C6	Indicators & application	Relevance and broadness	It will be important to make the tool sector specific and then further develop it with relevant indicators and allow for benchmarking scale, so we can see the maturity/progress.	No		It may indeed be beneficial to develop sector-specific tools, however this is currently not a focus of the research
#44	C1	Indicators & application	Broadness	Most indicators are product related, would be exciting to see some “radical”, “innovative”, “impressive”, “out of the box” indicators that can inspire company, can help us to communicate our work to the customers, partners and suppliers.	No		Outside the scope of this research.
#45	C5	N/A		CE is not easy. If it was easy everybody would be doing it now.	N/A		
#46	C3	N/A		At this stage, also considering the work and confusion with CE as a concept, we need more help with understanding the opportunity with CE and finding the idea to detail and work with. As a company, we still need more focus on circularity; the idea is to create “impact” (good).	N/A		
#47	C5	N/A		Sustainability indicators are a part of the answer. There are other important criteria to consider when making a decision - project manager.	N/A		

Appendix III – Summary of the qualitative feedback from expert review in Study C

Overview of industrial experts (IA) and academic experts (AE)

Expert ID	Area of expertise	Level of experience
Industrial experts (IE)		
IA#1	Product design, LCA modelling	>5 years
IA#2	Product design, manufacturing efficiency, circular economy design	>5 years
IA#3	Product design, circular economy design	>2 years
IA#4	Mechanical and environmental engineering	>25 years
IA#5	Health, quality and safety management, risk management	>2 years
IA#6	Product design, LCA modelling	>5 years
IA#7	LCA modelling, sustainability consulting	>10 years
IA#8	Environmental management, sustainable supply chain management	>10 years
Academic experts (AE) – collective		
AE#1-12	Product design, eco-design, LCA modelling	Mixed

Expert ID	Attribute	Criteria	Original feedback	Adopted feature	Integrated into	Elaboration on the adopted feature
IE#2, IE#4, AE	Generic	Relevance	#Who decides what criteria to include? How to choose them? Is the guidance needed? One criteria at a time + indicate acceptable range for each one by one #Which functions should participate? #who the actual user is? should there be a sustainability expert part of the discussion?	Yes	TONF introduction	Use context is defined to encourage work in multifunctional teams
AE	Generic	Relevance	I like that you show from which stakeholder the criterion comes from	Yes	Input data guidance	References / Sources for input data, including for acceptability ranges and their non-negotiability

IE#7, IE#8	Generic	Relevance	Descriptions are generic, since application aims at being generic. Maybe it makes sense to make a division into a strategic and a non-strategic decision in the beginning - usability is a lot about "for whom" in "which situation" - A promising approach.	Partially	TONF introduction	Added as a use context
IE#5, IE#7	Generic	Relevance	#Seems straightforward - gives a good idea how we are framing the decision. #The three steps make very much sense.	N/A		
IE#6	Generic	Relevance	After going through these steps and questions - you know where the problem is. It is a guidance for a conversation	N/A		
IE#1, IE#3 IE#5, AE	Generic	Ease of navigation and embedded features	#It would be nice to have a more interactive tool, to log all decisions and see changes; #Using excel's sliders and drop down menus can help making the tool more interactive.	No	Excel matrix, visualisation	Excel allows saving data and additional information Filtering was added
IE#8	Generic	Clarity and simplicity	the examples are crucial, in my view. Not to influence users but to supporting them in accurately picturing what has to be done.	Yes	Input data guidance; upcoming user guide	Examples of input data and how to negotiate are given
IE#3, IE#4	Generic	Clarity and simplicity	#What I learned is how simple it can be presented. I think you have included the right things in there in probably the most time efficient manner. This topic can potentially be very heavy and have a steep learning curve, so I think it is good to try and keep it a bit simple #First of all I liked very much this tool. Very helpful	N/A		
IE#8	Generic	Relevance	The preparation time can be daunting at first sight. Users should be properly informed of the high benefits that they might expect at the end of the session, therefore making it worth learning how to use the tool. However, the tool is so great in its outcomes that, again, I believe it must be widely spread as support to organizational practice. Perhaps providing	N/A	Upcoming user guide with more granularity for different teams	

			guidelines on how to use the tool within different types of teams would be very beneficial.			
AE	Generic	Relevance	Nice little technique to help us keep a track (both memory and justification) of our decisions around trade off prioritization. # ... that the tool has potential to support decision making especially as a sort of documentation and it improves on transparency	N/A		
IE#1, AE	Input data	Relevance	Guide to select fewer indicators - more indicators make it more difficult to prioritize Could aggregation of indicators be a way to represent more indicators using fewer? #How and how many extra criteria/indicators can be added - which also influence the result.	Yes	Input data guidance	Guidance was added to point at the optimal number of indicators and criteria and initiatives (alternatives)
IE#3, IE#4	Input data	Relevance	Performance could be measured not only by quantitative, but also qualitative, or pass/fail scale Asking to state performance really helps to understand the environmental side. Numbers really help visualizing	Yes	Input data guidance	Guidance provided to focus on qualitative or quantitative measures (indicators, criteria)
IE#1, IE#3, IE#4, IE#8, AE	Input data	Relevance	#Encourage companies to make surveys about how and what to prioritize.- How do companies know what to prioritize? It is because they know CO_2 and not human toxicity? #Customer dialogue is important #Understanding which criteria are a requirement and which are 'nice' to have , probably requires research from company #It might involve a lot of different stakeholders to create the input for the ranges also outside the project team itself. Both from a strategic, tactical to an operational perspective. #the precondition is to involve stakeholders who have the authority, knowledge and confidence in setting the 'right' criteria.	Yes	Input data guidance	Guidance to obtain acceptable ranges and the non-negotiability

IE#1, IE#2	Acceptable ranges	Clarity and simplicity	Useful to make ranges obvious to all decision makers It helps a lot to visualize the context	Yes	Excel matrix, visualisation	
IE#2	Non-negotiability	Clarity and simplicity	For negotiable guide as following: i) change acceptable ranges; ii) remove criteria/replace with more important use easier language and terminology - replace non-negotiable with 'Can I easily change this? Can I change the ranges for criteria X?	Yes	Input data guidance; Step 1 guidance; upcoming User guide	Guiding questions to make classification easier; supported by the questions in Step 1
IE#4	Non-negotiability	Relevance	When asking to re-consider the acceptable ranges and non-negotiable criteria - > it is a powerful way to encourage a company to seek confirmation of their objectives with design alternatives. There are cases there non-negotiable criteria were adjusted because of proactive move from a team of designers	Yes	A step-by-step guidance	Step 1 - encouraging to validate non-negotiability with relevant stakeholders
AE	Non-negotiability		Consider to add a weighting column to also get guidance if the alternatives score the same for the non-negotiate criteria	No	A step-by-step guidance	Step 1 encourages to proceed with all alternatives that satisfy non-negotiable criteria.
IE#4	A step-by-step guidance	Relevance	User guidance - to make a decision use a final number, however combine it with other criteria/aspects for a holistic picture	Yes	A step-by-step guidance	in Step 2 the guidance supports pairwise comparison; in Step 3, results of Step 1 and Step 2 are combined to support final decision
IE#3	A step-by-step guidance	Relevance	At first some might be non-negotiable, but I think things will change during conceptualisation and development as this will reveal e.g. if technical performance can be achieved for instance. Or if the concepts and available tech and timing and resources of the project fulfils what initially was acceptable	Yes	A step-by-step guidance	Step 1 - encouraging to validate non-negotiability with relevant stakeholders
AE	A step-by-step guidance	Relevance	Don't really agree on the ability to change scales (if the product developers are going to use them - the weights are already set)	No		

IE#6	A step-by-step guidance	Relevance	Q for units - does this capture what we want to capture? When we look at the result, is bad / good performance the alternative fault or is it how our units/ranges are set up? - It helps to discuss our requirements for our concepts. for some units/criteria the scale is not linear - e.g. is increasing lifetime indefinitely a good thing? - Encourage dialogue - make discussion explicit	Yes	A step-by-step guidance	Step 1 - encouraging to validate non-negotiability with relevant stakeholders; Step 3 - reiteration of the decision process - confirmation of the selected alternative

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November 2020

ISBN:978-87-7475-630-9

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DCAMM Special Report No. S283

ISSN: 0903-1685