Ex-Ante Environmental Decision-Support: A Quantitative Framework for Companies and Industrial Parks in a Circular Economy Context

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Declaration on Publications

In all three peer-reviewed articles (Publications I, II, and III) included in this cumulative dissertation, the author of this dissertation was the corresponding author and was primarily responsible for the conceptual development, methodological design, formal analysis, investigation, and writing. The individual contributions are summarized in Table 1.1.

Publication I: Verkic, Benedikt; Göbbels, Lieve; Greiff, Kathrin (2025): Analysis of environmental indicators assessing industrial symbiosis and urban symbiosis for an improved indicator selection process: A scoping review. In *Cleaner Environmental Systems* 19. https://doi.org/10.1016/j.cesys.2025.100363

Publication II: Verkic, Benedikt; Schröder, Elina; Drees, Kornelia; Dosch, Klaus; Buschbeck, Christian; Greiff, Kathrin (2025): Evaluation approach to assess actions and scenarios for improving climate and resource efficiency of municipalities and companies in industrial parks. In *Journal of environmental management* 398, p. 128442. https://doi.org/10.1016/j.jenvman.2025.128442

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Table 1.1: Ph.D. candidate contributions based on the Contributor Roles Taxonomy (Brand et al. 2015).

	Publication		
Contributor Role	I	II	III
Conceptualization	✓	✓	✓
Data Curation	-	-	-
Formal analysis	✓	✓	✓
Funding acquisition	-	-	-
Investigation	✓	✓	✓
Methodology	✓	✓	✓
Project administration	-	-	-
Resources	-	-	-
Software	-	-	✓
Supervision	-	-	-
Validation	-	-	-
Visualization	✓	✓	✓
Writing - Original Draft	✓	✓	✓
Writing - Review & Editing	✓	✓	✓

✓: contribution, -: no contribution

Further publications by Ph.D candidate:

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Declaration of generative AI in scientific writing

During the preparation of this work, the author used ChatGPT in order to check and improve spelling and syntax. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

Abstract

This cumulative dissertation develops and critically reflects on a generic, ex-ante framework for environmental decision-support for companies and industrial parks in a circular-economy (CE) context. The work is motivated by rising global environmental pressures, the transgression of planetary boundaries and by tightening international and European climate- and resource-policy frameworks, which demand quantifiable progress at sectoral and company levels. Existing methods such as life cycle assessment (LCA), greenhouse-gas accounting and diverse CE indicators provide a rich toolbox. Yet they are heterogeneous, often data-intensive, mostly used ex-post and offer limited support for comparing concrete future actions under realistic data and capacity constraints in companies and industrial parks.

The overarching aim is to design and critically assess an easy-to-use ex-ante framework that enables companies (micro level) and industrial parks (meso level) to evaluate and prioritize environmental improvement actions while explicitly representing CE aspects and uncertainties. The framework responds to four research gaps: (i) the lack of a structured CE-aware indicator base for industrial and urban symbiosis, (ii) the absence of a holistic ex-ante action evaluation approach across industrial-park life-cycle phases and CE levels, (iii) the lack of a low-effort LCA-MCDM decision-support tool, and (iv) limited empirical insight into the robustness and context-dependence of such integrated frameworks. Methodologically, the framework combines three pillars: (a) a systematically derived environmental indicator base, (b) an action- and scenario-based prospective LCA approach (KREGI approach), and (c) a simple but transparent integration of LCA with multi-criteria decision-making (MCDM) in a decision-support tool (DST).

Publication I addresses the first research gap by conducting a scoping review of 457 sources and identifying 624 distinct environmental indicators used to assess industrial and urban symbiosis, eco-industrial parks (EIPs) and related meso-level CE initiatives. The overview reveals a small core dominated by energy-, climate-, material-, waste- and water-related indicators and highlights the under-representation of circularity strategies such as Refuse. Based on these findings and on LCA and resource-indicator literature, the thesis adopts a compact core of five environmental indicators. Global warming potential (GWP), cumulative energy demand (CED), raw material input (RMI), water use (WU) and land use (LU) are used as the environmental evaluation basis for the subsequent methodological developments.

Building directly on this indicator base, Publication II addresses the second research gap by elaborating the KREGI approach, a generic action- and scenario-based prospective LCA methodology that is used ex-ante for companies and industrial parks. Actions are defined as targeted interventions relative to the status quo that aim to reduce environmental impacts, and each action must satisfy clearly defined inclusion requirements. Actions are organized along industrial-park life-cycle phases and across the CE levels nano, micro, and meso. Each action's impacts on GWP, CED and RMI are quantified through a three-step procedure (scoping, life-cycle inventory, life-cycle impact assessment) under status-quo, best-case and worst-case scenarios to capture contextual variability and

parameter uncertainty. A detailed car-sharing example shows how assumptions about mobility behavior and substitution patterns influence environmental outcomes and trade-offs among indicators. The KREGI approach and this example provide the methodological basis for quantifying a broader set of actions in Publication III, which then form the quantitative input for the DST.

Publication III builds on the indicator base from Publication I and the KREGI action quantifications from Publication II to address the third and fourth research gaps. It integrates these elements into an LCA-MCDM DST that ranks actions at company and industrial-park level by environmental performance while treating circularity as a complementary, non-compensatory dimension. The DST uses pre-quantified action effects on an extended environmental indicator basis of GWP, CED, RMI, LU and WU, normalized to company-specific maximum saving potentials, and aggregates them via equally weighted linear scoring. Circularity information is represented via R-strategy mappings and optional CE indicators. Uncertainty is represented through mean-based scores and additional scores for best- and worst-case scenarios, generating simple scenario bands around each action and portfolio score. The DST is designed as an Excel tool that requires only basic company data and a yes/no selection of actions to be considered.

The integrated framework is applied in four contrasting company settings: a consulting firm, an electronics manufacturer, a soil-treatment company and a detergent producer. The case studies show that the framework yields coherent but context-dependent rankings and identifies a small number of high-leverage actions per company. In service-oriented contexts, actions related to workspace use and employee mobility dominate the improvement potential for GWP and CED, while in material- and energy-intensive settings, logistics- and process-focused actions become more important. Renewable-energy and electrification actions reduce climate and energy impacts but can increase land and water use, and these trade-offs are visible in the multi-indicator results and scenario bands.

Overall, the results support the methodological hypothesis that a generic, low-effort (easy-to-use and interpret) ex-ante framework can provide decision-relevant relative environmental rankings of actions and portfolios under practically available data constraints. The framework combines a structured indicator base, scenario-based action-impact quantification and a transparent LCA-MCDM design while making key trade-offs and uncertainties explicit. Limitations include the focus on environmental indicators, equal weighting and additive aggregation, a Europe-centered literature basis for scenario quantification and the lack of explicit modeling of interactions among actions and rebound effects. Future research should broaden the environmental indicator set, extend the action catalog and regional scope, integrate economic and social dimensions, and further develop dynamic LCA and digital implementations.

Zusammenfassung

Diese kumulative Dissertation entwickelt und reflektiert einen generisch anwendbaren, ex-ante ausgerichteten Rahmen zur umweltbezogenen Entscheidungsunterstützung für Unternehmen und Industrie- bzw. Gewerbegebiete. Die Arbeit möchte einen Beitrag dazu leisten, globale Umweltkrisen, die Überschreitung planetarer Grenzen sowie verschärfte klima- und ressourcenpolitische Anforderungen zu adressieren. Bestehende Methoden wie Ökobilanzierung (LCA), Treibhausgas-Bilanzierung, unterschiedliche Indikatorensets und Anwendungen der Circular Economy (CE) sind heterogen, häufig daten- und ressourcenintensiv und überwiegend ex-post ausgerichtet. Sie unterstützen nur begrenzt den Vergleich konkreter zukünftiger Maßnahmen unter typischen Unternehmensanwendungen.

Ziel der Arbeit ist es, einen anwendungsfreundlichen ex-ante-Rahmen zu entwerfen und kritisch zu bewerten, der Unternehmen und Kommunen ermöglicht, Maßnahmen zur Reduktion von Umweltbelastungen auf Unternehmens- und Industrieparkebene zu bewerten und zu priorisieren. Dabei sollen CE-Aspekte und Unsicherheiten explizit abgebildet werden. Damit reagiert die Arbeit auf vier zentrale Forschungslücken: (i) das Fehlen einer strukturierten, CE-sensitiven Umweltindikatorbasis für industrielle und urbane Symbiosen bzw. Öko-Industriegebiete, (ii) das Fehlen eines ganzheitlichen, szenariobasierten ex-ante-Bewertungsansatzes für Maßnahmen über Industrieparklebenszyklusphasen und CE-Ebenen hinweg, (iii) das Fehlen eines niedrigschwelligen LCA-MCDM-Entscheidungsunterstützungstools für die Mikro- und Meso-Ebene sowie (iv) die begrenzte empirische Evidenz zum Verhalten, zur Robustheit und Kontextabhängigkeit solcher integrierter Rahmenwerke. Der Rahmen kombiniert drei methodische Säulen: (a) eine systematisch abgeleitete Umweltindikatorbasis für industrielle und urbane Symbiosen und Öko-Industriegebiete (EIPs), (b) einen maßnahmen- und szenariobasierten prospektiven LCA-Ansatz (KREGI-Ansatz), der ex-ante eingesetzt wird, und (c) eine einfach gehaltene, transparente Verknüpfung von LCA mit multikriteriellen Entscheidungsverfahren (MCDM) in einem quantitativen Entscheidungsunterstützungstool (DST).

Die erste Publikation führt ein Scoping-Review durch, in dessen Rahmen 457 Quellen ausgewertet und zu 624 Umweltindikatoren für industrielle und urbane Symbiosen, EIPs und verwandte meso-level-CE-Initiativen zusammengefasst werden. Dabei werden die wichtigsten energie-, klima-, material-, abfall- und wasserbezogenen Indikatoren sichtbar. Auf dieser Basis und einschlägiger LCA- und Ressourcenindikator-Literatur wählt die Arbeit einen kompakten Kern von fünf Umweltindikatoren (Treibhauspotenzial - GWP, kumulierter Energieaufwand - CED, Rohstoffinput - RMI, Wasserverbrauch - WU und Flächennutzung - LU) als zentrale Bewertungsgrößen und Umweltindikatorbasis für die nachfolgenden methodischen Entwicklungen.

Die zweite Publikation baut auf diese Indikatorenbasis auf und entwickelt den KREGI-Ansatz als generische, maßnahmen- und szenariobasierte prospektive LCA-Methodik, die ex-ante für Unternehmen und Industriegebiete eingesetzt wird. Maßnahmen werden anhand expliziter Auswahlkriterien definiert und entlang der Lebenszyklusphasen von Industriegebieten sowie der CE-Ebenen nano, mikro und meso strukturiert. Jede

Maßnahme wird über ein dreistufiges Verfahren (Untersuchungsrahmen, Sachbilanz, Wirkungsabschätzung) für die Indikatoren GWP, CED und RMI unter Status-quo-, Best-Case- und Worst-Case-Szenarien quantifiziert, um Unsicherheiten und Kontextabhängigkeiten abzubilden.

Die dritte Publikation integriert die Indikatorbasis und die KREGI-Maßnahmenquantifizierungen in ein LCA-MCDM-basiertes DST. Das Tool ordnet Maßnahmen auf Unternehmens- und Industrieparkebene nach potenzieller Umweltauswirkungseinsparung. Es verwendet vorab quantifizierte Maßnahmeneffekte für die erweiterten Umweltindikatoren GWP, CED, RMI, WU und LU, normalisiert diese über ein maßnahmenbasiertes Maximum je Indikator auf Basis des unternehmensspezifischen Einsparpotenzials und aggregiert die Ergebnisse mittels Gleichgewichtung der Umweltindikatoren und gewichteter Summe. CE-Aspekte werden über die Zuordnung zu R-Strategien und optionale Zirkularitätsindikatoren abgebildet. Unsicherheit wird durch die Berechnung von Mittelwert-, Best- und Worst-Case-Punkten und deren Darstellung als Szenariotrichter erfasst. Das DST ist als Excel-Tool umgesetzt und benötigt lediglich wenige Eingangsgrößen und eine Ja/Nein-Auswahl der potenziell anwendbaren Maßnahmen.

Der integrierte Rahmen wird in vier unterschiedlichen Unternehmenskontexten angewandt: einem Beratungsunternehmen, einem Elektronikhersteller, einem Bodenbehandlungsunternehmen und einem Wasch-/Reinigungsmittelhersteller. Die Fallstudien zeigen konsistente, aber stark kontextabhängige Rangfolgen und identifizieren jeweils wenige Maßnahmen mit hohem Umweltverbesserungspotenzial. In dienstleistungsorientierten Kontexten dominieren Arbeitsplatz- und Mitarbeitermobilitätsmaßnahmen die Verbesserung von GWP und CED, während in material- und energieintensiven Sektoren logistik- und prozessbezogene Maßnahmen stärker ins Gewicht fallen. Maßnahmen zur Nutzung erneuerbarer Energien und zur Elektrifizierung zeigen deutliche Zielkonflikte zwischen Klima- und Energieindikatoren einerseits und Flächen- und Wasserindikatoren andererseits, die in den Mehrindikatorergebnissen klar erkennbar sind.

Die Ergebnisse stützen die methodische Hypothese, dass ein generischer, anwendungsfreundlicher ex-ante-Rahmen unter praktischen Datenrestriktionen entscheidungsrelevante, relative Umweltbewertungen von Maßnahmen und Maßnahmenportfolios ermöglicht. Dieser Rahmen kombiniert eine strukturierte Indikatorbasis, szenariobasierte Maßnahmenquantifizierungen und ein transparentes LCA-MCDM-Design, mit der Darstellung zentraler Zielkonflikte und Unsicherheiten. Zugleich macht die Arbeit Grenzen der Anwendung und Methodik sichtbar, wie z. B. die Beschränkung auf Umweltindikatoren und Gleichgewichtung der Indikatoren, additive Aggregation und eine europazentrierte Parametrisierung. Daraus ergeben sich Perspektiven für zukünftige Forschung, etwa zur Erweiterung der Indikatorbasis und des Maßnahmenkatalogs, zur Integration ökonomischer und sozialer Dimensionen, zur Berücksichtigung zeitlicher Aspekte in dynamischen LCA-Ansätzen sowie zur digitalen Implementierung und empirischen Validierung des Rahmens in weiteren Sektoren und Regionen.

Table of Contents

Abstract iv

Zusammenfassung vi

List of Figures xi

List of Tables xiii

List of Abbreviations xiv

1 Introduction 1

1.1 Companies and industrial parks as hotspots of environmental impacts 1

1.2 Conceptual and methodological background for reducing environmental impacts in companies and industrial parks 3

1.2.1 Current environmental evaluation possibilities and tools for companies and industrial parks 5

1.2.2 Relationship between environmental impacts and circularity 14

1.2.3 Research gaps 16

1.3 Aim, research questions and hypothesis 20

1.4 Structure of the thesis 22

2 Publication I: Scoping review of environmental indicators for industrial and urban symbiosis and eco-industrial parks 24

2.1 Introduction 26

2.1.1 Current state-of-the-art in the evaluation of industrial symbiosis 27

2.1.2 Aim and scope 29

2.2 Methods 30

2.2.1 Central concepts for the scoping review 30

2.2.2 Scoping reviews 31

2.2.3 Database search 33

2.2.4 Search string 33

2.2.5 Source selection process 34

2.2.6 Data processing and analysis 36

2.3 Results 40

2.3.1 Chronological classification 40

2.3.2 Categorizing the indicators 41

2.3.3 Frequency of indicator use 45

2.3.4 Assignment to R-strategies 46

2.4 Discussion 49

2.5 Conclusions 54
3 Publication II: Methodological approach to identify improvements through actions and scenarios 56
3.1 Introduction 58
3.1.1 Concepts of industrial symbiosis & circular economy 58
3.1.2 Assessment approaches & scenario development 60
3.1.3 Identified research gap and aim of the paper 61
3.2 Methodology of the approach 62
3.2.1 Structure of the approach 62
3.2.2 Action definition and selection 63
3.2.3 Quantification and scenarios 64
3.3 Results 66
3.3.1 Application of the approach within the KREGI project and first results 67
3.3.2 Quantification and application for actions 68
3.4 Discussion 72
3.5 Conclusion & outlook 76
4 Publication III: Extension and application of the approach toward a decision-support tool 78
4.1 Introduction 80
4.2 Methodology of the decision-support tool 83
4.2.1 Theoretical framework and scope 85
4.2.2 Actions: definition and quantification 85
4.2.3 Criteria and indicator selection 86
4.2.4 Normalization 88
4.2.5 Weighting 89
4.2.6 Aggregation and scoring 89
4.2.7 Scenario-based uncertainty and sensitivity analysis 90
4.3 Results: application in case studies 91
4.3.1 Case study 1 – consulting company 91
4.3.2 Case study 2 – electronics industry 92
4.3.3 Case study 3 – soil treatment 94
4.3.4 Case study 4 – detergent manufacturer 95
4.3.5 Summary and comparison of the case studies 97
4.4 Discussion 98

4.4.1 Overview of key findings and positioning 98
4.4.2 Addressing SRQ 1: evaluation 99
4.4.3 Addressing SRQ 2: normalization, weighting, and aggregation 99
4.4.4 Addressing SRQ 3: usability 100
4.4.5 Addressing SRQ 4: effectiveness in application 100
4.4.6 Addressing SRQ 5: action set design and extensibility 101
4.4.7 Methodological reflections and limitations 101
4.4.8 Practical implications and future work 102
4.5 Conclusion 102
5 Synthesis & comprehensive discussion 104
5.1 Integrated synthesis of main findings 104
5.1.1 Environmental indicators for industrial and urban symbiosis and eco-industrial parks 104
5.1.2 Methodological approach to evaluate improvements for companies based on actions and scenarios 106
5.1.3 Decision-support tool 107
5.1.4 Added value of integrating the indicator base, KREGI approach and DST 110
5.2 Answers to the research questions and hypothesis 113
5.2.1 RQ1 - Indicator basis for industrial and urban symbiosis 114
5.2.2 RQ2 - Scenario-based action evaluation approach 114
5.2.3 RQ3 - LCA-MCDM design for low-effort scoring 115
5.2.4 RQ4 - Framework behavior, robustness and sensitivity 116
5.2.5 Answering the main research question and revisiting the hypothesis 116
5.3 Methodological contributions and scientific positioning 117
5.4 Practical implications 122
5.5 Critical appraisal and limitations 127
6 Conclusion & Outlook 134
6.1 Overview of the key findings and implications 134
6.2 Directions for future research and development 136
Publication bibliography 141
Appendices 194
Appendix A 195
Appendix B 216
Appendix C 227

List of Figures

Figure 1.1: Global context motivating this thesis: projected growth in global resource use (United Nations Environment Programme 2020; UNEP 2024), industry's share of global GHG emissions (International Energy Agency 2023; Liu et al. 2023), and the cumulative reduction potential of CE strategies in four high-impact sectors (2026-2050, based on WBCSD (2024)). 1
Figure 1.2: Conceptual positioning of the circular economy (CE), industrial ecology (IE) and R-strategies across the three working levels (nano, micro, meso) considered in this thesis. 5
Figure 1.3: Conceptual separation of circularity indicators and life-cycle environmental impact indicators with context-dependent interactions. 16
Figure 1.4: Structure of the cumulative thesis, showing the roles of Chapters 1-6, the three included publications and their links to research questions RQ1-RQ4. 23
Figure 2.1: Graphical abstract of Publication I. 24
Figure 2.2: Flow diagram of the conducted screening process. Visualization based on Page et al. (2021). 36
Figure 2.3: Probability (PDF) and cumulative density functions (CDF) of the sources over the years, ordered from most recent to least recent to show what proportion of works has been covered in the X most recent years. The gray bar on the left indicates the future, meaning that the density values are subject to chance. 41
Figure 2.4: Heat map of the number of sources per year across the different application areas. Green and large squares indicate high co-occurrence, whereas small and dark blue squares indicate low co-occurrence. I.Symb=industrial symbiosis; U.Symb=urban symbiosis; EIP=eco-industrial park; CE=circular economy. 41
Figure 2.5: Line plot of the time trends for indicator uses (i.e. the sum of sources for all indicators) across the different categories. The gray bar on the right indicates the future, meaning that the uses in these years are subject to change. 42
Figure 2.6: Boxplot of the unweighted use rate and relative use rates for indicators in each of the respective categories. The whiskers are set to contain 95 % of the items. The remaining outliers are indicated by the gray squares and median values are indicated by red lines. Means are indicated by black diamonds. The left figure contains all data points; the right figure contains all data points with a use rate between 1 and 40. 44
Figure 2.7: Heat map of the number of times indicators are linked to the respective R-strategies across the different categories. Green and large squares indicate high co-occurrence, whereas small and dark blue squares indicate low co-occurrence. 47
Figure 2.8: Line plot of the time trends for indicator uses across the different R-strategies. The gray bar on the right indicates the future, meaning that the numbers in these years are subject to change. 48
Figure 3.1: Graphical abstract of Publication II. 56
Figure 3.2: Theoretical methodology for the approach illustrating the application, structure, and interdependence of each step. 63
Figure 3.3: Summary of the methodology applied in the approach, including scoping, life cycle inventory (LCI) with scenario defining, and life cycle impact assessment (LCIA) as a three-step system. 65
Figure 3.4: The current results of the KREGI approach include identified life cycle phases, specific categories, criteria, operational indicators, and actions. The resulting scenarios interact iteratively with these actions and are quantified with three environmental indicators: global warming potential (GWP), cumulative energy demand (CED), and raw material input (RMI). 67
Figure 3.5: Results for impact reduction using the example of the action *implementing a car sharing station* in the best-case scenarios (BCS) and worst-case scenarios (WCS) compared to the status quo, including a comparison of a) GWP, b) CED, and c) RMI environmental impacts across all aspects. 71
Figure 4.1: Graphical abstract of Publication III. 78
Figure 4.2: Methodology summary for the DST. Definition, selection and quantification of actions and the scenarios adopted from Verkic et al. (Verkic et al. 2025b). Criteria and indicator selection are refined. Normalization, weighting, scoring, and sensitivity analysis are newly defined here. 84
Figure 4.3: Program flow chart of the DST to visualize the concept and application. 85

Figure 4.4: Results of the DST for case study 1: inputs, action savings, and scores. 92
Figure 4.5: Results of the DST for case study 2: inputs, action savings, and scores. 93
Figure 4.6: Results of the DST for case study 3: inputs, action savings, and scores. 94
Figure 4.7: Results of the DST for case study 4: inputs, action savings, and scores. 96
Figure 5.1: Cross-case environmental score potential by indicator. Aggregated normalized environmental scores (potential improvement) for each environmental indicator (GWP, CED, RMI, LU, and WU) are shown for the four company case studies (consulting company, electronics manufacturer, soil-treatment company, detergent manufacturer). 110
Figure 6.1: Key messages of the cumulative thesis, showing how the scoping review, KREGI approach and DST contribute to the overall framework. 136
Figure 6.2: Future research and development directions building on the current framework (indicator base, KREGI approach and DST), grouped into four areas: indicators & methods, actions & scope, sustainability integration, and digitalization & validation. 140

List of Tables

Table 1.1: Ph.D. candidate contributions based on the Contributor Roles Taxonomy (Brand et al. 2015). ii
Table 2.1: Search string and corresponding number of matches per database. 34
Table 2.2: Overview of the defined categories and corresponding examples of indicators. 38
Table 2.3: Summarized comparison of R-strategies which are linked to an exemplifying indicator. Additionally, an explanation for the assignment is given to reason the links. 39
Table 2.4: Table of the average unweighted use rate (frequency of utilization of indicators) and relative use rates per category. 43
Table 2.5: Overview of the number of (multicategory) indicators co-occurring across the different categories. 44
Table 2.6: Table of the five most-frequently used indicators with corresponding application areas and uses. 45
Table 2.7: Overview of the five most-frequently used indicators in each category with corresponding measurement data in the form of qualitative, quantitative or both (type) and uses. 46
Table 2.8: Overview of the total number of uses in sources (non-unique), number of indicators and use rate per indicator across the different R-strategies. 48
Table 3.1: Definition for the six requirements for actions in the form of innovation, unambiguity, effect on environmental impact, measurability, significance and impact in the current time. 64
Table 3.2: Aligning the six requirements for actions with the example of implementing a car sharing station. 69
Table 3.3: Alignment of KREGI contributions with the study's research questions and areas requiring further development. 76
Table 4.1: Actions are assigned to categories and to R-strategies based on the 9R framework by Potting et al. (2017). 88
Table 5.1: Publications I–III contributions and reuse in the cumulative framework. 104
Table 5.2: Added value of the integrated framework compared with standalone LCA and standalone CE approaches. 113
Table 5.3: Qualitative action-interaction codes and recommended handling rules for action portfolios (plausibility layer; no modification of underlying LCA results or the additive LCA–MCDM scoring logic). 132

List of Abbreviations

Abbreviation	Full term
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
BAT	Best Available Technique
CE	Circular Economy
CED	Cumulative Energy Demand
CEMAF	Circular Economy Maturity Framework
CSRD	Corporate Sustainability Reporting Directive
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen / German Sustainable Building Council
DST	Decision-Support Tool
EF	Environmental Footprint (EU LCIA method)
EIP	Eco-Industrial Park
EMAS	Eco-Management and Audit Scheme
EMS	Environmental-Management System
ESG	Environmental, Social and Governance
ETS	Emissions Trading System
EU	European Union
F-AHP	Fuzzy Analytic Hierarchy Process
GCP	Global Circularity Protocol (for Business)
GHG	Greenhouse Gas
GIS	Geographic Information System
GRI	Global Reporting Initiative
GWP	Global Warming Potential
HRM	Human Resource Management
IAM	Integrated Assessment Model
IE	Industrial Ecology
IED	Industrial Emissions Directive
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
KPI	Key Performance Indicator
KREGI	Klima- und Ressourceneffizienz in Gewerbe- und Industriegebieten (Climate and Resource Efficiency in Commercial and Industrial Areas)
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land Use
MATChE	Mapping, Assessing and Transitioning to a Circular Economy (MATChE tool for CE readiness)
MCDM	Multi-Criteria Decision-Making
MCI	Material Circularity Indicator
MFA	Material Flow Analysis
MICRON	Micro Circular Economy Index
MIPS	Material Input per Service unit
MRQ	Main Research Question
OEF	Organization Environmental Footprint
OLCA	Organizational Life Cycle Assessment
PEF	Product Environmental Footprint
PESTEL	Political, Economic, Social, Technological, Environmental, Legal
RMI	Raw Material Input
RQ	Research Question
R-strategies	“Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover” strategies in CE
SBTi	Science Based Targets initiative
SCP	Sustainable Circularity Performance (model)
SETAC	Society of Environmental Toxicology and Chemistry
SIMPL	Scenario-based Inventory Modelling for Prospective LCA
SME	Small and Medium-sized Enterprise
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRL	Technological Readiness Level
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
WBCSD	World Business Council for Sustainable Development
WU	Water Use
WWF	World Wide Fund for Nature

1 Introduction

1.1 Companies and industrial parks as hotspots of environmental impacts

The world faces a global environmental crisis. Environmental impacts continue to increase, for example through rising climate change and growing resource consumption. Assessments of planetary boundaries show that several Earth system processes, including climate change and biogeochemical flows, are already beyond a safe operating space for humanity (IPCC 2021; Richardson et al. 2023; Rockström et al. 2024). In parallel, global resource use is forecast to grow by around 60 % between 2020 and 2060, further intensifying pressures on climate, ecosystems and biodiversity (United Nations Environment Programme 2020; UNEP 2024). Recent macro-level modeling for the Global Circularity Protocol for Business (GCP) suggests that accelerated circularity in four high-impact sectors (manufacturing, construction, transport, agriculture) alone could avoid 100-120 Gt of material use and 67-76 Gt CO_2-eq emissions cumulatively between 2026 and 2050, compared to a no-protocol scenario (WBCSD 2024). Figure 1.1 summarizes these global trends and potentials. Building on this, industrial activities are strongly associated with both greenhouse gas (GHG) emissions and resource use (Hertwich and Peters 2009; World Bank 2021). In 2022, industrial processes emitted roughly 10 Gt CO_2 equivalent, accounting for about 28 % of global annual emissions (International Energy Agency 2023; Liu et al. 2023).

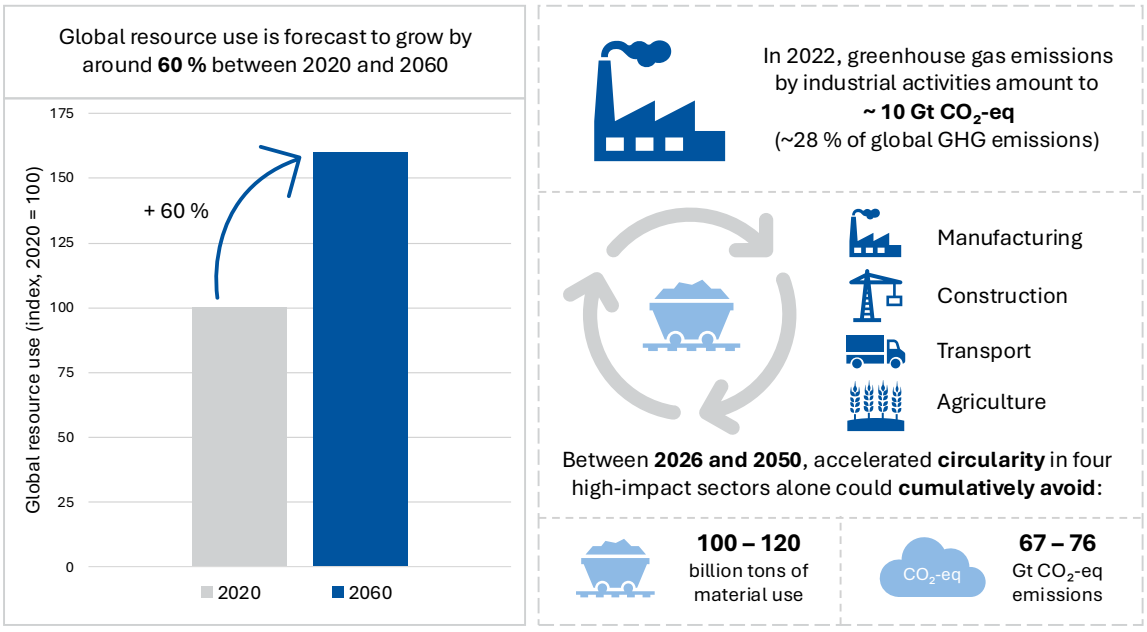


Figure 1.1: Global context motivating this thesis: projected growth in global resource use (United Nations Environment Programme 2020; UNEP 2024), industry's share of global GHG emissions (International Energy Agency 2023; Liu et al. 2023), and the cumulative reduction potential of CE strategies in four high-impact sectors (2026-2050, based on WBCSD (2024)).

Against this backdrop, international and European policy agendas, such as the Paris Agreement, the European Green Deal and the EU Circular Economy Action Plan, are

tightening climate and resource-related targets and increasingly require quantifiable progress at sectoral and company levels (United Nations 2015; European Commission 2019, 2020b). Recent systematic work on the European Green Deal shows that implementing its eight objectives depends on a broad set of enabling and hindering factors (Ozcelik et al. 2025). These include policy and regulatory conditions, economic aspects, available technology and infrastructure, supply-chain management, stakeholder involvement, and business competences (Ozcelik et al. 2025). This reinforces the need for operational tools that help companies and other actors contribute effectively to these goals. In parallel, the recent revision of the EU Industrial Emissions Directive (IED 2.0) explicitly adds CE and decarbonization to its main objectives and turns environmental permits into a central lever for improving resource efficiency and circular practices in industrial installations (European Parliament and Council 2024; Vázquez Calvo et al. 2025). A recent systematic review of 93 studies on IED 2.0 identifies sixteen key challenges and thirteen sets of enablers for embedding CE objectives into permits (Vázquez Calvo et al. 2025). They underline both the ambition of the new directive and the practical difficulties of implementation (Vázquez Calvo et al. 2025).

These developments create a strong demand for robust methods that help identify and prioritize actions which effectively reduce climate and resource burdens in industrial contexts. In this thesis, such actions are understood as targeted operational interventions relative to the status quo that aim to enable possible environmental improvements. Recent work on carbon neutrality emphasizes that traditional mitigation actions such as renewable energy, carbon capture and efficiency improvements are necessary but not sufficient (Oni et al. 2026). Complementary CE strategies like resource efficiency, product life extension and waste valorization need to be integrated to help decouple economic growth from environmental degradation (Oni et al. 2026).

Ex-ante applications of LCA and other prospective forms of LCA have been developed to bring environmental assessment into the early stages of technology and system development, rather than only analyzing mature systems ex-post (Cucurachi et al. 2018; Buyle et al. 2019; Pollet et al. 2025). Early application of LCA is considered crucial because decisions at this stage largely shape later environmental performance and can still be revised without major cost or disruption, helping to limit environmental burdens and reduce the risk of misguided investments (Jeswiet and Hauschild 2005; Cucurachi et al. 2018; Buyle et al. 2019; Pollet et al. 2025). Companies therefore have a vital role in influencing global environmental impacts and keeping human activities within planetary boundaries (Chrysafi et al. 2022; Erlandsson et al. 2023; WBCSD 2024).

Industrial parks cluster many firms together in one place, which creates possibilities for collaboration but also amplifies environmental risks (World Bank 2021; Shao et al. 2024) and therefore offer an improvement potential. In many cases, industrial parks have evolved with ineffective or uncoordinated structures, which leads to high energy and resource use and associated environmental impacts (Qiu and Luo 2021). It is therefore crucial to improve the design and operation of industrial parks, and of the companies located within them to reduce industrial environmental burdens (UNIDO 2016; World Bank 2021). Unsuitable site selection, weak planning and limitations of traditional evaluation

methods have contributed to underutilized or abandoned industrial parks (brownfields) that emit significant GHG (Nuhu et al. 2022). At the same time, this spatial concentration provides structural opportunities. Shared utilities, coordinated land use (LU), and industrial symbiosis can be planned and governed at the level of the industrial park, in addition to the level of individual firms (Chertow and Ehrenfeld 2012; Boons et al. 2017). Municipalities face a dual challenge in this context. They must attract and retain companies to create jobs and manage structural transitions in coal phase-out regions such as the Rhenish coal-mining area in Germany (Greiving et al. 2022), while simultaneously steering industrial parks toward climate and resource efficient development.

GHG emissions are typically categorized as scope 1, scope 2, and scope 3 emissions (WBCSD 2004). Scope 1 emissions refer to direct emissions generated by sources the company owns or controls, and companies can influence them through process and technology improvements that reduce material and energy demand (WBCSD 2004). Scope 2 emissions are indirect emissions associated with the production of purchased electricity, steam, heating, and cooling, so indirect influence arises through the type of energy used, for example by switching or purchasing to renewable electricity (WBCSD 2004). Scope 3 emissions cover other indirect, upstream and downstream impacts along the value chain, such as those associated with employee commuting, business travel, logistics, supplier practices and end-of-life treatment of products (WBCSD 2004; Harris et al. 2020).

To address these distributed impacts, several conceptual approaches have emerged, including industrial ecology (IE), industrial symbiosis, eco-industrial parks (EIP), and the circular economy (CE). The following section introduces these concepts and discusses existing methods and tools, as well as their limitations, for evaluating environmental improvements at company (micro) and industrial park (meso) levels, to derive research gaps.

1.2 Conceptual and methodological background for reducing environmental impacts in companies and industrial parks

A central approach to reducing companies' environmental impacts is IE. IE treats industrial activities as interconnected systems of processes and firms, aiming to improve performance by organizing material and energy flows in more cyclical, ecosystem-like ways (Jelinski et al. 1992; Azar 1997; Fischer-Kowalski 1998; Fischer-Kowalski and Hüttler 1998; Chertow 2000). A prominent concept within IE is industrial symbiosis. Industrial symbiosis brings together traditionally separate firms, typically in close geographic proximity, to share materials, energy, water, and services in ways that create joint environmental and economic benefits (Chertow 2000; Mallawaarachchi et al. 2020). The European Union (EU), among others, has highlighted industrial symbiosis as a practical solution to enhance environmental sustainability and as a key lever for increasing circularity in manufacturing and industrial systems (European Commission 2018; Domenech et al. 2019; European Commission 2020a).

EIPs represent a practical implementation of IE at a specific location (Roberts 2004; Gibbs and Deutz 2007). EIPs are industrial parks in which companies cooperate to improve environmental and economic performance through resource efficiency, symbiosis and shared services (Cohen-Rosenthal 2003; Roberts 2004; Gibbs and Deutz 2007). In many cases, industrial symbiosis is considered an essential element in transforming conventional industrial parks into EIPs (Scafà et al. 2018; Susur et al. 2019; Yu et al. 2023). EIPs are explicitly designed around industrial symbiosis principles and are one of the main models for implementing industrial symbiosis, while industrial symbiosis in turn is widely used to optimize EIP performance (Scafà et al. 2018; Perrucci et al. 2022; Yu et al. 2023). Empirical studies demonstrate that EIPs and industrial symbiosis can significantly reduce environmental impacts and increase economic value. Scenario analyses for cement production suggest that industrial-symbiosis implementations could reduce specific electricity consumption by about 30 % and specific heat consumption by about 5 % in a German cement cluster (Ammenberg et al. 2015). Implementing the 2030 industrial-symbiosis package envisaged by a European Cement Association (CEMBUREAU) is expected to cut emissions by roughly 39-80 kg CO_2 per ton of cement, with 68 kg/t used as the roadmap target (Capucha et al. 2023). Other evaluations report that a nationwide industrial symbiosis system in China could contribute about 18-43 % of the national industrial energy conservation and emission reduction targets (Cao et al. 2020). Additionally, eco-efficiency of individual symbiosis networks in an EIP can improve by up to 29 %, with an overall improvement of about 10 % across 21 firms (Park and Behera 2014).

The CE is closely related to the concepts of IE and EIPs. In prevalent definitions of CE levels, products and companies are placed together at the micro level, EIPs at the meso level, and cities, regions, or nations at the macro level (Kirchherr et al. 2017; Kristensen and Mosgaard 2020). Some authors introduce a fourth, nano level that focuses on products, components, and materials, in addition to the more traditional micro-meso-macro distinction (Saidani et al. 2017; Oliveira et al. 2021). This thesis adopts a distinction between the micro level (company level) and the nano level (product level) to reflect this difference and a focus on the company level. Overall, the methodological developments and empirical applications in this thesis include the nano-, micro- and meso-levels. Macro-level assessments (for example cities, regions or national economies) are considered only for contextualization and are not evaluated quantitatively.

At the meso level, CE is often understood as encompassing industrial symbiosis and EIPs, since both involve closing and slowing resource loops across organizations (Kalmykova et al. 2018; Merli et al. 2018; Kuzma et al. 2022; Kirchherr et al. 2023). The European Commission and other authors identify industrial symbiosis as a possibility to advance CE by enabling higher resource productivity and reduced waste (Daddi et al. 2017; European Commission 2020a; Rincón-Moreno et al. 2020; Yu et al. 2021b). In this broader perspective, Sewenet et al. (2026) conceptualize CE as a system-level economic model, circularity as the operational metric of how far CE principles are implemented, and sustainability as the higher-level normative goal that CE and circularity are meant to serve. While firms typically operate and make decisions at the micro level, there is growing recognition that performance measurement and management must also extend to the meso level

(Kristensen and Mosgaard 2020; Cagno et al. 2023). At this level, intercompany exchanges and industrial park-scale infrastructures, such as EIPs based on industrial symbiosis, play a crucial role (Kalmykova et al. 2018; Kristensen and Mosgaard 2020; Cagno et al. 2023). The ten R-strategy framework of Potting et al. (2017) provides a useful vocabulary for describing how specific aspects relate to circularity. For example, whether interventions primarily substitute primary materials (Reduce), intensify use phases (Rethink) or close loops via e.g., recycling (Potting et al. 2017; European Commission 2020a; Muñoz et al. 2023). Figure 1.2 summarizes how the CE, IE and R-strategies relate to the three working levels (nano, micro, meso) considered in this thesis.

The conceptual foundations outlined above must be complemented by suitable methods and tools if they are to lead to real world environmental improvements. The next subsection therefore reviews existing environmental evaluation possibilities and tools for companies and industrial parks.

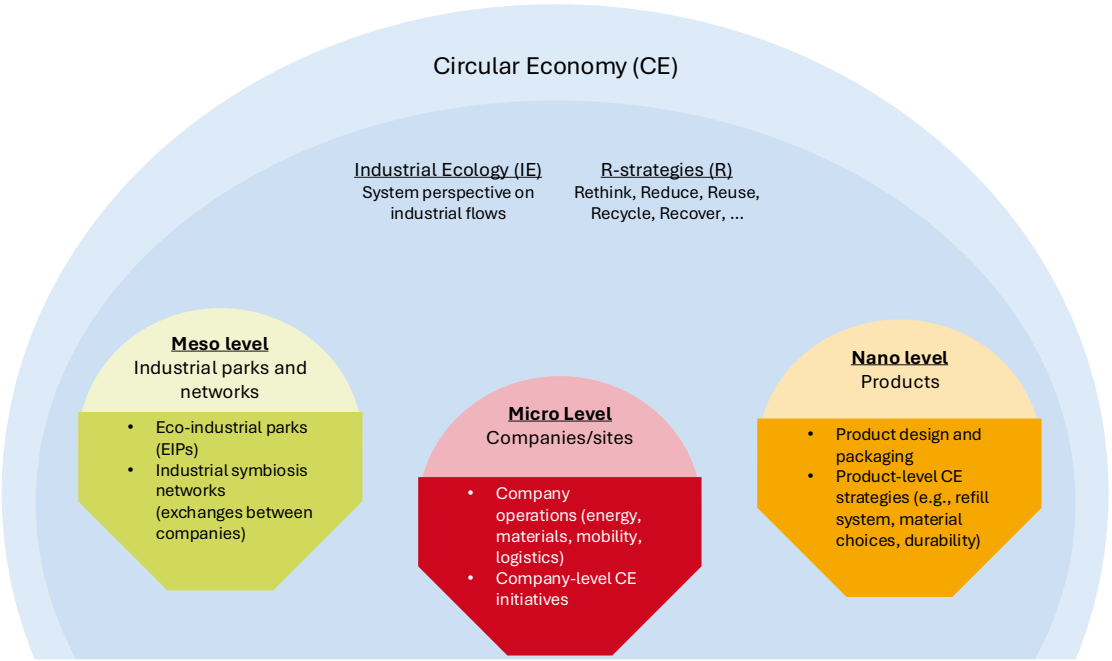


Figure 1.2: Conceptual positioning of the circular economy (CE), industrial ecology (IE) and R-strategies across the three working levels (nano, micro, meso) considered in this thesis.

1.2.1 Current environmental evaluation possibilities and tools for companies and industrial parks

To translate high-level concepts such as industrial symbiosis, EIPs, and the CE into practical improvements, companies and industrial parks require operational methods and tools that can quantify environmental performance and identify reduction potentials. The following overview structures this toolbox into their political backgrounds, established assessment approaches (LCA/footprinting and GHG accounting), and indicator- and decision-support approaches (CE indicators and MCDM-based frameworks). The synthesis highlights why many approaches remain heterogeneous, often data-intensive, and frequently applied ex-post, which motivates the research gaps summarized in Section 1.2.3.

Policy and regulatory drivers

Various international and European policy frameworks, including the Paris Agreement, national climate laws, the European Green Deal, the Circular Economy Action Plan, the Corporate Sustainability Reporting Directive (CSRD), the EU Taxonomy Regulation, the EU Emissions Trading System and the Energy Efficiency Directive, tighten requirements for standardized indicators and demonstrable progress on climate and resource objectives at sector and company level (United Nations 2015; European Commission 2019, 2020a; European Parliament and Council 2020, 2022, 2023a, 2023b). As outlined in Section 1.1, these policy developments (including IED 2.0) increase the demand for operational, LCA-based and indicator-based methods that support measurable and comparable decision-making in companies and industrial parks.

Environmental assessment methods

Over the past decades, a broad toolbox of environmental assessment methods has emerged to meet these demands. Life cycle assessment (LCA), material flow analysis (MFA), carbon and environmental footprinting, and GHG accounting are key pillars. LCA, standardized in ISO 14040 and ISO 14044 (International Organization for Standardization 2006), enables cradle-to-grave quantification of multiple impact categories such as global warming potential (GWP), cumulative energy demand (CED), and resource use (Guinée 2002; Hauschild et al. 2018). LCA has already been widely applied to assess industrial symbiosis systems and EIPs (Aissani et al. 2019; Kerdlap et al. 2020b).

Comparative studies show that the choice of commonly used life cycle impact assessment (LCIA) methods can produce substantially different absolute impact scores, even when the same system is assessed (Joseph and Stichnothe 2024; Rybaczewska-Błażejowska and Jezierski 2024). Examples include comparisons of ReCiPe 2016, EU Environmental Footprint (EF) method 3.0, and IMPACT World+ (Joseph and Stichnothe 2024) or of ReCiPe 2016, International Reference Life Cycle Data System (ILCD) 2011, CML-IA baseline method, and IMPACT 2002+ (Rybaczewska-Błażejowska and Jezierski 2024). Resource-related results can be especially sensitive to method choice and characterization coverage (e.g., whether characterization factors include construction aggregates such as sand and gravel, and differences in resource coverage across indicators) (Psyrri et al. 2024; Bayram et al. 2025). In addition, while absolute impact results can differ strongly between LCIA methods, the relative ranking of alternatives is often broadly consistent across methods, although some impact areas can still lead to ranking changes (Rybaczewska-Błażejowska and Jezierski 2024). Therefore, LCIA method choice is an additional methodological decision that influences LCA outcomes and sometimes even changes which scenario appears preferable in process development studies (Koch et al. 2022).

MFA complements LCA by systematically assessing flows and stocks of materials within companies, cities, or regions and providing decision-support for resource, waste, and environmental management (Brunner and Rechberger 2004; Liang et al. 2023). By systematically mapping flows, stocks, and accumulations, MFA reveals large in-use stocks and key pathways within value chains and thereby supports the design of resource-, waste-,

and environment-oriented management strategies (Brunner and Rechberger 2004; Liang et al. 2023). Carbon and environmental footprints, including the product environmental footprint (PEF) and organization environmental footprint (OEF) methods developed by the European Commission, provide streamlined LCA-based approaches for specific impact categories or system boundaries (European Commission 2021). Corporate GHG accounting, as defined in the Greenhouse Gas Protocol distinguishes between scope 1 (direct), scope 2 (indirect emissions from purchased energy), and scope 3 (other indirect, value-chain emissions) (WBCSD 2004). This scope classification is widely used in corporate GHG inventories and voluntary target-setting frameworks such as the Science Based Targets initiative (SBTi) (Science Based Targets initiative 2024). By contrast, cap-and-trade schemes such as the EU Emissions Trading System (EU ETS) regulate and trade verified emissions at the installation level (primarily corresponding to parts of scope 1) and do not cover scope 3 value-chain emissions (European Parliament and Council 2023a). For ETS-covered entities, EU ETS compliance data can be used to support and cross-check the ETS-relevant part of corporate scope 1 reporting, but the underlying rules, system boundaries, and verification requirements differ (WBCSD 2004; European Parliament and Council 2023a). In parallel, organizational LCA (OLCA), standardized in ISO/TS 14072 and supported by United Nations Environment Programme (UNEP) Society of Environmental Toxicology and Chemistry (SETAC) guidance, is applied to assess the environmental performance of entire organizations, including small and medium enterprises (SMEs) (UNEP 2015; Ahmed et al. 2026). For SMEs, lean data-collection strategies can still deliver decision-relevant results despite data and resource constraints (UNEP 2015; Ahmed et al. 2026).

Empirical evidence suggests that climate-focused tools dominate corporate practice: a study of ten Swedish water-intensive and bio-based companies shows that nine out of ten companies apply carbon-footprint methods, whereas only one uses a dedicated circularity-oriented tool (Chrispim et al. 2025). Most companies report that they do not explicitly assess circularity (Chrispim et al. 2025).

Despite this rich toolbox, there is still no single method that can adequately capture the sustainability of circularity for business and policy decisions (Verma et al. 2025; Bais et al. 2025). At the same time, reviews warn that practitioners may misuse assessment methods or combine them without clear guidance on how to integrate them coherently (Verma et al. 2025; Bais et al. 2025).

Prospective, ex-ante and dynamic LCA

A first conceptual aspect for classifying LCA studies is the temporal positionality of the modeled product system. This defines whether the system is positioned in the past, present, or future relative to the time at which the assessment is carried out (Arvidsson et al. 2024). In line with recent terminology recommendations (Arvidsson et al. 2024), prospective LCA is understood here as “LCA that models the product system at a future point in time relative to the time at which the study is conducted” (Arvidsson et al. 2024). Retrospective LCA denotes “LCA that models the product system at a recent or distant past point in time relative to the time at which the study is conducted” (Arvidsson et al. 2024).

Arvidsson et al. (2024) further emphasize that, in addition to temporal positionality, the maturity of the technologies included in the product system (e.g., emerging versus mature technologies) is a critical aspect that should be reported explicitly in future-oriented LCA.

This dissertation follows Arvidsson et al. (2024) and uses "prospective LCA" as the umbrella term for LCAs that model a system at a future point in time. The core framework developed in this dissertation applies prospective, time-integrated (static) LCA with parameterized scenarios (status quo, best-case, worst-case) to quantify action effects. Dynamic LCA and integrated assessment model (IAM) linked background databases are discussed as relevant extensions, but they are not implemented in the core framework. This clarification is necessary because terms such as "prospective", "anticipatory", and "ex-ante" LCA are used inconsistently in the literature (Cucurachi et al. 2018; Buyle et al. 2019; Arvidsson et al. 2024).

The term ex-ante is used for applications of LCA in decision contexts where LCA is employed before major investments or commercial implementation (Cucurachi et al. 2018; Buyle et al. 2019; Arvidsson et al. 2024). In these contexts, LCA is used to inform research, development, and planning decisions, including but not limited to emerging technologies (Cucurachi et al. 2018; Buyle et al. 2019; Arvidsson et al. 2024). In such ex-ante applications, emerging technologies are commonly modeled at a future industrial scale using scenario-based assumptions (Cucurachi et al. 2018; Buyle et al. 2019). Their prospective performance is compared with that of future versions of incumbent technologies rather than with today's baseline, in order to derive more realistic guidance for technology development and avoid misleading comparisons (Cucurachi et al. 2018; Buyle et al. 2019). Instead of forecasting a single outcome, these studies typically construct multiple scenarios that reflect alternative pathways of technological learning, market diffusion and background-system evolution (Cucurachi et al. 2018; Buyle et al. 2019). They use these scenarios to explore the range of possible environmental performances and to identify robust design and investment options under uncertainty (Cucurachi et al. 2018; Buyle et al. 2019). While ex-ante LCA is therefore often discussed in the context of emerging technologies, in this dissertation it is applied to action-level interventions in companies and industrial parks under scenario ranges.

A second methodological aspect concerns the temporal resolution of inventories and impact assessment. In conventional, time-integrated LCAs, all emissions and resource flows over the life cycle are aggregated into a single value per elementary flow and characterized using time-independent characterization factors, irrespective of when these flows occur (Cardellini et al. 2018; Arvidsson et al. 2024). The static nature of this approach and its neglect of temporal and spatial variation in flows and emissions have long been recognized as important limitations for accuracy and representativeness, particularly for long-lived systems and for impact categories where timing matters (Cardellini et al. 2018). By contrast, dynamic LCA uses time-resolved life cycle inventories, in which exchanges are explicitly distributed over time, and combines them with time-dependent characterization factors or characterization functions in the impact assessment (Cardellini et al. 2018; Arvidsson et al. 2024).

Applications of dynamic LCA demonstrate that both the temporal position of the system as a whole and the explicit timing of emissions can substantially influence calculated impacts (Cardellini et al. 2018). This is especially the case for climate-related impact categories and biogenic carbon in long-lived products (Cardellini et al. 2018). In parallel, advanced prospective LCA studies increasingly couple LCA databases with IAMs so that background inventories reflect socio-economic pathways and climate-mitigation targets in a consistent way (Sacchi et al. 2022). For example, the open-source PREMISE tool applies scenario-specific transformations to ecoinvent based on IAM scenarios, modifying electricity, fuels, cement, steel and road-transport activities for different assumptions and years and thereby generating prospective LCI databases for whole economies (Sacchi et al. 2022). These findings indicate that generic steady-state LCAs may significantly under- or overestimate climate impacts when long life cycles and delayed emissions or removals are relevant (Cardellini et al. 2018).

In summary, future-oriented LCA can be described along temporal positionality, technology maturity, and temporal resolution (Arvidsson et al. 2024). This dissertation applies the prospective, time-integrated, scenario-based approach specified above.

In parallel, Langkau et al. (2023) have proposed the SIMPL approach ("Scenario-based Inventory Modelling for Prospective LCA"), which gives a stepwise manual for integrating future-scenario development directly into goal and scope definition and inventory modelling. SIMPL also includes the identification of key factors, the derivation of future assumptions for foreground and background parameters and the use of tools such as PESTEL analysis, causal loop diagrams and cross-consistency assessment (Langkau et al. 2023). Therefore, it is designed for small-scale technology-focused prospective LCAs and aims to ensure that prospective inventories are consistent with foresight standards, transparent and systematically documented (Langkau et al. 2023). This method complements the more application-oriented, action-based use of prospective LCA pursued in this thesis.

Micro-level indicator frameworks and CE indicators

Building on these methodological foundations, a broad spectrum of indicator-based frameworks has been proposed to monitor and manage environmental performance at the company (micro) level. Many frameworks combine LCA, MFA and operational data into indicator sets that cover energy and material intensities, GHG and pollutant emissions, waste generation, water consumption and sometimes economic or social indicators (Azapagic and Perdan 2000; Azapagic 2003; Aravossis et al. 2019). These frameworks are often embedded in environmental-management systems (EMS) such as ISO 14001 or eco-management and audit scheme (EMAS) and in corporate reporting structures, where indicators are tracked over time and used to set internal targets (Azapagic 2003). However, content analysis of EMAS environmental statements shows that circularity-related information disclosed by industrial companies is still sparse, predominantly qualitative, and only rarely provided as comparable key performance indicators (KPIs) (Barón Dorado et al. 2022). This lack of scalable and comparable quantitative data limits the usefulness

of EMAS as a tool to measure and report companies' progress toward a more circular model in its current form (Barón Dorado et al. 2022).

In the CE context, several reviews and taxonomies have cataloged micro-level CE indicators, including sector-specific ones (Elia et al. 2017; Saidani et al. 2019; Pascale et al. 2021; Muñoz et al. 2023). Across these reviews, most reported indicators are tied to physical flows (such as masses of primary and secondary materials, waste, and emissions) or to operational loop-closing activities (like internal recycling and reuse) (Pascale et al. 2021; Muñoz et al. 2023). Only a smaller subset explicitly captures system-level performance or economic value creation (Pascale et al. 2021; Muñoz et al. 2023). Proposed metrics range from simple ratios such as recycled content, recycling and reuse rates, repair rates, and the share of waste sent to landfill (Elia et al. 2017; Saidani et al. 2019). Proposed metrics also include more complex constructs such as the Material Circularity Indicator (MCI), which summarizes the circularity of a product's material flows (Ellen MacArthur Foundation and ANSYS Granta 2019), and Material Input per Service unit (MIPS), which expresses the total material input required per unit of service provided (Liedtke et al. 2014).

However, most applications still calculate these circularity indicators beyond LCA tools, often with simple spreadsheets that ignore supply-chain effects (Cilleruelo Palomero et al. 2024). As a result, many assessments underestimate or omit full supply-chain and end-of-life impacts (Cilleruelo Palomero et al. 2024; Oni et al. 2026). Recent work embeds circularity metrics such as MCI and Cullen's Circularity Index directly into the LCA software openLCA and adapted ecoinvent databases (Cilleruelo Palomero et al. 2024). Through this, circularity variables are traced consistently along the entire life cycle (Cilleruelo Palomero et al. 2024). Broader mappings of CE indicators propose taxonomies with domains such as environmental, economic, social, circularity, technological and legislative, and show that CE indicators now cover all sustainability dimensions but remain unevenly distributed (Barahmand et al. 2026). Circularity and environmental indicators dominate and technological together with legislative indicators are underrepresented (Barahmand et al. 2026). They also confirm that many indicators are designed for meso and macro levels or span multiple levels, while their data show that micro-level indicators (defined as companies and products by Barahmand et al. (2026)) are comparatively few (Barahmand et al. 2026). At the same time, comparative analyses point to substantial variation in definitions, system boundaries, normalization procedures and data requirements across indicator sets and frameworks (Pizzol et al. 2017; Corona et al. 2019). Literature also shows that metrics with the same label (e.g., "recycling rate") can be defined and calculated differently, and that some composite indices combine heterogeneous dimensions in ways that are not fully transparent to users (Freudenberg 2003; Corona et al. 2019).

Corporate circularity tools and maturity frameworks

In addition to general indicator frameworks, several dedicated tools for corporate circularity and environmental performance have been developed. The Micro Circular Economy Index (MICRON) provides a quantitative index for assessing companies' CE performance

via category-based circularity sub-indices and an overall circularity index that can be used for benchmarking (Baratsas et al. 2022). The MICRON indicators are aligned with Global Reporting Initiative (GRI) Standards and cover resource consumption, waste generation, emissions, and energy use, which are combined into category-based and overall circularity metrics (Baratsas et al. 2022). It is typically quantified with data from annual sustainability, ESG and financial reports and is intended to be used for ex-post assessment and benchmarking (Baratsas et al. 2022). Recent work extends MICRON beyond company level by combining national-statistic data (e.g., Eurostat) with corporate GRI-type data to compute overall circularity indices for countries and case companies and to explore energy and emission scenarios (Drofenik et al. 2025). The Circular Flow tool includes an organizational circularity indicator that evaluates processes with internal and external material and energy flows (Barros et al. 2023). It also computes circularity scores between 0 % and 100 % at process and organizational level, for systems defined at micro, meso, or macro level (Barros et al. 2023). In practice, the Circular Flow tool is applied by collecting process-level data on internal and external material and energy flows, and the resulting visualizations and indicators highlight where along the system boundaries circularity can be improved (Barros et al. 2023). Yet, it has significant data requirements and only limited integration of comprehensive environmental-impact assessment (Barros et al. 2023).

Related developments for SMEs include the Circular Economy Maturity Framework (CEMAF), which assesses CE maturity across five dimensions: “take, make, distribute, use, and recover” (Bandeira et al. 2025). In parallel, the MATChE tool is a web-based self-assessment of manufacturing companies’ readiness across eight dimensions, including organization, innovation of product, service, strategy and business model, and manufacturing together with value chain (Pigosso and McAloone 2021). Both tools focus on organizational maturity or readiness rather than on quantitative flow-based performance. For example, MATChE focuses on qualitative organizational readiness dimensions rather than on tracking material and energy flow indicators, and it is not intended to set numerical performance targets or benchmarks for companies (Pigosso and McAloone 2021). CEMAF likewise evaluates CE maturity qualitatively and combines maturity scores into a maturity index, without directly modeling material or energy flows (Bandeira et al. 2025). Other micro-level frameworks propose custom indicator sets to assess sustainability or circularity performance at company or plant level, usually combining environmental, economic and social indicators and, in some cases, explicit circularity metrics and resource-efficiency aspects (Harik et al. 2015; Azevedo et al. 2017; Sacco et al. 2021; Rincón-Moreno et al. 2021; Preisner et al. 2022; Smol 2023; Bosco et al. 2025). However, these frameworks often require detailed data and lack standardized benchmarks or commonly accepted indicator sets, which makes it difficult to compare results or to prioritize actions and investments across sites, companies or scenarios (Azevedo et al. 2017; Rincón-Moreno et al. 2021; Preisner et al. 2022; Smol 2023; Bosco et al. 2025; Filippi et al. 2025). Reviews of company-level CE tools confirm that many are qualitative self-assessment (questionnaire-based) tools that mainly produce maturity/readiness scores from yes/no or Likert-type responses and therefore depend strongly on self-reported judgments rather than on verifiable operational flow data and LCA-based modeling (Chrispim

et al. 2023; Valls-Val et al. 2023; Bais et al. 2025). They typically emphasize resource and R-strategy topics, while social aspects, stakeholder engagement, and industrial symbiosis are less consistently covered (Chrispim et al. 2023; Valls-Val et al. 2023; Bais et al. 2025). Several reviews conclude that current company-level CE tools yield non-comparable scores and often lack clear guidance on how to turn qualitative ratings into concrete operational actions (Chrispim et al. 2023; Valls-Val et al. 2023; Bais et al. 2025).

Meso-level EIP indicators and multi-criteria frameworks

At the meso level, several indicator systems and tools focus specifically on EIPs and industrial symbiosis networks. Syntheses of this literature show that typical environmental indicators include total and specific energy consumption, the share of renewable energy, park-level GHG emissions, water use (WU), waste generation, and recycling rates (Valenzuela-Venegas et al. 2016). Several authors develop multi-criteria indicator frameworks and composite indices for evaluating EIPs, combining metrics for resource and energy consumption, pollution, industrial symbiosis, management practices and social aspects into overall sustainability or ecological performance scores (Zhao et al. 2017; Qiu and Luo 2021; Marinelli et al. 2021; Koch et al. 2022; Babkin et al. 2023). Methodologically, these frameworks rely on multi-criteria decision-making (MCDM) techniques such as gray- and fuzzy-based evaluation, analytic hierarchy process (AHP) type weighting and integrated geographic information system (GIS) MCDM models to derive indicator weights and aggregate scores (Zhao et al. 2017; Qiu and Luo 2021; Nuhu et al. 2022). One concrete example is an EIP site-selection study that uses AHP, analytic network process (ANP) and Fuzzy AHP (F-AHP) combined with GIS to identify suitable locations for converting brownfields into EIPs (Nuhu et al. 2022). Together, these frameworks demonstrate that industrial parks can be described and compared using structured indicators and scoring systems. Yet they are predominantly ex-post and index-based and rely on park- or region-specific indicator sets that can limit transferability. They also usually do not quantify the ex-ante environmental effects of specific planned actions via scenario-based LCA.

Standards, reporting frameworks and international EIP guidance

Beyond academic frameworks, companies increasingly rely on non-scientific or semi-standardized tools and standards to align with regulatory expectations and financial-market requirements. GRI standards include indicators for energy and climate, such as energy consumption and GHG emissions, which companies report at organizational or site level in their sustainability reports (Ibáñez-Forés et al. 2022). These reports are designed primarily to disclose non-financial performance to stakeholders, and the lack of homogeneity in reported data makes fine-grained comparison of individual actions difficult (Ibáñez-Forés et al. 2022). Environmental management standards such as ISO 14001 require organizations to set environmental objectives and define indicators to monitor progress as part of continual improvement, while leaving the selection of specific indicators and targets to the organization (ISO 14001:2015(E); Kristensen and Mosgaard 2020). ISO 14031:2021(E) provides categories and examples of environmental performance indicators but, as a guideline standard, does not define mandatory indicator sets or performance levels, which contributes to limited comparability and makes indicator selection

challenging in practice (Jasch 2000; Grigoroudis 2017; ISO 14031:2021(E)). For climate-related aspects, ISO 14064-1:2018(E), together with ISO 14067:2018(E), help close this gap (ISO 14067:2018(E); ISO 14064-1:2018(E); ISO 14064-2:2019(E); ISO 14064-3:2019(E)). They set principles and requirements for how organizations, projects, and products quantify and report GHG emissions and removals, including the carbon footprint of products (ISO 14067:2018(E); ISO 14064-1:2018(E); ISO 14064-2:2019(E); ISO 14064-3:2019(E)). However, these standards focus on GHG, and ISO 14067 in particular covers only the single impact category climate change and does not consider other environmental, social, or economic impacts (ISO 14067:2018(E)). They are also "program-neutral", so companies usually need additional schemes or tools (for example GHG programs or EMS frameworks) to set performance benchmarks and link GHG accounting to wider environmental strategies (ISO 14064-1:2018(E); ISO 14064-2:2019(E); ISO 14064-3:2019(E)).

Additionally, many organizational-level circularity indicators can in principle be calculated from existing GRI-based sustainability reports (Ibáñez-Forés et al. 2022). Corporate level frameworks such as the World Wide Fund for Nature (WWF) One Planet Business Framework and the World Business Council for Sustainable Development (WBCSD) GCP go a step further by aligning corporate indicators and targets with planetary-boundary-based climate, nature and resource goals, and by embedding CE strategies as a central lever (Metzke and Strahl 2024; WBCSD 2024). These frameworks define indicator sets for environmental footprints as well as circular product characteristics such as recycled content, reparability and lifetime (Metzke and Strahl 2024; WBCSD 2024). In addition, they encourage companies to adopt science-based and, where relevant, context-based targets for climate, water and biodiversity (Metzke and Strahl 2024; WBCSD 2024).

In the area of industrial symbiosis and EIPs, international organizations have developed an International Framework for Eco-Industrial Parks that sets out prerequisites and performance requirements for EIPs (World Bank 2021). These requirements are grouped into four key performance areas: environmental, park management, economic, and social (World Bank 2021). National standards, such as those in China, use indicator sets for energy, materials, water, land and pollution to classify industrial parks and guide their improvement (Huang et al. 2019a). These frameworks are useful for aligning practice with high-level sustainability and CE goals and for giving policymakers and developers reference criteria. Yet they are mainly used to evaluate existing parks at a given point in time rather than to support ex-ante action-level evaluation during planning and operation.

Summary

Taken together, the existing landscape of methods, indicators and tools provides a rich but heterogeneous basis for environmental evaluation at company and industrial-park level, reflecting both scientific advances and regulatory drivers (Ferrante et al. 2025). Existing CE performance methods are highly diverse, data-intensive, and often used for ex-post assessment, and they still lack a unified framework that integrates circularity and life cycle perspectives across levels, which makes their application complex and time-consuming (Ferrante et al. 2025; Verma et al. 2025; Battiston et al. 2025). As a result,

companies, industrial park operators, and municipalities still face challenges when they want to evaluate and compare specific future actions in a CE context in a consistent, low-effort way (Chrispim et al. 2025; Verma et al. 2025; Battiston et al. 2025; Ferrante et al. 2025). These challenges and the resulting research gaps are synthesized in Section 1.2.3.

1.2.2 Relationship between environmental impacts and circularity

The CE has become a central reference in debates on sustainable production and consumption and is widely promoted as a key strategy for narrowing, slowing and closing resource loops (Bocken et al. 2016; Mendoza et al. 2022). However, empirical studies and reviews increasingly show that higher circularity does not automatically translate into lower environmental impacts (Harris et al. 2021; Saadé et al. 2022; Elia et al. 2024; Filippi et al. 2025; Bressanelli and Saccani 2025; Sewenet et al. 2026). In some cases it can even increase certain burdens, for example when additional processing steps, energy-intensive recycling, or longer transport distances are involved (Corona et al. 2019; Harris et al. 2021; Saadé et al. 2022; Elia et al. 2024; Filippi et al. 2025; Bressanelli and Saccani 2025; Sewenet et al. 2026). These effects are also discussed under the label “CE rebound”, where gains in efficiency or circularity can trigger additional production or use, reducing or even nullifying the expected environmental benefits (Zink and Geyer 2017; Figge and Thorpe 2019; Castro et al. 2022; Zerbino 2023). The impact analysis of the GCP explicitly discusses potential rebound effects in the CE, even though these are not modeled quantitatively (WBCSD 2024). It stresses that improvements in circularity should be evaluated together with changes in absolute material use and GHG emissions (WBCSD 2024). Recent reviews argue that circularity indicators by themselves are not enough, and that integrated, multi-method sustainability assessments are needed to move beyond mono-dimensional circularity scores (Verma et al. 2025). They also highlight that such integrated frameworks are necessary to identify trade-offs and potential rebound effects of CE strategies (Ferrante et al. 2025).

From an assessment perspective, CE and environmental impacts must be clearly distinguished. Circularity indicators typically focus on flows and stocks of materials and products (Elia et al. 2017; Pascale et al. 2021; Muñoz et al. 2023). Examples are recycled content, cycling rates, lifetime extensions and composite circularity scores such as the MCI (Elia et al. 2017; Ellen MacArthur Foundation and ANSYS Granta 2019; Pascale et al. 2021; Muñoz et al. 2023). Environmental indicators quantify pressures and impacts on the environment, such as GHG emissions, energy demand, raw-material extraction, land occupation and WU (Liedtke et al. 2014; Muñoz et al. 2023). Although circularity indicators can correlate with environmental benefits, this relationship is neither linear nor guaranteed (Elia et al. 2017; Saadé et al. 2022; Elia et al. 2024). Depending on the technology and context, a recycling process may increase the share of secondary material (and thus improve circularity metrics) while at the same time requiring more energy and water than primary production (Elia et al. 2017; Saadé et al. 2022; Elia et al. 2024). In practice, closing loops through industrial symbiosis can reduce waste sent to landfill but also introduce additional processing and logistics steps (e.g., collection, cleaning, and transport of by-products), so that environmental burdens may be redistributed rather than simply

eliminated (Park and Behera 2014; Marinelli et al. 2021). Another example is bio-based plastics in waste systems: if only carbon impacts are considered, they can appear clearly better than fossil-based plastics, but once LU and WU are included, they may be equally or even more environmentally damaging overall (Salemdeeb et al. 2022). This illustrates how single-indicator assessments can hide relevant burden shifting.

At the same time, reviews of CE indicators across levels find that most indicators at micro and meso level focus on physical flows (mass of secondary materials, closing and slowing loops) and operational aspects (internal recycling, product lifetime) (Pascale et al. 2021; Muñoz et al. 2023). Fewer address system effectiveness or value creation, and high-circularity strategies such as Refuse, Rethink, Reduce or Reuse are less frequently quantified than Recycle and Recover (Pascale et al. 2021; Muñoz et al. 2023). This pattern is also shown at city scale (macro level) (Toboso-Chavero et al. 2025). Integrated sustainability assessments of urban waste management systems focus predominantly on Recycle and Recover, while higher-order strategies such as Refuse, Rethink, Reduce and Reuse are much less frequently considered (Toboso-Chavero et al. 2025). At company level, Recycle, Reduce and Rethink are the most frequent resource-retention options, whereas Recover, Repurpose and Refuse appear only rarely in reported practices (Izquierdo-Montfort and Rongé 2025).

Recent conceptual work proposes viewing the CE as a system-wide economic paradigm, with circularity as its measurable operationalization and sustainability as the higher-level normative goal (Sewenet et al. 2026). This framing implies that environmental, economic, and social indicators are needed to assess whether circular practices actually contribute to sustainability outcomes, rather than assuming this by default (Sewenet et al. 2026).

To conclude, circularity is treated in this thesis as a complementary but distinct perspective relative to environmental impacts. CE concepts and R-strategies are used to structure and interpret actions at nano, micro, and meso levels. These levels are aligned with policy frameworks such as the EU Circular Economy Action Plan, which sets out a comprehensive agenda for making products, value chains, and waste systems more circular in order to achieve a cleaner and more competitive Europe (European Commission 2020b). Environmental indicators derived from LCA are then used to quantify the actual impacts and trade-offs of circular strategies, reflecting the literature's emphasis on LCA-based evaluation of circularity and sustainability outcomes (Sewenet et al. 2026). Figure 1.3 illustrates the conceptual distinction between circularity indicators and environmental indicators and how it is implemented in this thesis.

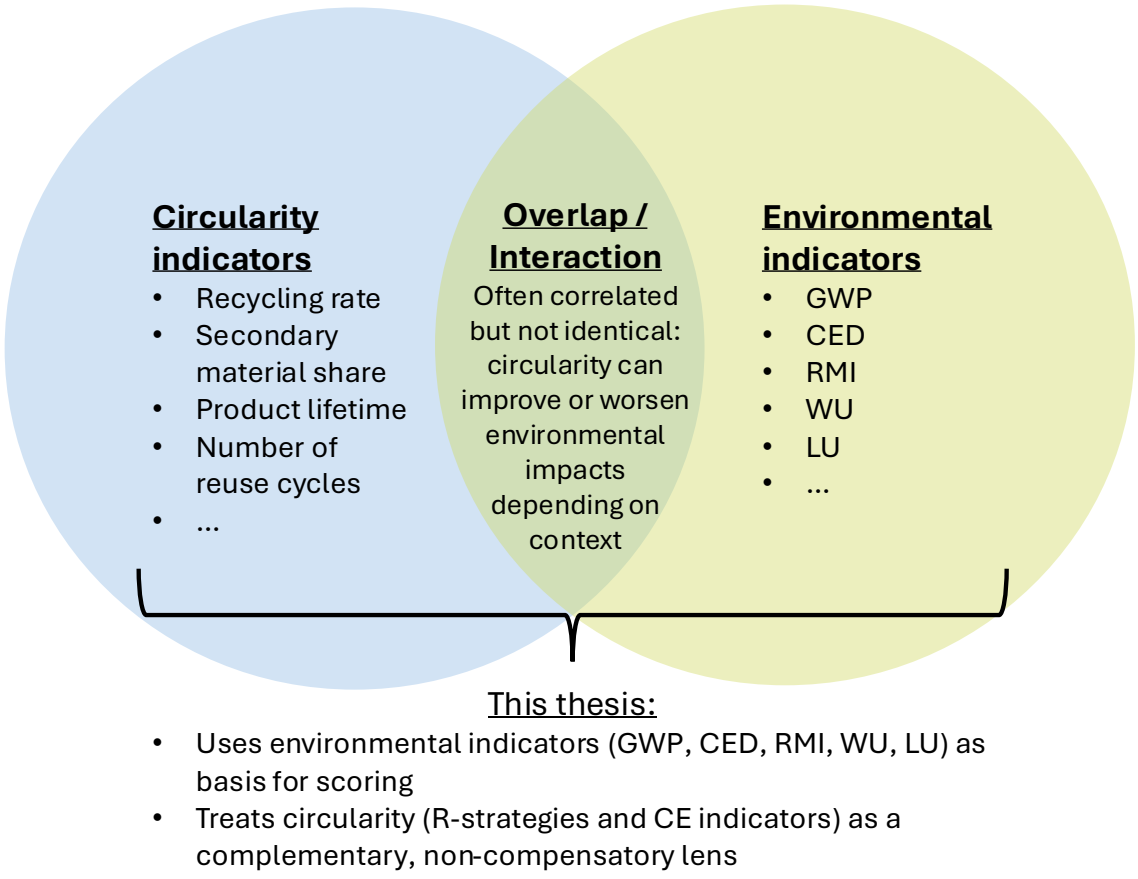


Figure 1.3: Conceptual separation of circularity indicators and life-cycle environmental impact indicators with context-dependent interactions.

1.2.3 Research gaps

The preceding sections have shown that a broad spectrum of concepts, methods and tools is available to support environmental evaluation in companies and industrial parks. They range from IE and industrial symbiosis to LCA, MFA, carbon accounting and diverse CE and sustainability indicator systems. Existing CE assessment approaches are often used for generic monitoring or ex-post evaluation rather than for supporting concrete decision-making (Ferrante et al. 2025; Verma et al. 2025). When companies and industrial parks attempt to select and prioritize specific future CE actions, important methodological and practical gaps remain, including limited use of CE-specific tools and substantial implementation barriers (Chrispim et al. 2025; Ferrante et al. 2025; Verma et al. 2025). Recent empirical studies show that many firms are only at the beginning of their CE transition, with most circular practices still concentrated in the manufacturing phase (Chrispim et al. 2025). These practices largely focus on waste reduction and improvements in energy and resource efficiency in production operations (Chrispim et al. 2025). At the same time, bibliometric work suggests that only a small number of studies explicitly synthesize green technologies, environmental sustainability, and business strategy or business models into a single, comprehensive framework (Pavesi et al. 2025). In parallel, the relationship between CE, circularity and sustainability is still not fully clarified, and many studies implicitly assume that circular strategies are sustainable without testing

this systematically (Multani et al. 2025; Sewenet et al. 2026). To compare circularity performance across companies, indicators need to be harmonized, with common definitions of what is evaluated, how it is calculated, and which scales are used (Ibáñez-Forés et al. 2022).

A first gap concerns the indicator landscape for environmental assessment of industrial and urban symbiosis, EIPs and meso-level CE aspects. Several reviews and case-specific frameworks compile indicator sets for assessing EIPs and industrial symbiosis, generally organizing indicators into economic, environmental and (to a lesser extent) social dimensions (Valenzuela-Venegas et al. 2016; Zhao et al. 2017; Qiu and Luo 2021; Marinelli et al. 2021; Dong et al. 2022). However, these indicator systems are typically tailored to particular programs, regions or case studies (such as national Chinese EIP standards, specific industrial networks or regional CE clusters) which leads to overlapping content and differences in definitions, social coverage and system boundaries (Valenzuela-Venegas et al. 2016; Zhao et al. 2017; Qiu and Luo 2021; Marinelli et al. 2021; Dong et al. 2022; Babkin et al. 2023). At the same time, recent reviews of CE indicators report that most existing metrics have been developed and applied at the micro and nano levels, whereas comparatively fewer indicators target meso-level applications such as exchanges within EIPs or industrial symbiosis networks (Saidani et al. 2019; Boulay et al. 2021). Additionally, only a few works explicitly map CE indicators to specific R-strategies (Saidani et al. 2019; Pascale et al. 2021). From a practitioner perspective, this fragmentation makes it difficult to identify which environmental indicators are most suitable for assessing industrial symbiosis and EIPs, as well as to select a manageable subset from the large number of available metrics (Valenzuela-Venegas et al. 2016). It also hampers understanding of how well different circular strategies are covered and how to construct indicator sets that are both comprehensive and practical. There is thus a need for a systematic, quantitative mapping and clustering of environmental indicators used in industrial and urban symbiosis. This includes analysis of their frequency of use, application contexts and links to CE concepts, in order to derive a structured, CE-aware indicator base for subsequent methodological work.

A second gap concerns the limited support for holistic, ex-ante evaluation of actions across industrial-park life-cycle phases and across CE levels. Many methodologies in IE and industrial symbiosis rely on ex-post case studies, where realized exchanges are evaluated via LCA, MFA or eco-efficiency metrics after implementation (Park and Behera 2014; Marinelli et al. 2021; Dong et al. 2022). International EIP standards are largely used to classify or benchmark industrial parks that already exist or are in operation (Huang et al. 2019a; World Bank 2021). In contrast, decisions about industrial sites are often taken in early planning and design phases, when many options are still hypothetical and their environmental implications under different boundary conditions remain uncertain. Prior work has characterized industrial site selection as a strategic decision problem and as the initial step in successful EIP development (Nuhu et al. 2022). Examples of such early-phase decisions include the choice of site itself as well as key transport and utility infrastructures, such as energy and industrial water networks, which are typically addressed during the design and layout phases of an EIP project (Belaud et al. 2019). Some

studies combine scenario analysis with LCA to explore alternative future configurations of industrial systems and technology options (Kerdlap et al. 2020b; Moshrefi et al. 2022). In addition, the SIMPL approach provides a structured procedure for building prospective inventories that combines key-factor analysis, stakeholder input and consistency checks, and thereby helps to improve transparency and alignment between LCA and scenario development at technology level (Langkau et al. 2023).

Yet, to the best of the author's knowledge, there is no widely adopted approach that simultaneously defines concrete actions, checks them against minimum requirements, and quantifies their effects under different scenarios across different phases of industrial parks and across several CE levels. Existing work provides only partial solutions for specific life-cycle phases and contexts and does not consistently integrate assessments across industrial park life-cycle phases (Adoue et al. 2015; Belaud et al. 2019) and different CE levels. Existing ex-ante and prospective LCA studies are predominantly conducted at the level of individual technologies or sectors and often address emerging technologies at defined technological readiness level (TRL) stages, rather than broader industrial-park systems or portfolios of coordinated actions (Cucurachi et al. 2018; Buyle et al. 2019; Arvidsson et al. 2024). Consequently, many current decisions in climate mitigation and CE initiatives are often based on fragmented or non-standardized assessments, which makes it difficult to compare different options on a transparent and comparable environmental basis (Oni et al. 2026; Krzeminski et al. 2026).

A third gap relates to the lack of easy-to-use and easy-to-interpret, or summarized "low-effort", decision-support methodologies and tools that integrate LCA, MCDM and CE for ex-ante prioritization of actions at micro and meso levels. Comparative studies highlight that many existing CE tools and frameworks are used primarily to diagnose or monitor how circular a company already is, rather than to guide the design of new solutions (Bais et al. 2025). Examples include indices and self-assessment frameworks such as MICRON, the Circular Flow tool, CE maturity and readiness frameworks, and composite sustainability or circularity indices (Harik et al. 2015; Azevedo et al. 2017; Sacco et al. 2021; Pigosso and McAloone 2021; Baratsas et al. 2022; Barros et al. 2023; Bandeira et al. 2025). Recent reviews of life-cycle-based and CE assessment methods similarly report that most tools are applied in an ex-post, monitoring mode rather than to support systematic ex-ante comparison of alternative courses of action (Chrispim et al. 2023; Bais et al. 2025; Filippi et al. 2025). From a decision-support perspective, this means that current tools offer limited support when firms need to compare several future options early on, under conditions of high uncertainty and limited data.

Companies, particularly SMEs, perceive several barriers to adopting dedicated CE assessment tools, including a lack of knowledge about CE tools, time and resource constraints and limited external demand for circularity metrics beyond CO_2 information (Ormazabal et al. 2018; Chrispim et al. 2023; Cagno et al. 2023; Ferasso et al. 2024; Chrispim et al. 2025). The literature on integrating LCA with MCDM in waste management shows that such combinations can provide more comprehensive, decision-relevant support for complex problems than using either LCA or MCDM (Goulart Coelho et al. 2017; Torkayesh et al. 2022).

More broadly, research on sustainability indicators and multi-criteria methods emphasizes that the choice and, where appropriate, combination of weighting and aggregation approaches critically influences the robustness and interpretability of composite assessments (Gan et al. 2017; Balali and Yunusa-Kaltungo 2025). Recent reviews and case studies suggest that many existing sustainability assessment applications in the CE focus on product- or process-level design decisions and rely on data-intensive, methodologically sophisticated frameworks such as detailed LCA, multi-objective optimization, and hybrid multi-criteria schemes (Kalboussi et al. 2022; Ferrante et al. 2025; Verma et al. 2025; Kadrić et al. 2026). As a result, they provide limited support for organizations seeking general, low-effort tools to assemble and prioritize firm- or industrial-park-level action portfolios specified for their use-case.

This is illustrated by the complexity of current EIP siting and evaluation models (Nuhu et al. 2022) and by indicator-rich frameworks. One example is an ESG-oriented policy evaluation framework based on entropy-weighted Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Zournatzidou et al. 2025). Moreover, many composite indicator and CE index approaches combine several environmental or circularity dimensions into a single score, for example in the form of single-score LCIA results or the MCI (Pizzol et al. 2017; Saadé et al. 2022). This kind of aggregation can allow trade-offs to remain hidden, for instance when high circularity coincides with increased environmental burdens or vice versa (Pizzol et al. 2017; Zink and Geyer 2017; Figge and Thorpe 2019; Saadé et al. 2022; Castro et al. 2022). Several authors therefore caution that such metrics, if used alone, do not guarantee environmental improvement and typically do not make uncertainty in underlying data or scenario assumptions explicit (Pizzol et al. 2017; Wulf et al. 2019; Saadé et al. 2022; Castro et al. 2022; Elia et al. 2024).

On the regulatory side, similar challenges appear. For example, Vázquez Calvo et al. (2025) identify numerous challenges and enablers for integrating CE objectives into best available technique (BAT) information exchange and permitting under IED 2.0. They emphasize gaps in existing indicators to capture installations' CE contributions and the importance of LCA-based tools for supporting competent authorities (Vázquez Calvo et al. 2025).

A fourth gap concerns the limited empirical insight into how integrated frameworks that combine a structured indicator base, scenario-based action evaluation and LCA-MCDM behave when applied in different organizational and sectoral contexts. Existing CE and EIP assessment tools are rarely evaluated for the robustness of their outputs and for how strongly their results depend on context-specific modeling choices. This includes the sensitivity of rankings or policy conclusions to indicator selection, weighting and normalization schemes, and to scenario assumptions about energy mixes, mobility patterns, or technology performance (Wulf et al. 2019; Harris et al. 2021; Laurentiis et al. 2023; Elia et al. 2024; Barros et al. 2024; Bais et al. 2025; Zournatzidou et al. 2025). Without such analyses, it is difficult to judge the practical usefulness and limitations of any proposed framework and to understand in which contexts and under which assumptions results remain robust or uncertain. In industrial operations with frequently changing conditions and

incomplete information, decision support that makes uncertainty explicit is especially important (Clausen et al. 2022).

In summary, four overarching research gaps motivate the methodological developments and empirical applications presented in this thesis:

- A lack of a structured, CE-aware indicator base for environmental assessment of industrial and urban symbiosis and EIPs.
- The absence of a holistic, scenario-based ex-ante evaluation approach for actions across industrial-park life-cycle phases and several CE levels.
- The lack of a low-effort decision-support tool (DST) that integrates LCA and MCDM for prioritizing micro- and meso-level actions while treating circularity as a complementary, non-compensatory perspective and making uncertainty explicit.
- Limited empirical insight into the behavior, robustness, context-dependence and sensitivity of such integrated frameworks when applied in different organizational and sectoral settings.

These gaps directly inform the overall aim, the main research question (MRQ) and the four specific research questions formulated in Section 1.3.

1.3 Aim, research questions and hypothesis

The overarching aim of this thesis is to develop and critically assess a generic ex-ante methodological framework that enables companies (micro level) and industrial parks (meso level) to evaluate and prioritize environmental improvement actions while explicitly representing CE aspects and uncertainty. In this thesis, such actions are understood as targeted operational environmental improvement possibilities in fields such as employee mobility, energy use, circularity and symbiosis such as shared infrastructure. The framework integrates three methodological pillars: (i) a systematically derived indicator base for environmental assessment in industrial and urban symbiosis contexts, (ii) a scenario- and action-based prospective LCA evaluation approach that is used ex-ante to assess actions, and (iii) a low-effort quantitative integration of LCA with MCDM to generate environmental scores while explicitly representing CE aspects and uncertainty.

This overall aim is captured in the following **main research question (MRQ)**:

How can a generic, low-effort ex-ante framework be developed and critically assessed that enables companies and industrial parks to prioritize environmental improvement actions under realistic data constraints in a CE context, while making key trade-offs and uncertainties explicit?

To operationalize this MRQ, the thesis addresses four specific research questions (RQ), each corresponding primarily to one methodological pillar of the cumulative work:

- **RQ1: Indicator base for industrial and urban symbiosis**

  Which environmental indicators are used to assess industrial symbiosis, urban symbiosis, EIPs and related meso-level CE initiatives, how are they distributed across applications and over time, and how can this evidence be synthesized into

a compact core indicator set aligned with CE R-strategies for environmental assessment?

- **RQ2: Scenario-based action evaluation approach**

  How can an action- and scenario-based prospective LCA approach be designed that allows consistent ex-ante evaluation of actions across industrial-park life-cycle phases (planning, building, operation) and across CE levels (nano, micro, meso)?

- **RQ3: LCA-MCDM design for low-effort scoring**

  How can LCA-based action results be converted into simple multi-indicator environmental scores that are transparent, suitable under limited data availability, and keep trade-offs and uncertainty between indicators visible for decision-makers?

- **RQ4: Framework behavior, robustness and sensitivity**

  How does the proposed framework behave in different organizational and sectoral contexts? What does this behavior reveal about its context dependence, its practical strengths and limitations, and the robustness of its scores and rankings under scenario uncertainty?

These RQ are addressed cumulatively in three peer-reviewed articles, which are briefly introduced in the following section.

Underlying this work is the following methodological hypothesis:

A generic, low-effort ex-ante framework that (i) uses a systematically derived core of environmental indicators, (ii) quantifies actions via scenario-based prospective LCA used ex-ante, and (iii) aggregates results through a simple and transparent LCA-MCDM scheme can produce decision-relevant relative environmental rankings of actions and action portfolios under realistic data constraints, while making key trade-offs and uncertainties explicit.

Within this overarching aim and research design, the thesis provides four main methodological contributions:

- A systematically derived, CE-aware environmental indicator base for industrial and urban symbiosis and EIPs, which consolidates a fragmented indicator landscape into a robust core set suitable for meso-level environmental assessment.
- The KREGI (Klima- und Ressourceneffizienz in Gewerbe- und Industriegebieten) approach as a generic, action- and scenario-based prospective LCA methodology that is used ex-ante and structures and quantifies environmental effects of actions along industrial-park life-cycle phases and CE levels.
- A low-effort LCA-MCDM scoring design, implemented as a DST, that aggregates pre-quantified action effects into composite environmental scores while treating circularity as a complementary, non-compensatory dimension and explicitly representing uncertainty.

- An integrated framework that combines these elements and is empirically tested in four contrasting company settings, providing insight into its behavior, robustness, context-dependence and practical usefulness for ex-ante prioritization of environmental actions.

While each of these methodological elements has been discussed in previous research, they are usually applied separately. Studies on industrial symbiosis and EIPs often focus on indicator systems or case-specific evaluations, while prospective LCA studies typically assess individual technologies rather than portfolios of operational actions. Likewise, existing CE tools frequently provide qualitative maturity assessments or ex-post monitoring rather than quantitative ex-ante prioritization through concrete actions. By combining a structured indicator base, an action-based prospective LCA method, and a low-effort LCA-MCDM decision tool, this thesis integrates these aspects into a single framework for practical environmental decision-support.

1.4 Structure of the thesis

This thesis is structured as a cumulative dissertation. It consists of six main chapters that build on one another both conceptually and methodologically.

Chapter 1 introduced the problem context and motivation. It outlined the relevance of companies and industrial parks for global environmental impacts, summarized the conceptual background in IE, industrial and urban symbiosis, EIPs, and the CE, and derived the research gaps. It then formulated the overarching aim, the MRQ, the four specific RQs, and the methodological hypothesis.

Chapter 2 presents the first paper (Publication I), a scoping review of environmental indicators used to assess industrial and urban symbiosis, EIPs, and related meso-level CE aspects. It systematically maps and clusters indicators, analyzes their use across application areas and over time, and links them conceptually to R-strategies. In doing so, it establishes the indicator base required for subsequent methodological development and directly addresses RQ1.

Chapter 3 contains the second paper (Publication II), which develops the KREGI action and scenario-based evaluation approach for ex-ante assessment of actions in industrial parks and companies. It defines methodological requirements for actions, structures them along industrial-park life-cycle phases (planning, building, operation) and CE levels (nano, micro, meso). The KREGI approach also quantifies the action environmental effects via ex-ante LCA under status-quo, best-case, and worst-case scenarios. A detailed car-sharing example illustrates the approach. This chapter primarily addresses RQ2.

Chapter 4 presents the third paper (Publication III), which builds on the indicator base and the KREGI approach by quantifying a broader set of actions and specifying the LCA-MCDM design. It implements these designs in the form of a low-effort quantitative DST. The chapter describes how pre-quantified action effects are normalized, weighted, and aggregated into composite environmental scores and how scenario-based uncertainty bands are constructed. The chapter also shows how circularity information is represented as a complementary, non-compensatory perspective. The tool is then applied in four company

case studies from different sectors to explore its behavior, robustness, and context-dependence. This chapter addresses RQ3 and RQ4.

Chapter 5 evaluates how this integrated chain behaves across different company contexts and derives thesis-level conclusions on added value, robustness/sensitivity, and transfer requirements. This chapter also compares and contrasts their results, and discusses the theoretical and methodological contributions to IE, industrial and urban symbiosis, EIP assessment, and CE measurement. It also reflects on practical implications for companies, industrial-park operators, and municipalities, and critically examines uncertainties and limitations of the proposed framework and its implementation.

Chapter 6 presents the overall conclusion and outlook. It summarizes how the RQs have been answered, revisits the methodological hypothesis in light of the cumulative findings, and formulates the main conclusions of the thesis. The chapter concludes with an outlook on future research and development, including extensions such as the indicator base and action catalog and further refinement of the LCA-MCDM scheme. Figure 1.4 provides a visual overview of how the six chapters and the three included publications relate to one another and to the four RQs.

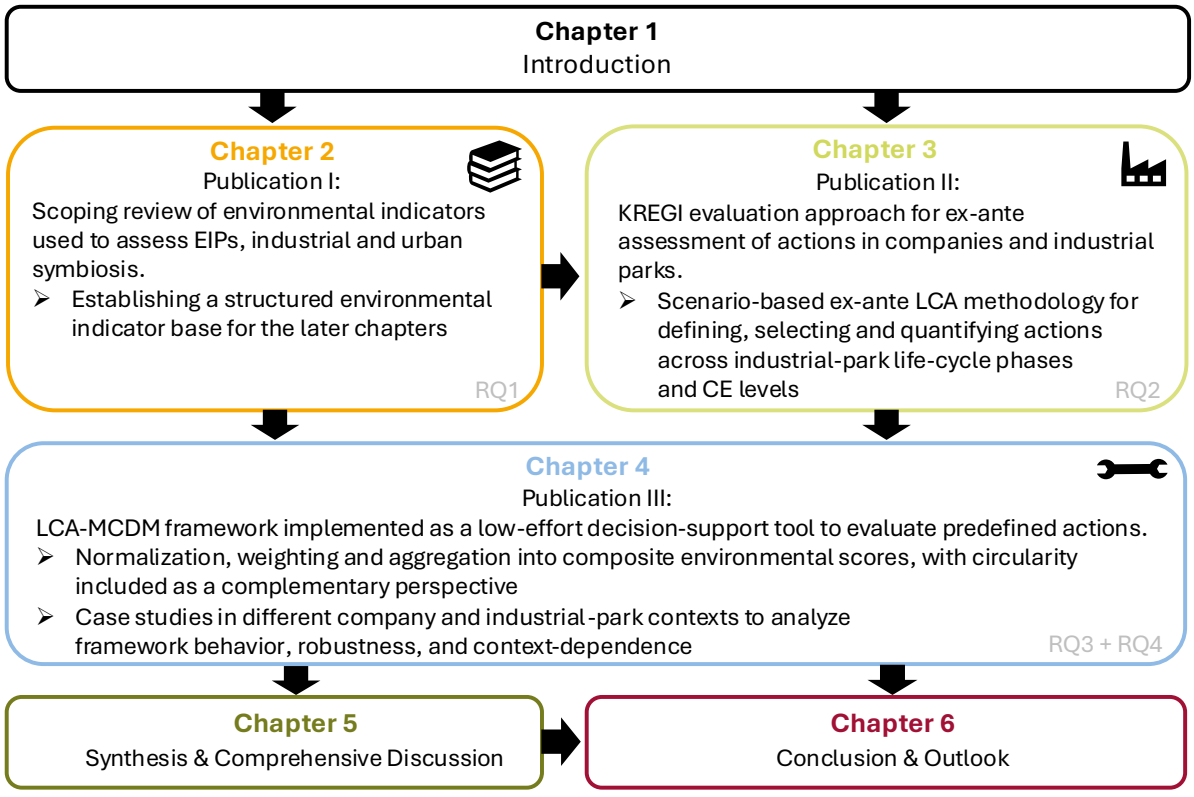


Figure 1.4: Structure of the cumulative thesis, showing the roles of Chapters 1-6, the three included publications and their links to research questions RQ1-RQ4.

2 Publication I: Scoping review of environmental indicators for industrial and urban symbiosis and eco-industrial parks

Verkic, Benedikt; Göbbels, Lieve; Greiff, Kathrin (2025): Analysis of environmental indicators assessing industrial symbiosis and urban symbiosis for an improved indicator selection process: A scoping review. In *Cleaner Environmental Systems* 19. https://doi.org/10.1016/j.cesys.2025.100363

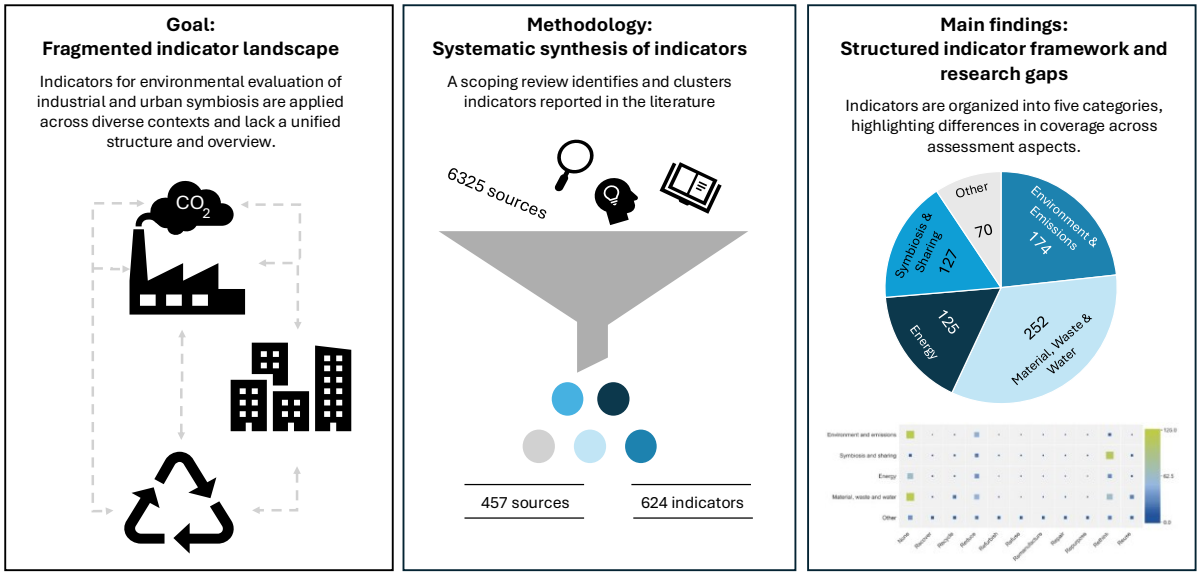


Figure 2.1: Graphical abstract of Publication I.

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This chapter summarizes Publication I, which addresses RQ1 by conducting a scoping review of environmental indicators used to assess industrial and urban symbiosis, EIPs and related meso-level CE initiatives. In doing so, it establishes the indicator base required for the subsequent methodological developments in Chapters 3 and 4. The review systematically screened the literature and, after clustering, identified 624 comprehensive indicators across 457 sources. Indicators mainly fall into the categories *material, waste and water*; *environment and emissions;* and *energy*, with LCA-based metrics such as GWP, CED and LU, as well as operational indicators like waste use and WU, among the most frequently applied. These widely used indicators form a robust core that can underpin future assessment frameworks, while the large number of rarely used, heterogeneous indicators reveals a high degree of fragmentation and redundancy. The review also shows that most indicators are employed in both industrial symbiosis and EIP contexts, although some remain context-specific. It also shows that high-circularity R-strategies such as Rethink, Reduce, Reuse and Recycle are better covered than strategies like Refuse, Refurbish or Remanufacture. Overall, the scoping review provides a structured, CE-aware indicator base that allows researchers, municipalities and companies to select and combine indicators without repeating the literature search, and highlights where further work, such

as harmonizing definitions and calculation methods, would be beneficial. In this cumulative dissertation, the resulting compact indicator core is used as the environmental evaluation basis in both the KREGI approach (Publication II) and the DST scoring and case applications (Publication III), ensuring methodological continuity across the three papers.

Abstract

Through innovative exchange of resources, industrial symbiosis can contribute to the circular economy and decrease environmental impacts. Similarly, urban symbiosis focuses on synergies involving cities. Even though many literature reviews exist in the field of industrial symbiosis, overviews on currently used and suitable indicators for measuring environmental impacts are lacking. Therefore, this scoping review provides an overview and descriptive analysis of relevant environmental indicators in the field of industrial and urban symbiosis used in scientific and gray literature. To ensure a comprehensive and exhaustive overview, eco-industrial parks and circular economy on the meso level are included. The aim is to provide a solid basis for future industrial and urban symbiosis assessment frameworks to improve and accelerate the identification of individually appropriate indicators. In total 3349 indicators across 457 sources were identified and clustered into 624 comprehensive indicators. The indicators are evaluated regarding overall use and use over time, category, type and R-strategy. Our results showed that most indicators are available in the area of material, waste and water, followed by environment and emissions. The paper identified good coverage of high-circularity R-strategies but limited coverage for other strategies. These results form a solid basis for the development of holistic and standardized assessment frameworks in the field of industrial and urban symbiosis. The most used indicators could for instance serve as a basis for relevance when utilized by companies, industrial park operators, and urban administrations.

2.1 Introduction

Sustainable development is gaining increasing attention and scientific disciplines such as *industrial ecology* (IE) are emerging to develop tools for investigating and implementing ways of sustainable development. IE focuses on industrial activities as a system of interconnected industries or processes. Being an interdisciplinary concept, IE includes a subsets of concepts such as industrial symbiosis (Jelinski et al. 1992; Azar 1997; Fischer-Kowalski 1998; Fischer-Kowalski and Hüttler 1998; Chertow 2000). Industrial symbiosis is in principle applicable to many companies and industries. For instance, according to the International Standard Industrial Classification of All Economic Activities, Revision 4 (ISIC, Rev.4) case studies have been identified for 14 of the 21 ISIC categories, where the category *manufacturing* contains the highest share of activities (Neves et al. 2020). This exemplifies that industrial symbiosis is spread among various economic activities. Most of the industrial symbiosis entities are industries, factories or companies for market production (Wadström et al. 2021). Given this background, industrial symbiosis can be a suitable tool for the reduction of environmental impacts while preserving or improving economic benefits (Yu et al. 2023). Among others, the European Union (EU) has defined industrial symbiosis as a toolkit for the improvement of circularity and a reduction in environmental impacts in a range of programs (European Commission 2018, 2020b). In the last years the concept of industrial symbiosis has gained attention, which has propelled a redevelopment of the conceptual definitions (Huang et al. 2019b; Mallawaarachchi et al. 2020).

Next to industrial symbiosis, urban symbiosis has been developed as an extension of the formerly mentioned concept. Here, the definition of urban symbiosis includes physical resources like waste or byproducts of geographically near cities or urban areas as an alternative input into industrial processes in the form of, among other things, raw materials or energy (van Berkel et al. 2009). The concept, however, often remains implicit as subfield of industrial symbiosis. Other concepts in this field include eco-industrial parks (EIPs) and the meso level of the circular economy (CE). Industrial symbiosis is applied within EIPs, while the meso level of CE encompasses the establishment and maintenance of EIPs (Kerdlap et al. 2020a; Kirchherr et al. 2023; Yu et al. 2023). Additionally, the use of the R-strategies framework to qualitatively assess aspects of circularity provides a complementary perspective. By integrating these concepts into our evaluation and elaborating on their interrelations and implications a comprehensive view of the topic of industrial and urban symbiosis is ensured.

2.1.1 Current state-of-the-art in the evaluation of industrial symbiosis

Within the field of industrial symbiosis, several literature reviews are available. The definition and development of the concept industrial symbiosis was evaluated by Zhang et al. (2015), Boons et al. (2017) and Mallawaarachchi et al. (2020). Existing literature reviews also analyze the application of industrial symbiosis within a case study (Kerdlap et al. 2020a; Neves et al. 2020) with a regional focus (Park et al. 2016; Vahidzadeh et al. 2021; Colpo et al. 2022) or with a comparison of applications across different countries (Neves et al. 2020; Fraccascia et al. 2021). Furthermore, optimization and modeling of industrial symbiosis (Kerdlap et al. 2020a; Lawal et al. 2021; Wadström et al. 2021; Demartini et al. 2022) and EIPs (Boix et al. 2015; Susur et al. 2019) are part of multiple reviews. Other reviews focus on the quantification of environmental benefits or general methods (Huang et al. 2019b; Neves et al. 2019; Fraccascia and Giannoccaro 2020; Wadström et al. 2021), specific methods, such as life cycle assessments (LCA) (Aissani et al. 2019; Kerdlap et al. 2020a), energy symbiosis and applications of renewable energy within industrial or urban symbiosis (Butturi et al. 2019), as well as the application of industrial symbiosis in urban areas (Fraccascia 2018) and the sustainability of industrial symbiosis life cycles (Ramírez-Rodríguez et al. 2024).

The quantification of environmental impacts of industrial symbiosis can be realized through various indicators, both those that have more general application possibilities and those specified for industrial symbiosis (Neves et al. 2020). Besides, evaluations can also be done by qualitative indicators. Existing studies show positive outcomes of industrial symbiosis in all three sustainability categories, i.e. ecological, economic and social (Fraccascia and Giannoccaro 2020; Neves et al. 2020; Yu et al. 2023). Where economic advantages are the main driver for companies to establish industrial symbiosis, social and environmental impacts prevail in the reasoning of government bodies for promoting industrial symbiosis (Neves et al. 2020). Yet, the most-frequently used indicators for measuring industrial symbiosis and EIPs are however environmentally oriented (Valenzuela-Venegas et al. 2016).

Even though multiple reviews focusing on industrial symbiosis indicators exist, there are relatively few that explicitly describe and systematically organize these indicators. For instance, in the work by Felicio et al. (2016), a new indicator was derived based on a systematic review but the authors fail to provide explicit descriptions and classifications of the collected indicators. On the other hand, the work by Valenzuela-Venegas et al. (2016) identifies and describes hundreds of indicators to measure sustainability of an EIP and categorizes them into economic, environmental and social indicators while taking into account the existing overlap between these aspects. Even though the work by Valenzuela-Venegas et al. (2016) is an essential part of developing a holistic way of measuring different aspects of industrial and urban symbiosis and their performance from an environmental, economic and social perspective, the work only deals with measuring sustainability of an EIP, leaving out other aspects of the CE and its applicability on a broader scope. Additionally, a comprehensive link between indicators of industrial symbiosis and corresponding R-strategies is lacking in literature.

Generally, the indicators collected by reviews like the works described previously are used – often in parallel – in assessment frameworks to analyze certain impacts of EIPs or industrial symbiosis. Cagno et al. for instance developed a framework for evaluating the performance of industrial symbiosis, CE, and sustainability and identified a full system and a core system of indicators (Cagno et al. 2023). The full system contains 91 indicators, of which 34 are related to industrial symbiosis, whereas the core system comprises 53 indicators, of which 21 pertain to industrial symbiosis, and is specially designed to be adaptable to company's needs (Cagno et al. 2023). Moreover, Lütje and Wohlgemuth (2020) developed an assessment framework that combines 15 different indicators to evaluate industrial symbiosis and Dong et al. (2022) provide an overview of various indicator systems for evaluating industrial symbiosis performance. The latter found 14 indicators that encompass sustainability and network indicators, with material flow analysis (MFA) being the most commonly used accounting approach (Dong et al. 2022). Additionally, research has been conducted on an evaluation of the usability of certain indicators for industrial symbiosis. For instance, in the work by Mantese and Amaral (2018), four categories were defined: not recommended for unique use, most complete, simplest, and combinations for holistic evaluation. Other studies assess industrial symbiosis by integrating LCA and MFA with additional indicators such as Water Footprints (Fallahi et al. 2024). This analysis of industrial symbiosis together with environmental impacts happens more often (Sun et al. 2017; Chen et al. 2022a), namely on company-level as a micro level of CE, but can also explicitly regard evaluations of multiple companies as a meso level of CE (Kalmykova et al. 2018; Merli et al. 2018; Fan and Fang 2020; Kuzma et al. 2022; Kirchherr et al. 2023). Additionally, Santhappan et al. (2025) summarize the advantages and key areas of various life cycle impact assessment methods for integrating bioenergy in industrial symbiosis.

So, recent works demonstrate that a wide variety of indicator systems and assessment frameworks have been developed to evaluate the environmental performance and impacts of industrial symbiosis, EIPs, and CE initiatives. These frameworks often integrate multiple indicators, ranging from core sets tailored to company needs to comprehensive

systems encompassing sustainability, material flows, and network dynamics. Approaches such as LCA and MFA are frequently used in combination to provide holistic evaluations at both micro- and meso-levels. However, none of these publications rely on an objective indicator basis. That is, in each of these works, a separate literature review is conducted to identify suitable indicators, which likely results in the omission of relevant indicators.

2.1.2 Aim and scope

Based on the review of current literature in the scope of industrial symbiosis, urban symbiosis, EIPs and CE on the meso level, several research gaps have been identified. Information regarding 1) usage trends of indicators (Valenzuela-Venegas et al. 2016); 2) non-product resource sharing (Wadström et al. 2021) and 3) quantitative indicators and quantitative applications of the indicators in the field of industrial and urban symbiosis (Domenech et al. 2019; Neves et al. 2020; Wadström et al. 2021) is lacking. Moreover, the aspect of failing industrial symbiosis, the multidimensionality of sustainability and the non-exhaustiveness of social indicators are often ignored (Valenzuela-Venegas et al. 2016; Fraccascia and Giannoccaro 2020; Neves et al. 2020; Mallawaarachchi et al. 2020; Ramírez-Rodríguez et al. 2024). Additionally, relations between the different R-strategies of CE and both industrial and urban symbiosis have not yet been comprehensively described, possibly due to a lack of exhaustive depictions of all R-strategies in these contexts (Kristensen and Mosgaard 2020; Superti et al. 2021; Syu et al. 2022). Yet, the R-strategies are seen as a vital part of CE because of its adoption in the EU for evaluating circular categories (European Commission 2020a) and are also stated as significant in literature (Muñoz et al. 2023).

As environmental indicators are a central aspect in EIPs and as such important in the context of industrial symbiosis, evaluations of its potential are relevant. However, before this can be done, it is vital to have a clear overview of which environmental indicators exist, which is currently lacking. By making such an overview available and providing a first analysis, the current review aims to reveal usage trends, the variety of indicator types, and the indicators' coverage levels regarding among other things application areas and R-strategies. Additionally, a clear link to the CE in terms of R-strategies lacks in current literature. To address these gaps, we aim to (i) provide a comprehensive overview of used indicators regarding the environmental evaluation of industrial and urban symbiosis, (ii) give a holistic categorization, fitting current CE frameworks in the form of R-strategies and (iii) reveal gaps in the current evaluation possibilities for future research. Following this goal, we identified the following central research question: *What indicators are relevant for the environmental assessment of industrial and urban symbiosis and how can these be organized in such a way that guidance for the selection of suitable indicators is provided for companies, industrial park operators and urban administration.* To map the available indicators and use a systematic categorization procedure, as well as to identify the scope of use of these currently used indicators regarding the different aspects of environmental assessment of industrial and urban symbiosis for answering the central question, a scoping review has been conducted.

The purpose of the overview is to enable companies, industrial park operators, and municipalities to use it as a basis for an efficient and effective indicator selection process. With a categorized overview, evaluation possibilities for potential exchanges between companies or municipalities can be conducted without the need for time-consuming individual literature searches, providing a comprehensive perspective.

In the following, the methods are described in detail in Section 2.2 and in Section 2.3 the results are presented. In Section 2.4, these results are interpreted and discussed. Lastly, in Section 2.5 the most important conclusions are drawn and recommendations for further research are given.

2.2 Methods

2.2.1 Central concepts for the scoping review

The first documentation of industrial symbiosis as it is currently defined has been described by Frosch and Gallopoulos (1989). Even though the concept of industrial symbiosis was neither explicitly mentioned in this work, nor was it an established concept at the time, its workings were described as an exchange of waste between different industries in order to transform it into productive input (Frosch and Gallopoulos 1989). The first explicit definition of the concept was described by Chertow (2000): “[t]he part of industrial ecology known as industrial symbiosis engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and byproducts. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity” (Chertow 2000). Even though some newer definitions describe industrial symbiosis as being independent of geographic proximity (Gregson et al. 2012; Lombardi and Laybourn 2012), it is generally still considered a vital aspect. For instance, Jensen et al. (2011) and Shi et al. (2010) investigated that the median distance of symbioses lies at approximately 30 kilometers. Similarly, newer definitions also include cooperation between traditionally separate entities and the use of innovative processes (Chertow and Ehrenfeld 2012; Lombardi and Laybourn 2012; Herczeg et al. 2018). In contrast to the original definition, newer definitions include exchange of immaterial aspects such as information (Lombardi and Laybourn 2012). Moreover, the co-usage of infrastructure and services has been added as a part of industrial symbiosis (Chertow et al. 2008). However, the main characteristics of the original definition of industrial symbiosis are still at the core of redefinitions of industrial symbiosis, which have generally been developed to adapt to changing environments, industries and demands (Mallawaarachchi et al. 2020). That is, most redefinitions as well as the definition by Chertow (2000) see exchange (of physical materials) between classically separate entities and geographic proximity as a factor of collaboration or synergy as the main factors embedded in industrial symbiosis (Mallawaarachchi et al. 2020). As such, in this work, the definition by Chertow (2000), albeit slightly adapted to fit current environments, industries and demands, is used. Thus, industrial symbiosis in this work is defined as *an exchange of immaterial goods or physical material between classically separate entities within a geographic proximity*.

Framing industrial symbiosis in the context of the CE, the CE Action Plan developed by the EU, describes industrial symbiosis as a tool for strengthening the CE (European Commission 2020b). Similarly, other authors also indicate the possibilities of using industrial symbiosis for the transformation towards a CE (Daddi et al. 2017; Rincón-Moreno et al. 2020; Yu et al. 2021b) or as guiding implementation of closed loop concepts (Wen and Meng 2015). This can for instance be done by adhering to the R-strategy framework, among others described by Potting et al. (2017) and the European Commission (2020a). R-strategies enable an evaluation of CE in respect to the range of circularity. For example, realization of the R-strategy Rethink can decrease the absolute amount of natural resources used, whereas for example Recovering is often linked to a resulting pollution, quality reduction and energy use (Potting et al. 2017). This is one of the reasons why the R-strategies framework is seen as significant aspect of the CE (Muñoz et al. 2023).

Within the CE, EIPs are considered the meso level of an economy (Kalmykova et al. 2018; Merli et al. 2018; Kuzma et al. 2022; Kirchherr et al. 2023). At the same time, EIPs are at the core of industrial symbiosis, as an EIP is defined as a multitude of businesses that optimize their performance through resource and knowledge sharing (President's Council on Sustainable Development 1996; Lowe 2001; UNIDO 2016; Perrucci et al. 2022). Therefore, the development of an EIP can be a way to realize industrial symbiosis and work towards a CE (Felicio et al. 2016; Scafà et al. 2018; Perrucci et al. 2022; Yu et al. 2023). EIPs and their symbiotic industrial networks can also adopt a nature-based approach and design to facilitate improvements (Genc et al. 2020; Genc and Kurt 2024). Additionally, several works describe the necessity to implement industrial symbiosis into conventional industrial parks to form an EIP (Scafà et al. 2018; Yu et al. 2023) and the synonymity of EIP to the concept of industrial symbiosis (Kerdlap et al. 2020a). Accordingly, industrial symbiosis can be seen as being a part of CE (Vinante et al. 2021; Chrispim et al. 2023).

The global nature of the concept of EIP is highlighted by the World Bank (2021), which established an international assessment framework for EIPs to promote sustainable development in alignment with the sustainable development goals (SDGs) defined by the United Nations. This framework can be applied to both existing EIPs and industrial parks aiming to become EIPs (World Bank 2021). Additionally, China has implemented a standard for assessing and improving industrial parks and EIPs (Huang et al. 2019a). In Japan, the concept of eco-towns is used to incorporate industrial and urban symbiosis for the reduction of environmental impacts (van Berkel et al. 2009).

2.2.2 Scoping reviews

To answer the main research question and systematically acquire and organize indicators relevant for the assessment of industrial and urban symbiosis in the context of environmentality, a scoping review has been conducted. There can be a variety of goals as to why a scoping review is conducted. That is, one can use it to 1) map and evaluate the current state of knowledge on a certain topic; 2) clarify key concepts or definitions; 3) examine how research on a certain topic is conducted; 4) identify key characteristics or factors related to a concept; 5) map essential knowledge or concepts as a precursor to systematic reviews and 6) identify and analyze gaps in the knowledge base (Munn et al. 2018).

Consequently, scoping reviews generally have a broader *scope* compared to traditional systematic reviews (Munn et al. 2018).

Previous scoping reviews in the fields of industrial symbiosis, urban symbiosis, and EIPs are not available. However, scoping reviews exist that address other topics related to environmental assessment, supply chains, and CE to provide an overview of these areas. These works often provide an overview of subjects such as the environmental assessment of CE (Harris et al. 2021), which is also specified for the construction industry (Muñoz et al. 2023). Harris et al. (2021) address the topic of industrial symbiosis in their search string by incorporating aspects of CE, along with assessment or quantification related to direct industrial symbiosis, EIP, meso-level concepts, or synergy concepts, using Scopus as the database. This shows the combination of industrial symbiosis, EIP and CE resulting in a comprehensive coverage of the topic, however the narrow search procedure nonetheless led to a relatively limited collection of works and subsequent analysis. They nevertheless found that the most commonly used environmental assessment method is LCA and that indicators for evaluating industrial and urban symbiosis material exchanges at the industrial park level are lacking (Harris et al. 2021). Additionally, they argue that the temporal focus in assessment studies is primarily retrospective rather than prospective (Harris et al. 2021).

A review with a specific application context was conducted by Muñoz et al. (2023) who identified 249 indicators for the construction industry and found that the 10R framework is the most commonly used indicator topic, highlighting its significance. The search string encompasses aspects of CE, life cycles, and the environment, specifically related to construction or building applications in the Scopus and Web of Science databases, highlighting the interconnection of various concepts for environmental evaluation (Muñoz et al. 2023). Another study focuses on the coverage of R-strategies in the context of consumer behavior regarding electronic waste, in which it was found that the strategies Repair, Recycle and Reuse are well-covered (Hunger et al. 2024). In yet another scoping review, a value chain-based taxonomy for CE indicators was developed, including the meso level of CE with 55 key performance indicators, of which 28 are environmentally related (Khedmati-Morasae et al. 2024). However in this work specifically, the meso level appears to emphasize industry-wide aspects rather than exchanges between companies typical in industrial symbiosis (Khedmati-Morasae et al. 2024). The used search string includes aspects of CE, general indicators, and key performance indicators or metrics, along with reviews, using Scopus and Web of Science as databases (Khedmati-Morasae et al. 2024). These works show that, even though different approaches are taken, the scoping review procedure is a suitable framework to establish overviews of indicator collections. Moreover, it shows the breadth and intertwinement of concepts and indicators. This knowledge can be used to form a broad enough search procedure in order to establish a currently lacking exhaustive overview of indicators around the intersection of industrial symbiosis and CE aspects.

In this work, the focus is therefore on the identification and extent of existing (environmental-related) indicators of industrial and urban symbiosis. Moreover, as indicated in the previous section, a secondary goal is to explicitly describe further research gaps

within the topic of assessments of industrial and urban symbiosis in the context of CE so that evaluation methods can be improved further in the near future.

To conduct the scoping review in a systematic, valid and exhaustive way, the established Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) framework has been used as a guideline (Tricco et al. 2018; Peters et al. 2020). Following this framework, a protocol in the advised structure has been developed. This protocol can be found in Indicator overview.

2.2.3 Database search

The search strategy used in this scoping review has been developed to be as transparent and systematic as possible to enhance reproducibility. The search has been carried out in three databases: Scopus, Web of Science and IEEEXplore, following the tendency of other literature reviews conducted in this research area, as outlined in Section 2.1.1, but with an extended focus on conference works. Moreover, it has been decided to use multiple large databases to maximize the search coverage. The decision to use these specific databases has also been made based on the given that these databases allow the use of wildcard operators, making it possible to develop more suitable search strings.

The scoping review was conducted on June 26, 2024. To only include relevant literature, exclusion criteria were iteratively optimized and multiple filtering stages were implemented. It was decided to only take into account works written in either English or German as these could be fully comprehended by all authors. That is, still over 87 % of all works were included in the unfiltered database. Moreover, no constraints were placed in terms of publication year, meaning that all publications – ranging from 1974 up until 2024 – have been included. All types of publications and thus also gray literature within the database search have been included in the search, since even non peer-reviewed publications present relevant applications of industrial symbiosis and possible new indicators (Neves et al. 2020). Furthermore, gray literature is important in the context of CE (Muñoz et al. 2023; Kirchherr et al. 2023), which makes it relevant to include. As the aim of this work is to provide an overview of existing indicators and to show how industrial and urban symbiosis can be evaluated using these criteria, without actually evaluating the results of the case studies, bias in terms of quality or sponsorships is considered insignificant. The search string is applied to the title, keywords and abstract in order to make as few restrictions as possible on the search and to identify and screen all relevant literature.

2.2.4 Search string

The definition of the search string was defined on the basis of the already reviewed literature and reviews in this area and their used keywords as well as synonyms to identify indicators in the realm of industrial and urban symbiosis, as outlined in Section 2.2.1. Additionally, since the focus is on collecting relevant indicators, the definition of the term indicator, as described by Baratsas et al. (2022) and Corona et al. (2019), also played a fundamental role in the development of the used search string and the consecutive selection process. The definition used in this work can best be described as: a value that can be used quantitatively or qualitatively to measure a goal, standard or principal

category, in this case industrial or urban symbiosis. As such, the first part of the search regards variations of the concepts industrial and urban symbiosis. Since industrial symbiosis is often implemented within EIP and since both concepts embed the goal of saving resources through cooperation in geographical proximity, variations of the concept EIP are also included. Additionally, *industrial park* – being a general term – was intentionally included to identify additional industrial symbiosis and exchanges between industries and cities not included by the more restrictive EIP concept. This is considered an essential broadening as works describing symbiosis and relevant indicators sometimes merely describe these concepts in the text body, but do include the term industrial park in their title, abstract or keywords. Moreover, the meso level aspect of the CE was included due to its defined relevance (see Section 2.1), but other CE-aspects were excluded as their relevance in the context of this work could not be proven. Following these criteria, the search string was defined as follows:

("industr* symbiosis* OR “urban* symbiosis*” OR "industr* park*")
OR
("circular* econom*” AND meso*)

However, multiple publications do not explicitly refer to indicators within the title, keyword or abstract and the previously mentioned search string results in a number of works that is infeasible to process by a human in the available time frame, further synonyms were added for comprehensive identification (Saidani et al. 2019). Here, a specification on environmental or ecological aspects was not yet made due to the high number of synonyms and terminologic variations. The complete search string with the corresponding number of matches is shown in Table 2.1.

Table 2.1: Search string and corresponding number of matches per database.

			# Matches		
			Scopus	Web of Science	IEEE Xplore
Title, Keywords, Abstract	Aspects of industrial symbiosis and urban symbiosis, EIP or CE-meso level	("industr* symbiosis* OR “urban* symbiosis*” OR "industr* park*") OR ("circular* econom*” AND meso*)[1]	3067	2667	538
		AND			
	Aspect of evaluation	assess*OR evaluat* OR measur* OR index* OR indices* OR metric* OR Indicator*			

[1]: For IEEE Xplore: "industr* symbiosis*" OR "industr* park*" OR "urban* symbiosis*" OR circular* econom* meso

2.2.5 Source selection process

After collecting all potentially relevant publications using the predefined search string, all duplicates were eliminated and book titles, complete conference proceedings and conference reviews were excluded due to lack of relevance. The remaining works are

deliberately filtered by *exclusion criteria* to ensure a more conservative filtering approach and thus maximizing the potential of including a near-complete collection of papers. First, the title of each work was screened using the exclusion criterion that a work is excluded when topics of industrial or urban symbiosis in the form of symbiosis, industrial parks, waste management – specifically waste utilization – exchange between companies or cities, CE or circularity is not mentioned in the title. As such, synonyms of industrial parks, such as mentions of industrial zones or industrial regions were considered as eligible.

In the next step, the publications' abstracts were screened: when an abstract does not mention industrial or urban symbiosis, EIP or the CE-meso level, the work was excluded. Alternatively, there should be explicit mentioning of exchange between companies or cities, as this is a core aspect in the definitions of industrial and urban symbiosis, and the scope of this contribution is to evaluate (environmental) indicators of the symbiotic relationship(s) between independent entities. For the same reason, in the final step of the selection process, publications were only considered relevant if indicators for the evaluation of the environmental aspects of industrial or urban symbiosis are explicitly mentioned in the form of graphs, tables or explicit descriptions. This ensures a more objective adoption of indicators, avoiding interpretation of passages where indicators are merely implicitly described. However, if an indicator only expresses monetary value, even if related to an environmental factor, it is considered out of scope due to it being defined as an economic indicator. Moreover, for an indicator to be included in the final collection of indicators, it must also relate to industrial or urban symbiosis, EIP or the CE-meso level. Therefore, indicators not relating to industrial or urban symbiosis but depicting general changes in material or energy consumption such as national data or data of a specific industrial sector or industrial plant are classified as irrelevant. Additionally, even though life cycle inventories or inputs are needed for an LCA, the related specific processes or materials are considered irrelevant because of their high individuality and hence, such indicators were also excluded. Technical parameters such as temperature or pressure and material properties such as energy content or density are not considered relevant either, because these relate directly to the material or machine and not the symbiosis.

As the focus is on industrial and urban symbiosis, these concepts form the primary class for defining the scope of the different publications. However, if a publication cannot be classified under industrial or urban symbiosis, but instead regards only EIP or CE-meso, the work will be classified under this respective concept. An overview of the complete procedure and the corresponding relevant number of publications considered at the end of the corresponding step can be found in Figure 2.2. In total, 457 works were considered relevant for review while the source handling was done with the program Citavi.

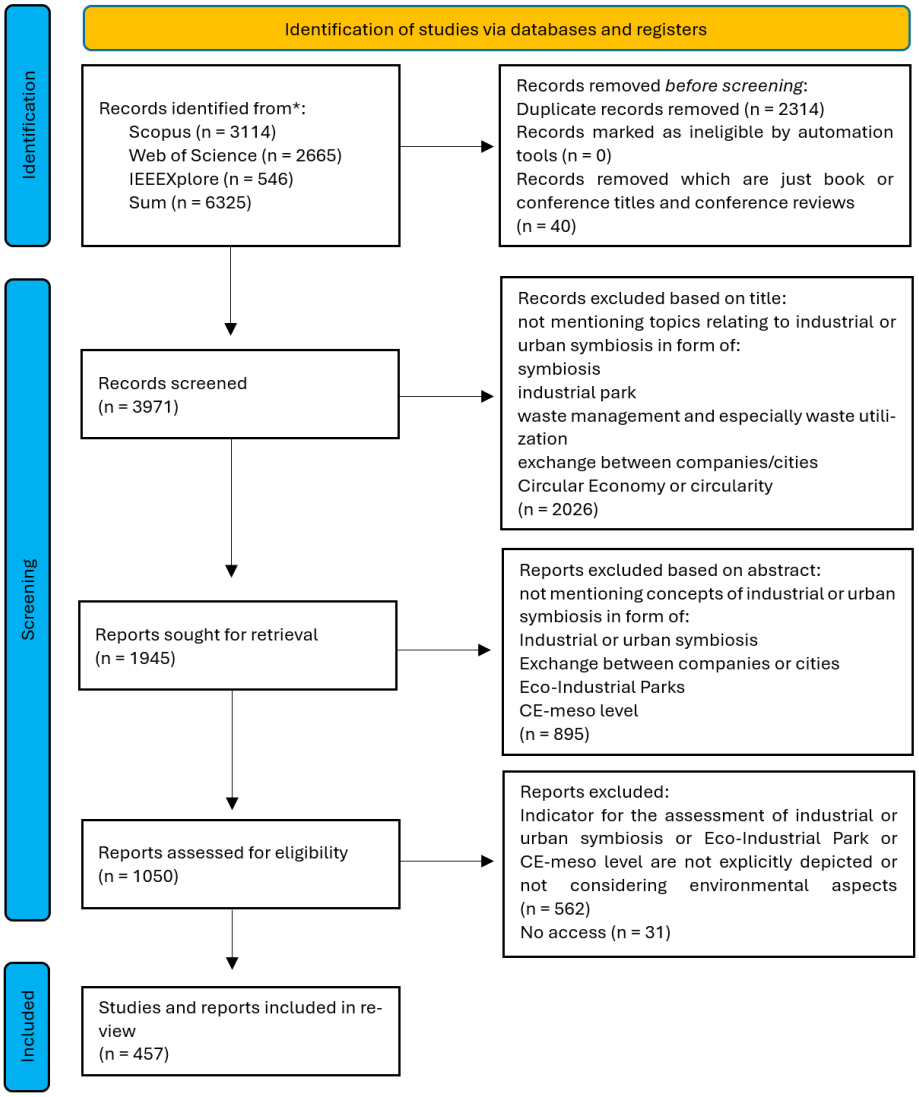


Figure 2.2: Flow diagram of the conducted screening process. Visualization based on Page et al. (2021).

2.2.6 Data processing and analysis

During and after collecting all indicators, varieties of interchangeable indicators were clustered into comprehensive indicators each. The clustering of synonyms and the generalizing of specific indicators has the aim to provide an exhaustive overview of indicators that can be easily implemented in the application case at hand due to their high generalizability (Saidani et al. 2019). That is, following Rousseaux et al. (2017), a collection of indicators principally applicable to all sectors or companies was established. For instance, the indicators *substitute clinker* or *waste plastic substituting coke*, will be converted to *substitute input material* and *substitution through waste utilization*.

For further comprehension and increased interpretability of the analyses conducted, an additional step of clustering was implemented. In this second-stage clustering, indicators with the same or a highly similar meaning were merged to not have parallel indicators which merely have a difference. If parallel aspects are clustered, they are marked by a "/" between the aspects, such as water/wastewater. For instance, the two indicators *water generation* and *water production* were merged into the overarching indicator description

water/wastewater generation/pro-duction/discharge. If not all sources include an aspect, that aspect is marked by "()" as in *water/wastewater (reduction)*.

Moreover, it is necessary to define categories, to further increase the handling of the indicators and reduce the effort to find relevant indicators. Therefore, each indicator was assigned to one or more categories, which are based on the focus areas of this contribution. The definition of these categories was done in an iterative way to have as few categories as possible with as few overlapping indicators as possible. As such, the defined categories are: 1) environment and emissions; 2) symbiosis and sharing; 3) energy; 4) material, waste and water; and 5) other.

The category *environment and emissions* includes for example emissions of pollutants such as nitrogen oxides or sulfur oxides and focusses on elements or compounds. Additionally, effects on the environment which include midpoint indicators such as the GWP, land use or the acidification potential are herein categorized. Also, indicators relating to changes of environmental performance such as air quality or ecosystem quality are included.

Symbiosis and sharing as next category includes a material or non-material exchange which can be considered as symbiotic, sharing and cooperation between companies in general as well as networks and aspects relating to these.

The category *energy* covers aspects relating to energy use and generation as well as the results following from energy use and conversion. This also includes, for example, energy infrastructure.

Included in the category *material, waste and water* is the use of these aspects. This can cover a direct use in a production process or side aspects such as transportation or treatment. Differentiating from the category *symbiosis and sharing* is the fact that no exchange or interaction between companies are named. Differentiation between the aspects material from emissions is that here are material groups relevant such as byproducts, waste and water instead of elements or compounds.

In the category *other* all indicators are contained which could not be assigned to one of the former named categories. Examples for this are aspects involving product design, mobility or direct application of CE without enough information to assign it to one of the other categories. An overview of the different categories, along with example types of indicators is additionally summarized in Table 2.2.

The assignment of the indicators to each category was based on the name of the indicator and which category it relates to. As some indicators are multidisciplinary, an indicator can be assigned to multiple categories. For example, the indicator *Energy resource exchange* was assigned to both *energy* and *symbiosis and sharing* because both categories are related.

Lastly, to allow for a multifaceted analysis, each indicator was further described according to the following variables: 1) measurement (SI-) unit; 2) applicability of one or more contexts in the form of industrial symbiosis, urban symbiosis, EIP or CE-meso; 3) type in

the form of qualitative or quantitative nature; 4) applicability to which R-strategies; and 5) publications that include the indicator. The assigning and processing of the sources was done with the program Microsoft Excel.

Table 2.2: Overview of the defined categories and corresponding examples of indicators.

Category	Example types of indicators
Environment and emissions	Emissions of pollutants such as SO_2 Results of environmental impacts (midpoint indicators) such as climate change Indicators relating to a change of environmental performance such as environmental performance index
Symbiosis and sharing	Sharing, exchange and cooperation of any sort such as material exchange or infrastructure sharing Networks such as information sharing networks Symbiosis indicators such as the Industrial Symbiosis Indicator (ISI)
Energy	Energy use and generation such as heat demand Aspects relating to energetic efficiencies such as exergy efficiency Energy infrastructure such as new building energy saving standard enforcement
Material, waste and water	Use of material, waste and water such as waste recycling or byproduct reuse Treatment of material, waste and water such as wastewater treatment Transport of material, waste and water such as transport distances
Other	Product design Mobility CE

To have an additional insight into the data, relative use rates will be calculated. The average use rate is defined as the number of uses in the literature divided by the total number of sources. To calculate the relative use rate, both the relative use rate in terms of number of indicators as well as number of sources has been taken into account as seen in formulae (1) to (3).

$$\text{use rate}_{\text{relative, indicator}} = \text{use rate} \cdot (1 + (1 - p_{\text{indicator}}) \quad (1)$$

Where $p_{\text{indicator}}$= share of unique indicators of the corresponding category

$$\text{use rate}_{\text{relative, source}} = \text{use rate} \cdot p_{\text{sources}} \quad (2)$$

Where p_{sources}= share of unique sources of the corresponding category

$$\text{use rate}_{\text{relative, combined}} = \frac{\text{use rate}_{\text{relative, indicator}} + \text{use rate}_{\text{relative, source}}}{2} \quad (3)$$

That is, in the relative indicator use rate more weight is added to the use rate of indicators being present in a category that does not contain many indicators (i.e. bonus for pioneering indicators regarding application category). Therefore, if an indicator has a higher increase in the indicator relative use rate compared to its unweighted use rate, the indicators are relatively novel in the respective category in the sense that there are fewer indicators. Conversely, the source relative use rate penalizes the use rate of indicators present in categories with a small number of unique sources (i.e. penalty for lack of disseminated use within a category). This penalty is included as a way to quantify reduced validity if different sources use different indicators, instead of there being a consensus on what set of indicators to use. The combined relative use rate is then the average of both relative use rates: if the proportion of indicators in the respective category is balanced with the

number of unique sources in that category, the relative use rate will be equal to the unweighted use rate. However, when an indicator has a high use rate, even though the proportion of indicators in the corresponding category is low or has a high proportion of unique sources, the relative use rate will be higher than the unweighted use rate.

Another aspect of processing the indicators is the assignment to R-strategies which is based on the 9R framework (Potting et al. 2017) which is also used an adopted by European Commission (2020a). Additionally, Muñoz et al. (2023) emphasized the significance of this framework, which is why it will also be evaluated here, with each indicator assessed for relevant R-strategies. The relation will be determined by the information available through the name of the indicator. This has the advantage that indicators can be assigned to R-strategies without consideration of individual and differing calculation methods which cannot be covered by the clustered indicators. Frequently, the literature does not specify the approach to calculating quantitative values for a given indicator. Additionally, the choice of life cycle impact assessment method influences the results of LCA indicators. However, the aim of this scoping review is not to examine calculation methods or their evolution but rather to highlight how often each indicator is applied in the literature, thereby indicating its potential significance, also in regard to the R-strategies. One example for linking each R-strategy is shown in Table 2.3.

Table 2.3: Summarized comparison of R-strategies which are linked to an exemplifying indicator. Additionally, an explanation for the assignment is given to reason the links.

R-strategy	Exemplifying indicators for assignment	Explanation
Refuse	CE related consumer/employee training	No direct assignment for refuse was possible; it could only be inferred by implementing CE strategies
Rethink	Byproduct exchange/synergies	Synergetic exchanges and sharing of (by-) products are seen as Rethink because the implementation of an innovative exchange and possible business model.
Reduce	Energy (saving) efficiency	Energy saving and increased efficiency are linked to Reduce
Reuse	Byproduct reuse	R-strategy is included in the name of the indicator
Repair	Objects repaired	R-strategy is included in the name of the indicator
Refurbish Remanufacture	Use Rate of Recovered Used Products (URRUP)	The already used and recovered products can be further refurbished or remanufactured before further use
Repurpose	CO_2 utilization	Instead of emitting, CO_2 will be used for other purposes
Recycle	Waste recycling (potential/rate)	R-strategy is included in the name of the indicator
Recover	Incineration/combustible amount	For example, waste will be incinerated and therefore an energetic benefit result

Some indicators are also linked to more than one R-strategy. One example is the indicator *Energy resource exchange* which is related to Rethink as well as Reduce. The R-strategy Rethink has been assigned because the resource exchange within the application of industrial symbiosis is seen as Rethink. This is because it involves in the context of industrial symbiosis an innovative business model, product sharing or multiple use leading to an intensification of the product or material use (Potting et al. 2017; European

Commission 2020a). Additionally, through the energy resource exchange, other energy sources are substituted and less needed which results in the R-strategy Reduce.

Another example of a multiple R-strategy assignment are indicators which are not clarified by their name but could relate to one or more R-strategies. The indicator *Use Rate of Recovered Used Products (URRUP)* could include already used and recovered products being further Refurbished, Remanufactured, Repaired or Repurposed before further use. Additionally, CE indicators such as *cyclicity* can be linked to various R-strategies. Though, a clear assigning to one R-strategy based on the name is not possible, it is nevertheless clear that at least one R-strategy is linked to this indicator. Therefore, indicators whose names do not allow for a clear assignment to an R-strategy are assigned to all possible and context-dependent R-strategies. To distinguish between these interpretated and the clearly assigned indicators, the context-dependent indicators are marked with a star in the indicator overview file which is given in the supplementary materials. If no clear relation to any R-strategy is visible through the name, the indicator will not be assigned to any of the R-strategies. An overview of the processed data including all found and processed indicators is given in Indicator overview.

2.3 Results

2.3.1 Chronological classification

Most of the publications (66 %) regard industrial symbiosis, whereas EIP (23 %) and a combination of industrial and urban symbiosis (7 %) are less frequent application areas. Only a small number of works deal with urban symbiosis as an isolated area (3 %) and the meso level of CE (1 %). Moreover, more than 90 % of the works have been published in the last 13 years (see Figure 2.3). When analyzing the publication time trends visualized in Figure 2.4, an increase in the number of publications can be distinguished for all application areas. However, these increases are most visible for industrial symbiosis, EIP and the combination of industrial and urban symbiosis. Moreover, it can be seen that the number of publications within industrial symbiosis and EIP is comparable in the early years of the previous decade but increases more significantly for industrial symbiosis in later years. Within the 457 relevant publications, 3349 used indicators and 624 unique indicators were identified after the two clustering steps. Out of the 624 indicators, 431 are quantitative only and 98 are qualitative only. The remaining indicators could either not be categorized (50 indicators) or can be covered by both (45 indicators). An overview of all publications and indicators can be found in Indicator overview and as Excel file in the supplementary materials.

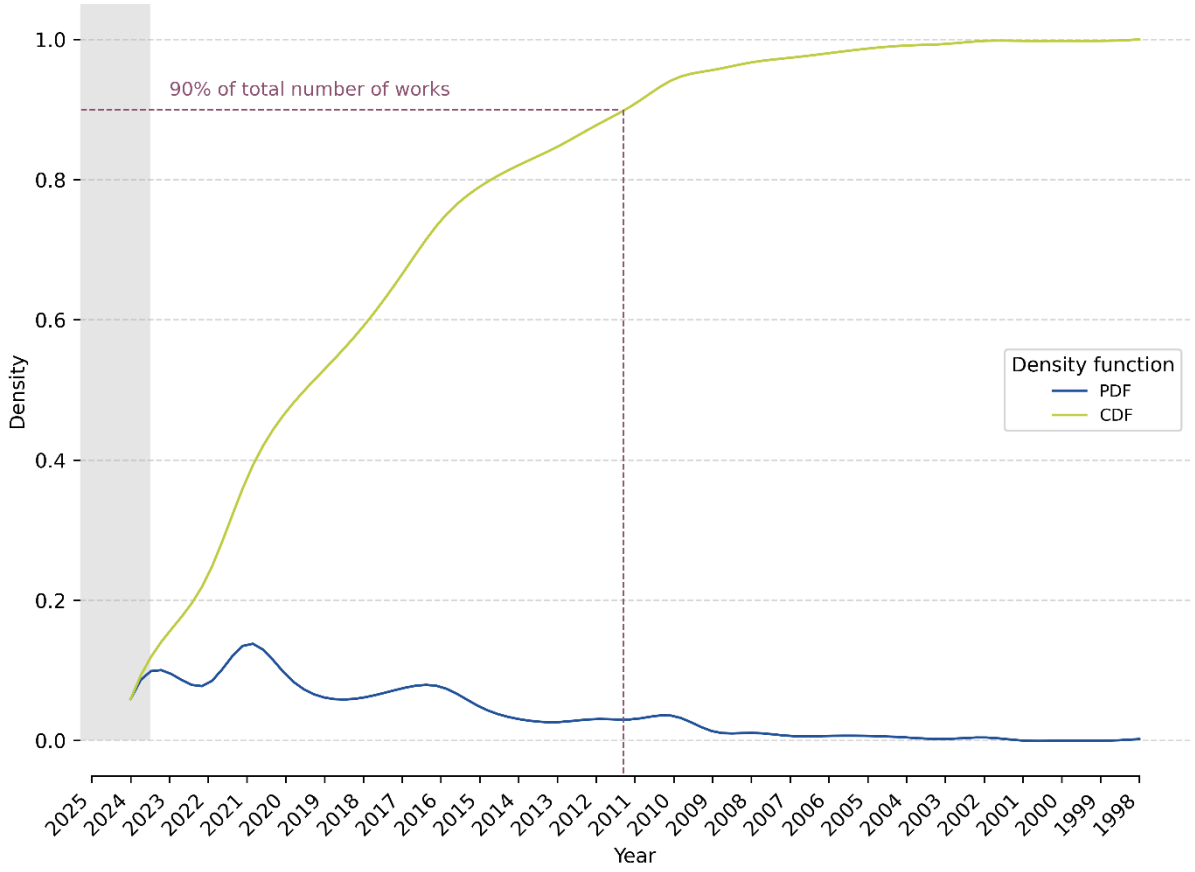


Figure 2.3: Probability (PDF) and cumulative density functions (CDF) of the sources over the years, ordered from most recent to least recent to show what proportion of works has been covered in the X most recent years. The gray bar on the left indicates the future, meaning that the density values are subject to chance.

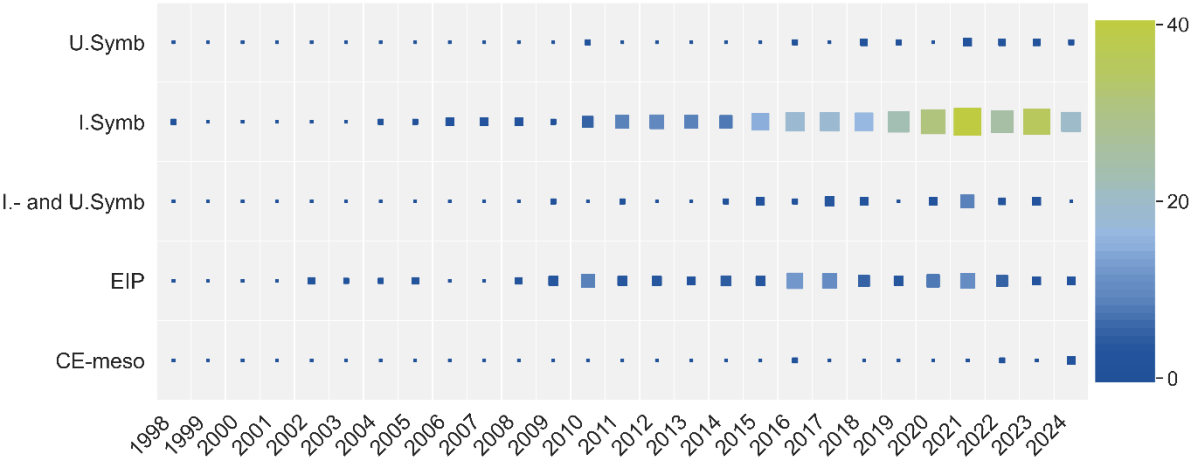


Figure 2.4: Heat map of the number of sources per year across the different application areas. Green and large squares indicate high co-occurrence, whereas small and dark blue squares indicate low co-occurrence. I.Symb=industrial symbiosis; U.Symb=urban symbiosis; EIP=eco-industrial park; CE=circular economy.

2.3.2 Categorizing the indicators

Similar to the trend described regarding the publications, most indicators are used within the context of industrial symbiosis, followed by EIP. The lowest number of indicators is used (i.e. occurring) within the context of urban symbiosis and the meso level of CE.

The indicators have been organized into five categories and are summarized in Figure 2.5. The categorization has been done based on the scoping review findings. When an indicator relates to more than one category, this indicator is added to each of the categories. The distribution of the indicators within the categories *symbiosis and sharing* and *energy* is relatively equal, with 127 and 125 indicators, respectively. In the category *other,* there are, however, merely 70 indicators present. With 252 indicators, the largest category is *material, waste and water*, followed by *environment and emissions* with 174 indicators.

When analyzing the change over time, especially the category *material, waste and water* has a trend with large spikes. In the years 2017 and 2021, the use rate is notably higher than that of indicators related to *environment and emissions*, even though the overall time trends of these two categories look similar. For the category *symbiosis and sharing,* it can be noted that a steep decline is visible in the year 2018, followed by steady increase. Interestingly, this trend is not present in other categories.

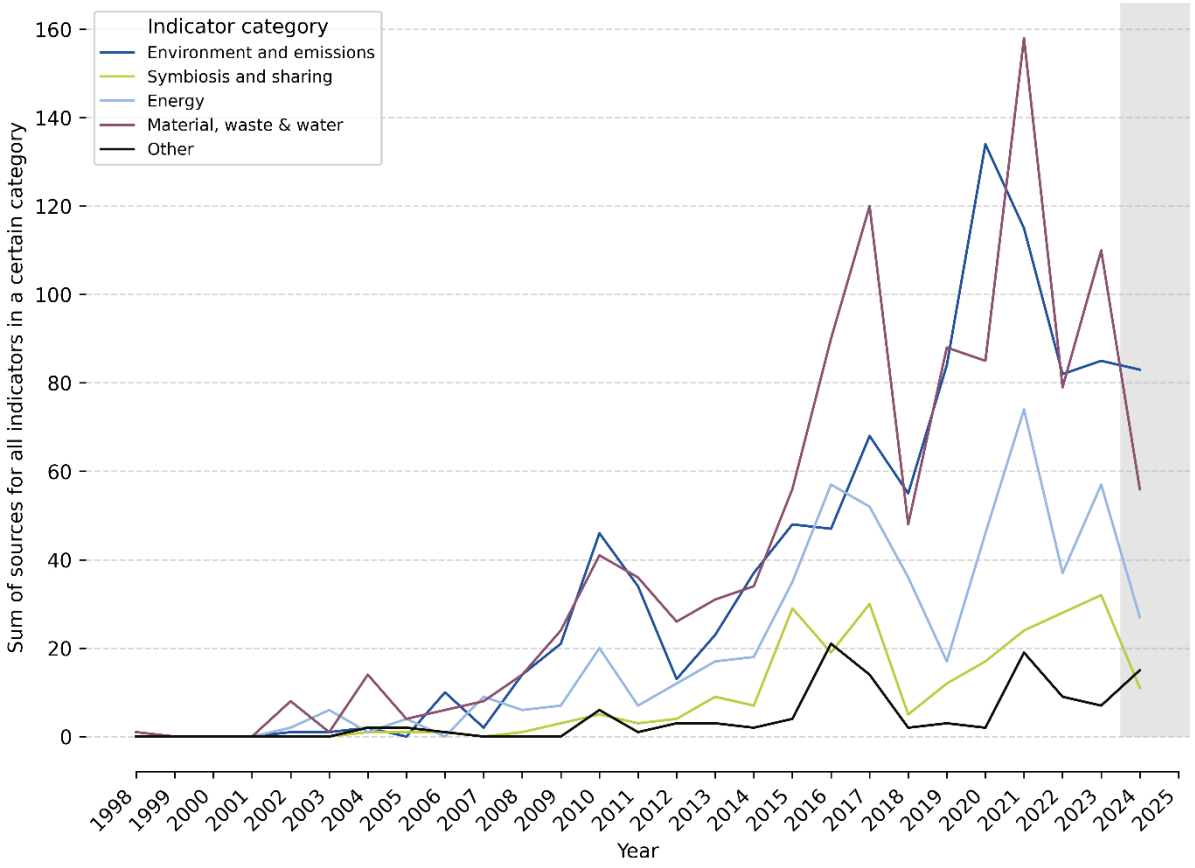


Figure 2.5: Line plot of the time trends for indicator uses (i.e. the sum of sources for all indicators) across the different categories. The gray bar on the right indicates the future, meaning that the uses in these years are subject to change.

When analyzing the relative use rates, indicators in the categories *environment and emissions*, *material, waste and water* and *energy* have in comparison to the other categories higher relative use rate compared to the mean unweighted use rate. Another interesting example is the comparison of average use rates between *energy* and *material, waste and water*, which have almost equal unweighted use rates and combined weighted use rates. However, zooming in on the aspects the combined relative use rate is built from, i.e. the relative indicator and relative source use rates, clear differences are visible: *energy* has a

higher novelty bonus (larger increase for relative indicator use rate) of almost 80 %, whereas *material, waste and water* gains the high increase in combined relative use rate especially from a high consensus in indicator use (lower decrease in relative source use rate). Besides *energy* and *material, waste and water*, only *environment and emissions* has a strong increase when comparing the unweighted use rate with the combined relative use rate, which also largely stems from consensus on which indicators to use within that area. Both *symbiosis and sharing* and *other* have merely small increases, indicating that the novelty-dissemination trade-off is relatively balanced. An overview of all use rates per category, including the percentage change compared with the unweighted use rate, is given in Table 2.4. Moreover, these findings are visualized in Figure 2.6. Besides the strong increased combined relative use rate of *environment and emissions*, *energy*, and *material, waste and water*, these results also indicate the high variation of use rates and the median (relative) use rate being around 1 for nearly all categories. *Symbiosis and sharing* shows relatively more condensed use rates, with maximum (unweighted) use rates around 20.

Table 2.4: Table of the average unweighted use rate (frequency of utilization of indicators) and relative use rates per category.

Category	Average use rate	Indicator average relative use rate	Percentage change with unweighted use rate	Source relative average use rate	Percentage change with unweighted use rate	Combined relative average use rate	Percentage change with unweighted use rate
Environment and emissions	5.8	9.9	72 %	3.9	-32 %	6.9	20 %
Symbiosis and synergies	1.9	3.4	80 %	0.47	-76 %	1.9	2.0 %
Energy	4.4	7.9	80 %	2.1	-51 %	5.0	14 %
Material, waste and water	4.5	7.2	60 %	3.1	-31 %	5.2	15 %
Other	1.7	3.2	89 %	0.29	-83 %	1.7	3.0 %

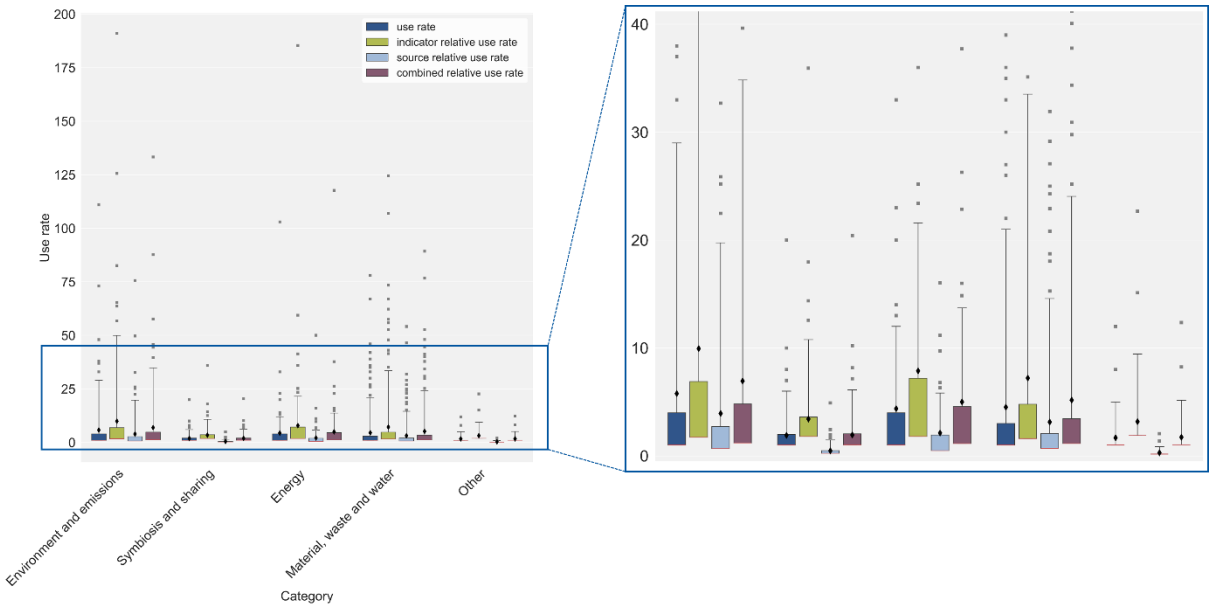


Figure 2.6: Boxplot of the unweighted use rate and relative use rates for indicators in each of the respective categories. The whiskers are set to contain 95 % of the items. The remaining outliers are indicated by the gray squares and median values are indicated by red lines. Means are indicated by black diamonds. The left figure contains all data points; the right figure contains all data points with a use rate between 1 and 40.

When analyzing the subset of so-called multicategory indicators, indicators from the category *symbiosis and sharing* have also been assigned to one or more additional categories, of which most often to *material, waste and water* with 50 co-occurrences. This co-occurring is to be expected because the category *symbiosis and sharing* includes non-material exchanges but also material exchanges which are part of the above-mentioned co-occurring categories. Indicators of the category *material, waste and water* also often co-occurs with the category *environment and emissions* with 20 cases. These cases mostly cover environmental benefits or environmental impacts resulting from the processing of material, waste or water. Additionally, *energy* indicators being placed in the *symbiosis and sharing* as well as *environment and emissions* category (14 indicators each) also occur frequently. Co-occurrences for the categories *energy* and *symbiosis and sharing* are for example indicators relating to an exchange of energy. Indicators relating *energy* together with *environment and emissions*, cover for example environmental impacts resulting from the processing of different energy-types. An overview of the number of indicators co-occurring in the different categories can be found in Table 2.5.

Table 2.5: Overview of the number of (multicategory) indicators co-occurring across the different categories.

Category combinations	Number of co-occurrences
Symbiosis and sharing – Material, waste and water	50
Environment and emissions – Material, waste and water	20
Symbiosis and sharing – Energy	14
Environment and emissions – Energy	14
Material, waste and water – Energy	8
Environment and emissions – Symbiosis and Sharing	6
Material, waste and water – Energy – Symbiosis and sharing	3
Environment and emissions – Symbiosis and sharing – Energy	2
Environment and emissions – Material, waste and water – Symbiosis and sharing	1

2.3.3 Frequency of indicator use

Looking at the independent indicators and their uses, few indicators have more than 20 uses, but nonetheless, nearly 18 % of the indicators (i.e. 114 indicators) are used more than four times and are therefore present in at least 1 % of the total body of works. Furthermore, as can be seen in Table 2.6, the most frequently used indicators all relate to multi-context applications. Most of these application areas regard industrial symbiosis, EIP and urban symbiosis. The indicators *terrestrial acidification (potential)* and *byproduct produced* are the first, most-frequently used indicators being applied to merely one context (i.e. industrial symbiosis) with 11 uses each. Relating to the most used indicators with the categories, *environment and emissions* and *energy* prevails in the most-frequently used indicators.

Table 2.6: Table of the five most-frequently used indicators with corresponding application areas and uses.

Indicator	Context	Uses	Category
CO_2 (equivalent) / carbon (emissions/intensity) (reduction/saving)	I.Symb+U.Symb+EIP+ CE-meso	111	Environment and emissions
Energy/power consumption/demand/use (reduction/save/avoided/conservation)	I.Symb+U.Symb+EIP	103	Energy
Waste generated/produced/emission (intensity/reduction/diversion/saving/mitigation)	I.Symb+U.Symb+EIP	78	Material, waste, water
Global warming (potential) / climate change (reduction)	I.Symb+U.Symb+EIP	73	Environment and emissions
Water/wastewater/freshwater/groundwater use/demand/consumption (reduction/saving/conservation)	I.Symb+U.Symb+EIP	67	Material, waste, water

I.Symb=industrial symbiosis; U.Symb=urban symbiosis; EIP=eco-industrial park; CE=circular economy

Within *symbiosis and sharing*, the two most-frequently used indicators both regard exchange and use of waste as a resource, whereas the following three most-frequently used indicators regard immaterial (e.g., knowledge) and unspecified resource exchange. The top indicators in the *energy* category on the other hand focus primarily on energy consumption or consumption of factors producing energy, with a smaller focus on (renewable) energy production. In the category, *material, waste and water*, indicators regarding masses or (mass) percentages of (non-)renewable materials, waste treatment facilities, reuse potentials and efficiencies are most prominent. Lastly, *other*, embeds (eco-)efficiency, cyclicity, green building and (eco-)design as the most frequent measurement areas of the respective indicators. For all categories, the five most-frequently used indicators per category are predominantly quantitative as shown in Table 2.7. Interestingly, the ten most-used indicators all relate to the R-strategy Reduce, with the exception of the indicator *water/wastewater/freshwater/groundwater use/demand/consumption (reduction/saving/conservation)*, which relates to the R-strategies Reuse and Recycle.

Table 2.7: Overview of the five most-frequently used indicators in each category with corresponding measurement data in the form of qualitative, quantitative or both (type) and uses.

Indicator	Type	Uses
Environment and emissions		
CO_2 (equivalent) / carbon (emissions/intensity) (reduction/saving)	Both	111
Global warming (potential) / climate change (reduction)	Both	73
Greenhouse gas (CH_4/N_2O) (emissions) reduction/mitigation/saving/offset/removal	Quantitative	48
Acidification (potential) (reduction)	Quantitative	38
Land use/occupation/area/conversion/change/transformation (intensity/rate/saved)	Quantitative	38
Symbiosis and sharing		
(Centralized) Waste/sewage/wastewater treatment facilities/plants/system (rate/concentration)	Both	20
Waste/residuals exchanged (symbiotic)	Quantitative	10
Information/knowledge sharing networks/platform (completeness)	Both	8
(Symbiotic) Synergy/cooperation (creation)	Both	7
Resource exchange (unspecified)	Both	7
Energy resource exchange (potential) (energy, heat, steam)	Quantitative	7
Energy		
Energy/power consumption/demand/use (reduction/save/avoided/conservation)	Quantitative	103
Fuel/biofuel consumption/demand/flow/use (reduction/intensity/efficiency)	Both	33
Electricity (consumption/demand) (density/intensity/saving/conservation)	Quantitative	23
(Local) Renewable energy/emergy use ratio/share/produced/renewability	Both	20
Energy (saving) efficiency	Both	14
Material, waste and water		
Waste generated/produced/emission (intensity/reduction/diversion/saving/mitigation)	Both	78
Water/wastewater/freshwater/groundwater use/demand/consumption (reduction/saving/conservation)	Quantitative	67
(Raw/virgin) Material consumption/use/output/type/demand (saved/avoided/reduced)	Both	46
Waste (dangerous/hazardous) to landfill/disposal (rate/diversion/saving/reduction)	Both	42
Water/wastewater recycling/regeneration/reclaim/treatment/reuse (rate/efficiency)	Quantitative	39
Other		
Eco-Efficiency	Quantitative	12
Efficiency (current, highest achievable, production, sorting, utilization, technical, area, entrepreneurs managing green logistics)	Quantitative	8
Cyclicity	Quantitative	5
(Product) Eco-design / design for environment	Qualitative	5
Green building / sustainable architecture design (ratio)	Quantitative	5

2.3.4 Assignment to R-strategies

Most indicators that could be assigned to one or more R-strategies relate to Rethink (166 indicators) and Reduce (144 indicators), of which most occurrences of Rethink happen in the category *symbiosis and sharing* (112). For Reduce, the most popular category is *material, waste and water* (49 occurrences) but Reduce is also frequent in the categories *environment and emissions* (48 occurrences) and *energy* (37 occurrences). However, even though the R-strategy Rethink is most often linked to the different indicators, Reduce has higher overall uses. That is, there are 1361 uses of an indicator assigned to Reduce, whereas this number equals 335 for Rethink. It must be noted that the sum of uses within the sources can exceed the maximum number of sources because of multiple assignments to R-strategies.

It is nonetheless important to note that many indicators could not be assigned to any of the R-strategies. This accounts for nearly 53 % (328 indicators) of the indicators. Most of these indicators are categorized under *environment and emissions* (119 indicators) and *material, waste and water* (117 indicators). These numbers have been taken into account in the analysis and are also visible in Figure 2.7, where an overview of the co-occurrences of the different categories and R-strategies is presented. Additionally, some CE-meso indicators in the category *other* are presumed to be connected to all R-strategies, but their actual assignment to R-strategies depends on the specific context in which it will be applied.

Figure 2.8 visualizes the yearly time trends for each R-strategy in terms of number of indicators. The number of indicators not being assigned to any of the R-strategies shows a similar trend over the years compared to the number of indicators being assigned to Reduce. All other R-strategies are relatively clustered, showing comparable trends of slow growth in the last decade. Interestingly, in 2018 all R-strategies have a strong decrease.

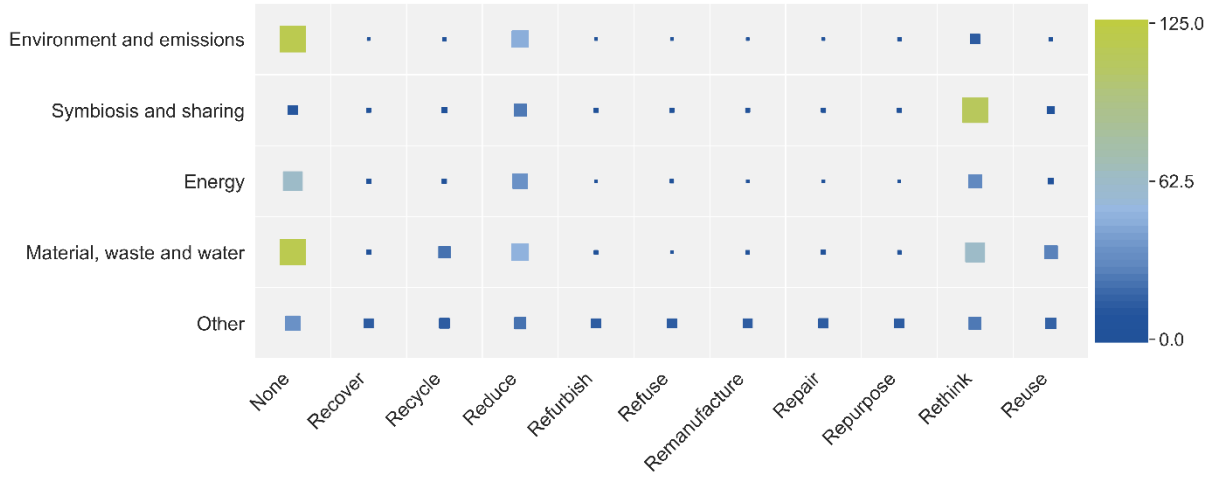


Figure 2.7: Heat map of the number of times indicators are linked to the respective R-strategies across the different categories. Green and large squares indicate high co-occurrence, whereas small and dark blue squares indicate low co-occurrence.

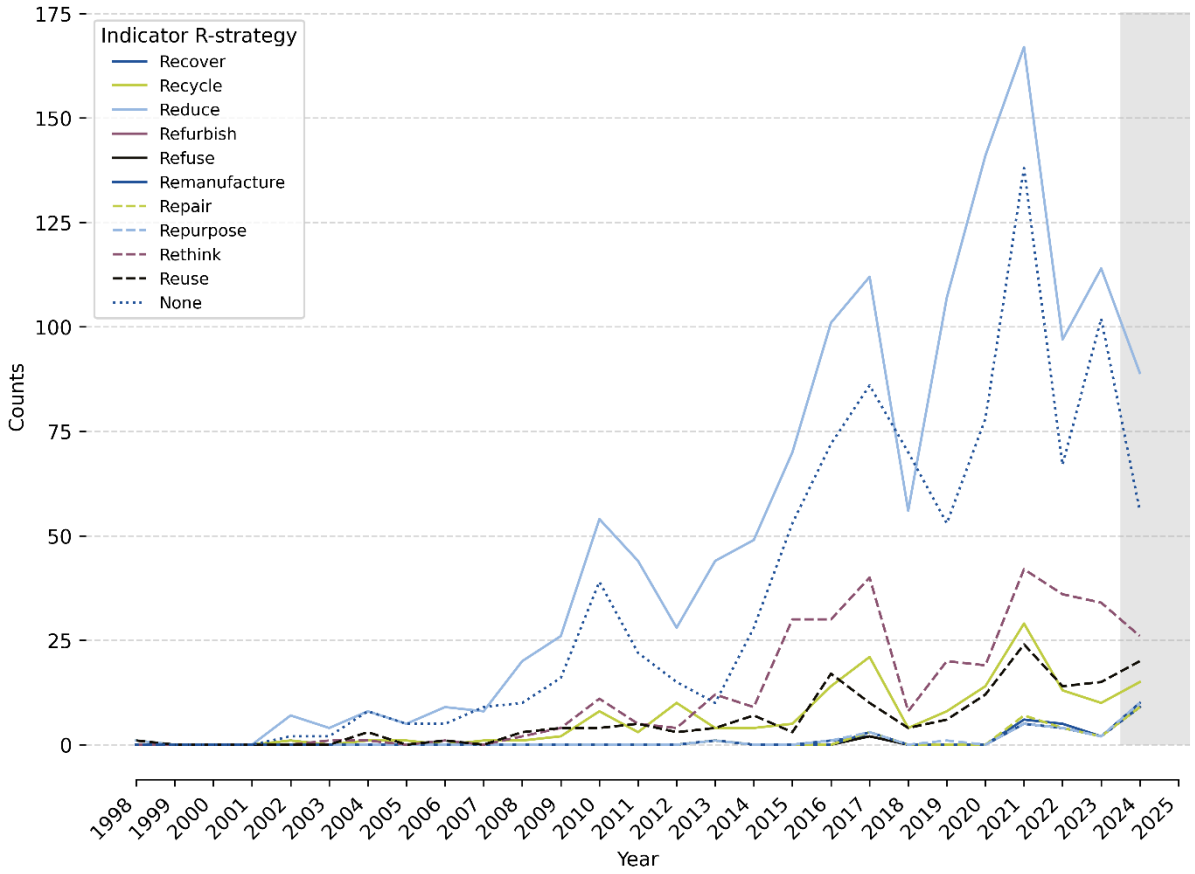


Figure 2.8: Line plot of the time trends for indicator uses across the different R-strategies. The gray bar on the right indicates the future, meaning that the numbers in these years are subject to change.

When comparing the number of indicators linked to the respective R-strategies with the indicator use rates across the different R-strategies, as seen as in Table 2.8, additional insights are visible. For example, Reduce is the R-strategy with the highest use rate but only the third most assigned R-strategy for the indicators. Additionally, most indicators are relating to no R-strategy, followed by Rethink and Reduce. This is also reflected in Reduce having a ratio of indicator uses per indicator of 9.45 compared to None with a rate of 2.87 and Rethink of 2.02.

Table 2.8: Overview of the total number of uses in sources (non-unique), number of indicators and use rate per indicator across the different R-strategies.

	None	Recover	Recycle	Repurpose	Remanufacture	Refurbish	Repair	Reuse	Reduce	Rethink	Refuse
Sum of uses in sources	942	28	170	27	24	24	26	160	1361	335	23
Indicators count	328	19	43	18	17	17	19	50	144	166	16
Use rate per indicator	2.87	1.47	3.95	1.50	1.41	1.41	1.37	3.20	9.45	2.02	1.44

2.4 Discussion

By identifying 618 comprehensive indicators and describing a multifaceted analysis on different trends embedded in this collection, nearly three times as many indicators and more than three times the number of environmental indicators could be presented compared to the already elaborated work by Valenzuela-Venegas et al. (2016) in 2016. Most of the 457 publications at the basis of the results presented in this work have been published in the last decade, adhering to the trend of increased publicity of environmental aspects in the context of industry and industrial cooperation (Mallawaarachchi et al. 2020).

Applicability and generalizability of indicators

Interestingly, contrary to the identified source publications, most indicators are used in multiple contexts, indicating that a large share of indicators is generalizable and applicable to multiple focus areas. This is especially the case for urban symbiosis indicators, which are often also used in the context of industrial symbiosis and EIP. As indicators applied to urban symbiosis are occasional and have relatively low use rates, it is recommended to supplement these indicators with indicators that have high adaptability from other application areas. For example, industrial symbiosis- or EIP-related indicators could be used when assessing environmental aspects of urban symbiosis, to enhance comparability and generalizability of the results. Emissions such as SO_2, *nitrogen* and *wastewater* as an example are not used in the context of urban symbiosis yet but could also provide further insight into these symbioses. Also, EIP applications could be extended with industrial symbiosis indicators such as *byproduct produced*, *terrestrial acidification (potential)* or *primary energy (demand)* as well as other indicators.

Relation between industrial symbiosis and CE concepts such as R-strategies

While EIPs and industrial symbiosis are seen as part of CE, differences between the concepts and aims exist. This should also be considered when searching for or applying indicators in each field. The main difference between the concepts of industrial symbiosis and CE is the involvement of traditionally separate entities (Neves et al. 2020). A combined example which relates industrial symbiosis as well as a CE is the EIP in Kalundborg in which industrial symbiosis is applied through various industries involving around a power plant (Chertow 2000). The industrial symbiosis involves waste heat and steam of the power plant which is used in local industries, for example in a refinery and pharmaceutical site (Chertow 2000). Additionally, byproducts such as scrubber sludges are used for gypsum wallboard production (Chertow 2000). Therefore, the R-strategies Reuse and Recycle are realized. If waste heat of the power plant is used in district heat for urban buildings, an urban symbiosis is established. In contrast, an example of CE which is not part of industrial symbiosis or urban symbiosis is manufacturers take back of products to realize the R-Strategies reuse, repair or recycle (Uhrenholt et al. 2022). Additionally, industrial symbiosis focuses on technical processes and systems and their end-of-life aspects in a limited geographic area, whereas CE covers societal impacts as well as addresses pre-use and use-phase aspects including a global level (Angioletti et al. 2017; Parida et al. 2019; Mallawaarachchi et al. 2020; Cagno et al. 2023; Kirchherr et al. 2023).

The results from the quantitative evaluation of the R-strategies of the indicators show that the statement by Kristensen and Mosgaard (2020), Superti et al. (2021) and Syu et al. (2022), that there is a lack of coverage when it comes to indicators related to Refuse, Rethink and Reuse, seems to be partially invalid. That is, indicators are most often connected to Rethink, especially within the category *symbiosis and sharing*. Moreover, Reuse is one of the three most-widely applied strategies. The strategies Recover, Refurbish, Remanufacture, Repair and Repurpose are, however, barely present. This is partly in line with industrial symbiosis cases focusing on Reuse, Recycle and Reduce and – with the exception of Rethink – lack of coverage for the remaining R-strategies (Ramírez-Rodríguez et al. 2024). In the scoping review focusing on R-strategies of electronic waste (Hunger et al. 2024), Recycle, Repair, and Reuse were identified as the most dominant R-strategies, which aligns with our findings, except for Repair. This may be a consequence of the applied scope in our work, which mostly excludes products still being in their use phase. So, our results indicate that, of the high-circularity R-strategies, only Refuse lacks sufficient coverage and that indicators linked to lower-impact strategy only Recycle is abundant.

Quantitative vs qualitative indicators

Even though there are qualitative indicators, the statement by Domenech et al. (2019), that there is a lack of quantitative indicators to assess industrial symbiosis activity cannot be verified with the results acquired, as nearly all frequently-used indicators regard quantitative measurements or a combination of both. Additionally, quantitative-only indicators encompass the largest share of indicators. This is also the case for indicators focusing on industrial symbiosis such as *(centralized) waste/sewage/wastewater treatment facilities/plants/system (rate/concentration)* with 20 uses and *waste/residuals exchanged (symbiotic)* with 10 uses where both are quantitative expressible. Nevertheless, the indicators focusing on industrial symbiosis are not the most used ones but rather the resulting effects are the focus of evaluation.

Yet, it is apparent that not all identified indicators were actually used in calculations in the source publications and therefore resulting values useful for assessment are sometimes lacking, which tends to verify the statements of Neves et al. (2020) and Wadström et al. (2021). As such, increased use of quantitative indicators in assessment models and calculations within case studies could be a way to address this gap.

Within the category *symbiosis and sharing,* generally, qualitative indicators are connected to non-product resource sharing and the Rethink strategy. Yet, the share of non-product resource sharing is, with 12 indicators, low. Examples are *knowledge sharing (networks)* with eight uses and *infrastructure or technology sharing* with four uses. This supports the statement made by Wadström et al. (2021).

Implication of the indicator categories

The steepest increase in indicator use rates can be identified for the categories *material, waste and water* and *environment and emissions*. Together with *energy*, indicators in these categories have higher relative use rates. As the aforementioned three categories are also the three biggest categories in terms of number of unique sources, it can be

stated that these categories are currently most popular when it comes to assessing environmental aspects of industrial and urban symbiosis. *Material, waste and water* being the category with the most indicators is in line with physical material being the most studied synergy (Wadström et al. 2021). The topics *environment and emissions*, *symbiosis and sharing* as well as *energy* have less diverse indicators than *material, waste and water* but have similar indicator use rates. It should however be noted that this categorization – albeit based on existing research and the acquired results – is subjective, and hence, a different categorization could yield different results and insights. Our evaluation was based on self-defined categories which were iteratively defined to have as few categories as possible with as few overlapping indicators as possible. Yet, the definition of the categories has a big impact on the evaluation. For example, the categories could be divided into more subcategories, especially for the category *material, waste and water* to have further evaluation aspects. When defining materials, waste, and water as individual categories, the focus of each aspect could be evaluated individually and compared to the other categories and therefore evaluate the possible importance of each category. Also, the category *symbiosis and sharing* in the current assignment has a relatively high share of co-occurrences with other categories. Another categorization procedure could address this and try to differentiate this category from the other categories in a stronger way. Further research could focus on the investigation of the most suitable depth- and specificity-level when categorizing indicators for the purpose of developing a holistic basis for symbiosis assessment frameworks. For instance, it may be advantageous to apply a higher level of specificity to the indicators currently categorized as *other,* such as *CE*.

Harris et al. (2021) found that LCA is the most commonly used environmental assessment method, supported by a high number of LCA indicators and a significant average usage rate in the literature. For example, GWP ranks among the five most used indicators, while land use and acidification potential are ranked 10th and 11th, respectively. However, the assertion of Harris et al. (2021), that material exchanges at the industrial park level are lacking could not be verified, as the categories of material, waste, and water contain the highest number of indicators with various options available in this field.

Limitations and considerations

Limitations include the ever-present problem of identifying all available indicators through evaluation aspects as criteria in the search string, which may overlook literature using different terminology or does not mention evaluation at all in abstracts. Therefore, more and other indicators could be identified, which influences the results and could also influence the category definition. Even though gray literature could enhance indicator diversity, a more targeted focus on scientific sources may be advantageous for researchers. Future research should consider expanding database searches and reducing exclusion criteria, also for title and abstract, to uncover more relevant insights.

Additionally, the method of clustering the indicators could be adapted to yield other results. For example, the optional aspects of indicators such as the aspect of reduction of the indicator *global warming (potential) / climate change (reduction)* could be disaggregated. This could yield even further information and other insights, though the number of

indicators would increase. Because one main goal of this paper is to give a comprehensive overview of possible indicators, a rather compact overview was favored above a more detailed approach. This also has the consequence of limitations in clearly describing the specific definitions of the indicators besides the existing limitations due to failing descriptions in publications. However, by providing detailed descriptions of the implemented procedure, we aim to provide full transparency and hence reproducibility, so that the presented overview can be compared with different approaches in future research. So, for future work, it would be interesting to de-cluster the provided overview and add more detailed definitions, so that indicators can be used in a more systematic and objective way.

The definition of categories could be changed to yield significant different results. Even though 89 % of the indicators could be assigned to the four self-defined categories, a revision of the categories could improve the handling of the indicators. Including evaluating aspects of industrial symbiosis, such as exchange methods, reasons for failure, and geographical distribution of indicator use, will enhance understanding of trends in CE applications. Additionally, identifying relevant case studies will further advance our findings. Moreover, engaging stakeholders can help verify and rank indicators or categories by importance, while industry knowledge can refine relevant considerations.

With the identified indicators it has been shown that around 40 % of the indicators have been used by more than one source, showing that a fair share of indicators is not just relevant for an individual case. However, still more than 60 % of the indicators were used merely once, indicating that research and applications regarding environmental assessments in the context of industrial and urban symbiosis are still highly disseminated. This not only shows the importance of efficient knowledge dissemination – for instance by providing exhaustive overviews and developing a holistic industrial and urban symbiosis assessment framework – but also supports the research gap described by Valenzuela-Venegas et al. (2016) which states the lack of knowledge about existence, use rates and time trends of indicators.

Multidisciplinarity & scope extension

Among other things the results describing the multidisciplinarity of the identified indicators show that most indicators measuring an aspect of the meso level of CE are already embedded in other application contexts. This illustrates that in itself, the scope extension has limited effect. However, the indicators that would have been excluded, in the case the aspect CE-meso was not included as an application context, cover a different part of assessment frameworks. That is, these indicators mostly regard qualitative- and quantitative-only indicators of cyclicity, which is an essential aspect of assessing environmentality of industrial or urban symbiosis on a meso level, as these indicators possibly cover all R-strategies and steps of pre-use, use- and post-use phases of products. Therefore, these indicators could shift the current findings when interpreted in another way. Future research could focus on these indicators to explicitly assign relevant R-strategies depending on the context of existing case studies.

Applications and practical implications

With the help of the conducted scoping review, the defined research question and aims could be addressed. Through the indicator overview, a comprehensive overview of currently used indicators regarding the environmental evaluation of industrial symbiosis has been established. By subdividing these indicators into different sets of categories and supplementing these data with the number of occurrences in the analyzed body of works, a starting point for the development of a holistic guideline for selecting indicators to assess environmental aspects of industrial and urban symbiosis is provided. Users such as companies, industrial park operators and urban administrators could for instance better determine relevant aspects of industrial symbiosis during the search and application process of suitable indicators, due to clear indications of relevant categories and aspects in which certain (sets of) indicators can be found depending on the purpose of the assessment. For example, if the focus is on evaluating symbiotic performance, indicators in the category *symbiosis and sharing* can be considered. A possible application is the evaluation of a current or future industrial park for identifying the most fitting companies to settle in, which assessment can for instance be conducted by an urban administrator or industrial park operator. Additionally, a company seeking to identify evaluation possibilities for a planned symbiosis with another company can use the indicator overview as a basis for consideration. The resulting effects could then be evaluated with the help of one of the categories such as *environment and emissions*. If a user aims to evaluate CE at the meso level, the limited available CE indicators indicate that expanding the scope to include industrial symbiosis or EIP is crucial for a broader perspective on the topic, with our indicator overview serving as a starting point. Additionally, if industrial park planners, such as municipalities, aim to establish a new (eco-) industrial park, the indicators in the categories of symbiosis and sharing can serve as a foundation for selecting appropriate evaluation methods. They can also raise awareness of key topics to enhance the industrial park's development into an EIP that facilitates industrial or urban symbiosis.

Additionally, users can also focus on most used indicators to ease comparison between other industrial parks with indicators relating frequently used topics such CO_2 emissions, energy consumption or waste generation. Companies, for example, can measure their own performance and compare it with literature values to possibly reveal further optimization potential. If further aspects of the indicators such as the way of calculation or benchmark values are necessary, the indicator overview in the Supplementary materials names each source to provide a direct link to primary sources.

If one wants to address one of the R-strategies directly, the given overview is a starting point to identify possibilities to measure these. Yet, gaps for some R-strategies could be identified which have to be addressed by future research to comprehensively address all R-strategies with industrial symbiosis. Additionally, the topic of urban symbiosis can be investigated with more detail in future work, as our overview provides the possibility to more efficiently identify indicators for potential use in the urban (symbiosis) context.

2.5 Conclusions

In this work, indicators regarding environmental evaluation of industrial and urban symbiosis have been systematically identified to provide a holistic categorization, fitting current CE frameworks. Clustering the identified 3349 indicators has resulted in an exhaustive, tabular overview of 624 different indicators used by 457 unique sources published between 1997 and 2024 which is shown in Indicator overview. Most of these indicators have been used in the last decade and in multiple application contexts. Where indicators measuring environmental and emission-related factors, together with material, waste and water, are most popular, indicators focusing on symbiosis are lagging behind. Therefore, the indicators measure the effects of symbiosis rather than symbiosis itself. Few of the identified indicators are connected to the R-strategies Refuse, Recover, Refurbish, Remanufacture, Repair and Repurpose. As such, further research regarding the importance and measurement methods of these strategies within the context of environmental assessment of industrial and urban symbiosis is required. To advance this research, this scoping review can be used as a basis in several ways.

Future research should focus on refining current indicators and verifying R-strategy assignments. Revising these strategies to distinguish between primary and secondary approaches, along with clarifying their calculations, can address gaps in background information for CE-indicators. Additionally, exploring and expanding the Refuse strategy is essential to cover this high-circularity area. Nonetheless, our findings provide a comprehensive overview for measuring environmental aspects within industrial and urban symbiosis. However, future studies should assess the usefulness and impact of indicators used alone or collectively to standardize their application, an essential step toward developing a holistic assessment framework.

This overview serves as a solid foundation for creating an assessment framework that incorporates all identified categories for comprehensive evaluation. Generalizable frameworks must be developed through collaboration between industry experts and academia to address diverse application areas effectively. Concrete frameworks could emerge from this overview, enabling companies or urban administrations to evaluate their symbiosis performance or evaluate site selections for new industrial parks. Emphasizing widely used indicators, like carbon emissions or energy consumption, will facilitate systematic comparisons with existing evaluations. When quantitative data is unavailable, qualitative indicators should be considered to enable users to apply both evaluation types effectively. Therefore, the indicator overview streamlines the selection process by providing time-efficient options that include various information about each indicator's application area and R-strategy assignment. It also establishes a basis for researchers to fill existing gaps and enhance evaluation possibilities.

To conclude, our work has the following application and practical implications:

- Companies can benchmark performance against literature values using widely applied metrics like CO_2 emissions or waste generation.

- Industrial park operators and urban administrators can select relevant categories based on their objectives, for instance evaluating potential tenants via symbiosis and sharing aspects and indicators.
- Municipalities planning new parks may leverage these categories when designing EIPs that foster synergies.
- Researchers can identify existing gaps requiring further investigation and seek targeted extension of less covered R-strategies

3 Publication II: Methodological approach to identify improvements through actions and scenarios

Verkic, Benedikt; Schröder, Elina; Drees, Kornelia; Dosch, Klaus; Buschbeck, Christian; Greiff, Kathrin (2025): Evaluation approach to assess actions and scenarios for improving climate and resource efficiency of municipalities and companies in industrial parks. In *Journal of environmental management* 398, p. 128442. https://doi.org/10.1016/j.jenvman.2025.128442

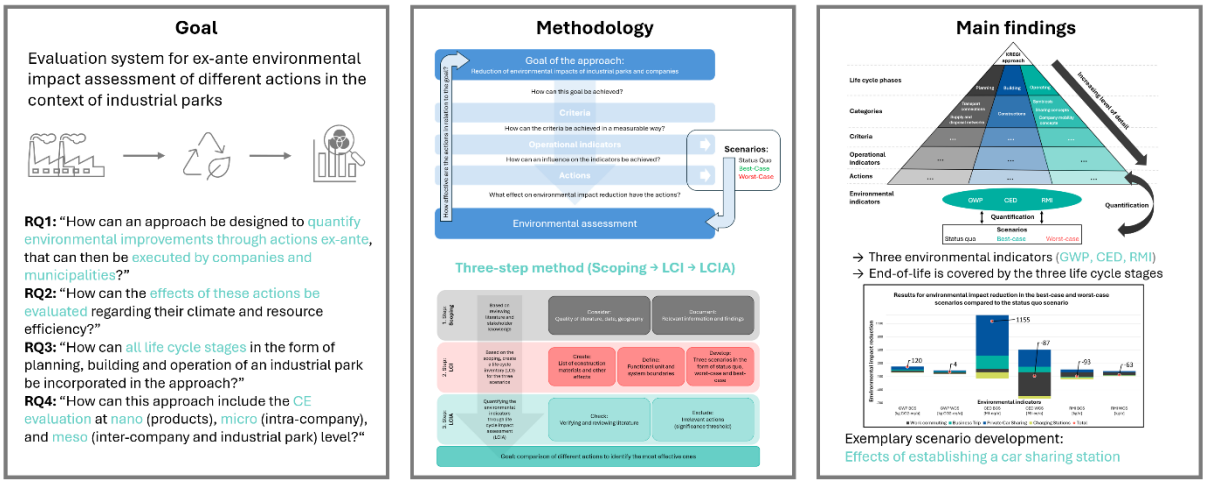


Figure 3.1: Graphical abstract of Publication II.

*This section is a reprint of **Verkic et al. (2025b)**. The content is reproduced "as is" with the exception of formatting changes.*

This chapter summarizes Publication II, which addresses RQ2 by developing the KREGI action- and scenario-based evaluation approach for ex-ante assessment of actions in industrial parks and companies, grounded in prospective LCA with future scenarios. In doing so, it builds on the indicator base established in Chapter 2 and specifies the quantification procedure, illustrated in detail with one exemplary action (car sharing). Publication II therefore delivers the reusable KREGI quantification workflow (action requirements, operative indicators, and status-quo/best-/worst-case logic), but it does not yet constitute a full quantified action library. Publication III subsequently applies this KREGI workflow to quantify a broader set of generic and case-specific actions (15 + 5) that together form the pre-quantified action library used by the DST scoring and ranking layer in Chapter 4.

The KREGI approach is structured along the life cycle of an industrial park (planning, building and operation), with end-of-life aspects embedded in all phases, and links these phases to CE levels. It follows a clear chain from goals to interventions: criteria capture the overarching objective of reducing environmental impacts; operational indicators measure whether these criteria are met; and actions are defined as targeted interventions that influence the indicators. Actions are defined and must satisfy requirements such as innovation beyond the status quo, unambiguous definition, measurable environmental effect, significance and relevance in the current planning horizon. Quantification follows

a three-step procedure based on literature-based scoping, construction of LCI and LCIA for GWP, CED and raw material input (RMI). In the cumulative thesis logic, Publication III applies the same environmental indicators but extends it based on Publication I by adding LU and WU.

Each action is evaluated under status-quo, best-case and worst-case scenarios to capture uncertainty and contextual variation. A detailed case study on introducing a car-sharing station illustrates how changes in mobility behavior can be translated into environmental impacts and how potential trade-offs between indicators can be identified. In this way, the KREGI approach provides a structured, comparable and ex-ante method for evaluating and contrasting different actions across industrial-park life-cycle phases. Crucially for the cumulative thesis logic, the scenario-based action effects produced by the KREGI workflow form the standardized quantitative input for Publication III, where this logic is reused to build the low-effort scoring and ranking layer of the DST without requiring case-by-case LCI model building by end users.

Abstract

To stay within planetary boundaries, it is essential to reduce environmental emissions from industrial activities commonly found in industrial parks. This study addresses the issue by developing an integrated approach that comprehensively evaluates industry-related environmental impacts. The approach encompasses the planning, building, and operating phases of an industrial park to support decision-making for municipalities and companies across the nano, micro, and meso levels of the circular economy. The aim is to suggest a methodological approach as a basis to assist municipalities to efficiently evaluate industrial park site selection and identify effective actions for companies seeking to establish climate- and resource efficient eco-industrial parks. Our climate and resource protection in commercial and industrial areas (KREGI) approach includes criteria for reducing environmental impacts, operational indicators for compliance with these criteria, and actions to achieve them. The potential for reducing environmental impacts is quantified by three key indicators: global warming potential, cumulative energy demand, and raw material input. This Quantification follows a three-step system comprising literature review, self-conducted life cycle assessments, and stakeholder involvement. The results illustrate potential benefits from proposed actions by providing three scenarios in the form of status quo, best-case and worst-case. This approach is demonstrated through a case study quantifying the establishment of a car sharing station as one possible action. The example achieves environmental benefits under specific conditions, though not all environmental indicators show universal improvements. By comparing these results with other actions, the most beneficial ones can be identified for effective execution considering each environmental indicator.

3.1 Introduction

Evidence shows that some planetary boundaries have already been surpassed due to human influence, with climate change being one such boundary driven by greenhouse gas and aerosol emissions (Rockström et al. 2024; Sakschewski et al. 2025). Resource use has also exceeded sustainable levels, particularly in high-income countries, and is expected to increase further (UN Environment 2019; Hickel et al. 2022). In addition to the objective of mitigating climate change, it is essential to reduce material use and energy consumption to enhance efficiency through principles of consistency and sufficiency (Milford et al. 2013; Harpprecht et al. 2024; Rudolf and Schmidt 2025). Greenhouse gas emissions and resource consumption are linked to industrial activities (World Bank 2021). Approximately 10 billion tons of carbon dioxide equivalent are emitted by industrial processes in 2022, representing around 28 % of global annual emissions (International Energy Agency 2023; Liu et al. 2023). Additionally, resource use and greenhouse gas emissions relate with energy consumption (Harris et al. 2020).

3.1.1 Concepts of industrial symbiosis & circular economy

Industrial symbiosis is a concept that aims for mutual benefits through exchanges between traditionally separate entities in close proximity (Chertow 2000; Mallawaarachchi et al. 2020). Eco-industrial parks (EIP) provide a practical way to implement industrial ecology for multiple companies (Roberts 2004; Gibbs and Deutz 2007) and facilitate

industrial symbiosis (Scafà et al. 2018; Yu et al. 2023). EIPs also help reduce the environmental impact of industrial parks and companies through collaboration (President's Council on Sustainable Development 1996; Lowe 2001; European Commission 2018, 2020b; Perrucci et al. 2022). In practice, both concepts aim to minimize environmental impacts by reducing waste, utilizing by-products, and fostering sharing among companies (Chertow 2000; Lombardi and Laybourn 2012; Felicio et al. 2016; Mallawaarachchi et al. 2020).

Also, the topic of circular economy (CE) is related to industrial symbiosis and EIP. CE at the meso level is considered as application of these concepts (Kalmykova et al. 2018; Kuzma et al. 2022; Kirchherr et al. 2023). The European Union (European Commission 2020b) and other publications (Daddi et al. 2017; Rincón-Moreno et al. 2020; Yu et al. 2021b) identified industrial symbiosis as possibility to improve CE. Although the focus of companies is at the micro level, it is considered important to extend performance measurement to the meso level (Kristensen and Mosgaard 2020; Cagno et al. 2023). The micro level of CE can be defined as encompassing companies and products (Kristensen and Mosgaard 2020). Alternative definitions interpret company-wide perspectives as micro-level CE, while product-specific as nano level (Saidani et al. 2017; Oliveira et al. 2021). This definition will be adopted in the scope of this study.

Industrial parks concentrate industries and processes, leading to both possibilities and difficulties (World Bank 2021; Shao et al. 2024). Their often ineffective structure contributes to environmental impacts (Qiu and Luo 2021). Therefore, improving industrial parks and their resident companies is crucial for reducing these impacts (World Bank 2021). To help industrial parks increase climate and resource efficiency, targeted actions should be identified and measured with indicators (Collins et al. 2016). This can be done within an evaluation framework, which can be supported by scenario development to reflect alternative implementations (OECD 2008; Hendry and Pretis 2023).

The creation of new jobs through the establishment of new industries is linked to the development of new industrial parks, especially due to structural transitions such as those in the Rhenish Region of Germany (Greiving et al. 2022). The scientific research project *climate and resource protection in commercial and industrial areas* (KREGI) aims to develop an evaluation system for climate and resource efficient industrial parks and test the approach in a real-life laboratory on-site. The real-life laboratory will consist of two municipalities in the Rhenish Region serving as case studies to apply the KREGI evaluation system. The evaluation system is therefore a method to evaluate environmental impacts and mitigation strategies for industrial parks. Our KREGI approach is a key component in designing the KREGI evaluation system as it provides the methodology to formulate and select quantified actions and their corresponding scenarios. By quantifying various actions, the most effective ones can be identified to support decision-making for municipalities and companies.

The KREGI approach defines and selects quantifiable actions and evaluates them via three scenarios: a status quo baseline (no action) and two explorative cases: best-case (optimal execution and acceptance) and worst-case (poor execution and acceptance).

Quantification follows a three-step process, literature-based scoping, life-cycle inventory (LCI), and life-cycle impact assessment (LCIA), with stakeholder input. CE, industrial symbiosis, and EIP concepts are considered for the action design, enabling a comprehensive evaluation across life-cycle stages.

3.1.2 Assessment approaches & scenario development

Our approach aims to evaluate different actions regarding their impact on resource efficiency. Therefore, as a first step, existing frameworks are examined to discuss their suitability for our purposes. Previous evaluation frameworks, such as those analyzing buildings (Janjua et al. 2021; Palumbo et al. 2022), already work with different indicators to compare the specific environmental impacts of different materials for the same application (Barni et al. 2022). Other systems for example analyze manufacturing processes and compare different variations of those processes in life cycle assessments (LCA) (Laurenti et al. 2016; Cherrafi et al. 2017; Barni et al. 2022).

Defining criteria and indicators to measure the performance of actions aiming to improve resource efficiency is the standard practice in existing multi-criteria decision-making (MCDM) frameworks (Bae and Smardon 2011; Cherrafi et al. 2017; Akhanova et al. 2020; Hemmati et al. 2024; Mais et al. 2025) and will be adopted in our approach. Along with using indicators, the literature also addresses the definition of improvement actions. Böckin et al. (2020) provide an initial evaluation of various actions for increasing resource efficiency. However, most comparable frameworks focus on a limited number of actions related to products and production processes for achieving resource and cost efficiency (Winroth et al. 2016; Zeng et al. 2023).

Several reviews examine potential indicators for assessing CE at the meso level (Su et al. 2013; Kulakovskaya et al. 2023). Specifically for EIP, Dong et al. (2022) give an overview of different indicator systems for performance evaluation of EIP, though not all frameworks in this field are identified. Valenzuela-Venegas et al. (2016) develop a framework to assess EIP indicators based on a literature review, and define the following criteria: *understanding*, *pragmatism*, *relevance*, and *partial representation of sustainability*.

Site selection is a key aspect of industrial parks such as an EIP (World Bank 2021). To evaluate potential EIP locations, Fernández and Ruiz (2009) established a framework that analyzes new and existing industrial areas for sustainability. They compare different sites based on three scopes in the form of regional, local, and plot (Fernández and Ruiz 2009). As a result, the framework defines a score to evaluate and compare several sites to help decision-making. Nuhu et al. (2022) developed a framework for assessing EIP site selection that considers the presence of other industries while focusing on geographic and infrastructural factors. Other frameworks also evaluate industrial site selections while considering environmental aspects (Zhu et al. 2010; Choudhary and Shankar 2012; Kuo et al. 2013; Huang et al. 2022; Uscha et al. 2022; Rikalovic et al. 2017) emphasizing distance to infrastructure, protected areas, and geographical conditions as key aspects. Le Tellier et al. (2022) developed a sustainability assessment for industrial parks that aggregates various criteria into composite indicators. Environmental aspects encompass multiple CE levels, focusing on buildings and infrastructure, transportation, natural environmental

preservation, and eco-industrial synergies (Le Tellier et al. 2022). The assessment supports decision-making for industrial park managers by providing an aggregated score for each sustainability aspect, along with an overall performance score (Le Tellier et al. 2022).

In addition to the meso level of the CE, companies (micro level) within the industrial park and their building construction methods (nano level) are also relevant. For CE, the focus is on micro level (Rossi et al. 2020), with several reviews providing an overview of potential indicators for assessment (Su et al. 2013; Kulakovskaya et al. 2023). An example of a quantitative evaluation framework at this level is MICRON (Micro Circular Economy Index), which assesses seven principal categories, focusing on environmental aspects (Baratsas et al. 2022).

Numerous frameworks, developed by both scientific and non-scientific sources, focus on environmental assessment within the building sector (Khadim et al. 2022) as considered CE nano level. These frameworks address various aspects, including new buildings at the international level (Tokazhanov et al. 2022), specific types of buildings (Kamali et al. 2018; U.S. Green Building Council 2019; Cottafava and Ritzen 2021), or specific parts of the building (Moussavi Nadoushani et al. 2017; Finch et al. 2021; Struck and Flamme 2023). Some frameworks also include the site of the building (Cerway 2014; U.S. Green Building Council 2019; DGNB 2020). For measuring the effects, many of these frameworks address energy demand, global warming potential (GWP), carbon emissions, and material use.

3.1.3 Identified research gap and aim of the paper

As shown, literature lacks approaches to holistically examine the environmental impacts of different actions aiming to reduce resource consumption across the nano, micro, and meso levels of the CE. Especially in the context of industrial parks which are complex due to varying sectors, company sizes, and locations (Kreiner and Franco-García 2019), an approach to quantify actions regarding environmental impacts is not available. Some frameworks utilize scenario approaches as forecasting tools to describe future conditions, such as energy and electricity mixes (Ghisellini et al. 2023; deLlano-Paz et al. 2024; Ju et al. 2024). Yet, none evaluate different combinations of actions and their impact on environmental impacts as an ex-ante evaluation. Literature also identified a lack of methodology to evaluate CE across different levels (Pascale et al. 2021; Araujo et al. 2025).

A holistic and comprehensive framework to address these aspects can help municipalities reduce the effort required to evaluate companies, leading to decreased environmental impacts. In this context, municipalities serve as the executive authorities for regulations enacted, for example, at the EU level. Additionally, companies can be assessed, or can self-assess, their ability to implement actions that reduce environmental impacts through collaboration and targeted building practices. Thus, CE aspects at the meso, micro, and nano levels are interconnected and considered holistically. Before constituting a comprehensive framework, an approach is developed to address these gaps by following these research questions:

- How can an approach be designed to quantify environmental improvements through actions ex-ante, that can then be executed by companies and municipalities?
- How can the effects of these actions be evaluated regarding their climate and resource efficiency?
- How can all life cycle stages in the form of planning, building and operation of an industrial park be incorporated in the approach?
- How can this approach include the CE evaluation at nano (products), micro (intra-company), and meso (inter-company and industrial park) level?

Our KREGI approach offers a novel method for systematically defining actions and assessing industrial parks to reduce the environmental impacts of companies and municipalities. To quantify these impacts, we utilize literature, stakeholder involvement, and LCA to define three scenarios for evaluation. The application will be exemplified by quantifying the action to establish a car sharing station, illustrating how the approach is implemented. In Section 3.2 the methodological approach is described. The resulting approach, specified for the KREGI project, is presented and applied in Section 3.3. Section 3.4 discusses the approach, followed by a conclusion in Section 3.5.

3.2 Methodology of the approach

3.2.1 Structure of the approach

We developed a new approach to evaluate and reduce environmental impacts in industrial parks. The overarching goal is to lower climate and resource burdens. To do so, we define clear criteria and select operational indicators that directly measure whether the criteria are met at the level of industrial parks and resident companies. These indicators establish a baseline, enable tracking of changes over time, and support target setting (Collins et al. 2016; Cagno et al. 2023). The criteria are organized to cover the most relevant aspects for industrial parks across their life cycle (planning, building, operation), ensuring a comprehensive yet manageable structure (Junaid et al. 2022; Cagno et al. 2023). Operational indicators are chosen because they are directly linked to the criteria and can be measured consistently at the industrial park and company level. To focus the evaluation on actual environmental outcomes, we use environmental indicators. This design keeps the approach targeted and decision-oriented. The theoretical methodology is also visually summarized in Figure 3.2.

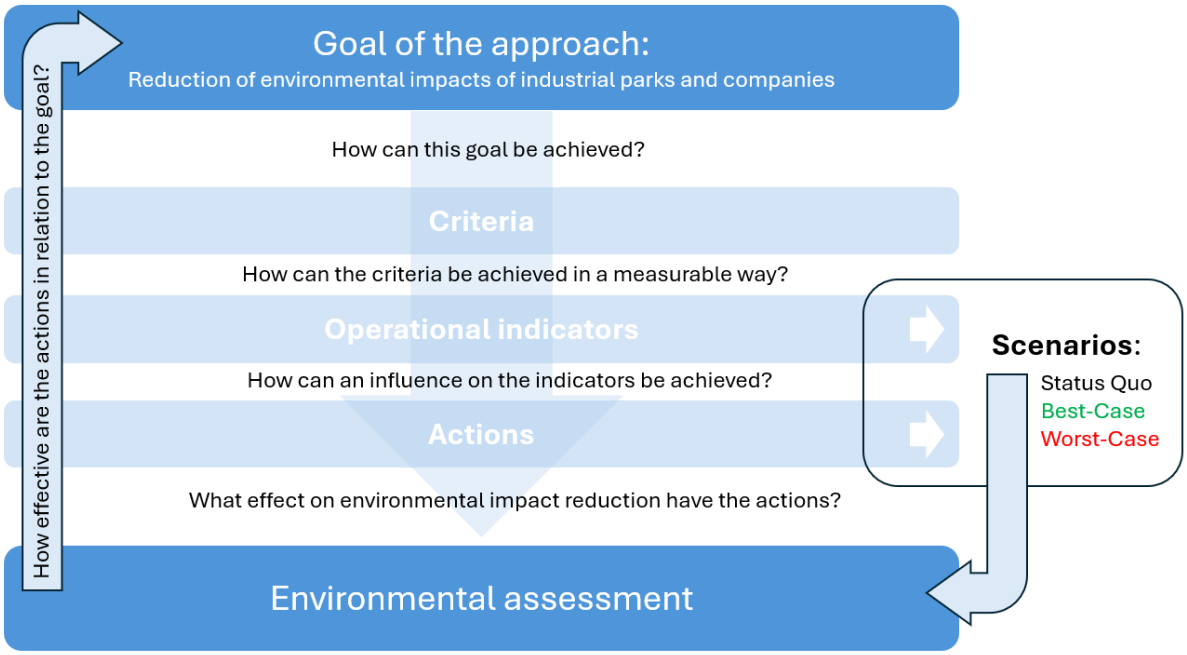


Figure 3.2: Theoretical methodology for the approach illustrating the application, structure, and interdependence of each step.

3.2.2 Action definition and selection

Actions are targeted interventions to the status quo that aim to reduce environmental impacts. To ensure consistency and relevance, we apply six requirements to every action. These requirements guide inclusion, justify exclusions, and allow future expansion as new actions emerge. Table 3.1 provides an overview of the six requirements for actions in the form of *innovation*, *unambiguity*, *effect on environmental impact*, *measurability*, *significance* and *impact in the current time* along with their definition. The defined requirements were selected based on stakeholder knowledge, current literature and adapted to our approach's topic.

Table 3.1: Definition for the six requirements for actions in the form of innovation, unambiguity, effect on environmental impact, measurability, significance and impact in the current time.

Requirements for actions	Definition
#1: Innovation	Actions must go beyond existing plans or standard practices in the park or company. Implementing the status quo will not deliver improvements.
#2: Unambiguity	Actions must be described clearly enough for users to know what to implement. For example, "innovative construction materials" is too vague; instead, define specific materials and quantities (bill of materials) to enable impact calculation. In literature, this is corresponding to the criterion understanding (Valenzuela-Venegas et al. 2016; Cagno et al. 2023). In our approach, this aspect is specified as unambiguity.
#3: Effect on environmental impact	Actions must address the defined key environmental areas climate change, energy consumption, and material use. This aligns with criteria defined in the literature, such as relevance and representation of the goals (Valenzuela-Venegas et al. 2016).
#4: Measurability	Actions must be quantifiable, either directly via environmental indicators or via a bill of materials that can be assessed in LCA. This corresponds to literature criteria such as pragmatism (Valenzuela-Venegas et al. 2016) and is here set as measurability.
#5: Significance	Actions should deliver a meaningful share of environmental benefits compared with other options. This is assessed iteratively when multiple actions are quantified. The significance of evaluating one action will be determined by whether environmental benefits are achievable.
#6: impact in the current time	Actions should generate benefits in the current planning horizon, acknowledging higher uncertainty in far-future scenarios.

Because our goal is environmental improvement, we evaluate actions against environmental indicators rather than using circularity indicators as the primary basis. It is recommended to set environmental targets rather than for example circularity targets because increasing circularity does not always lead to a reduction in all environmental impacts and may even increase energy use (Saadé et al. 2022; Elia et al. 2024).

3.2.3 Quantification and scenarios

We quantify each action with a three-step process: **scoping**, life cycle inventory (**LCI**), and life cycle impact assessment (**LCIA**). This aligns with established LCA practice such as ISO 14040 (International Organization for Standardization 2006) and scenario development guidance (Arushanyan et al. 2017). Figure 3.3 summarizes the sequence and information flow.

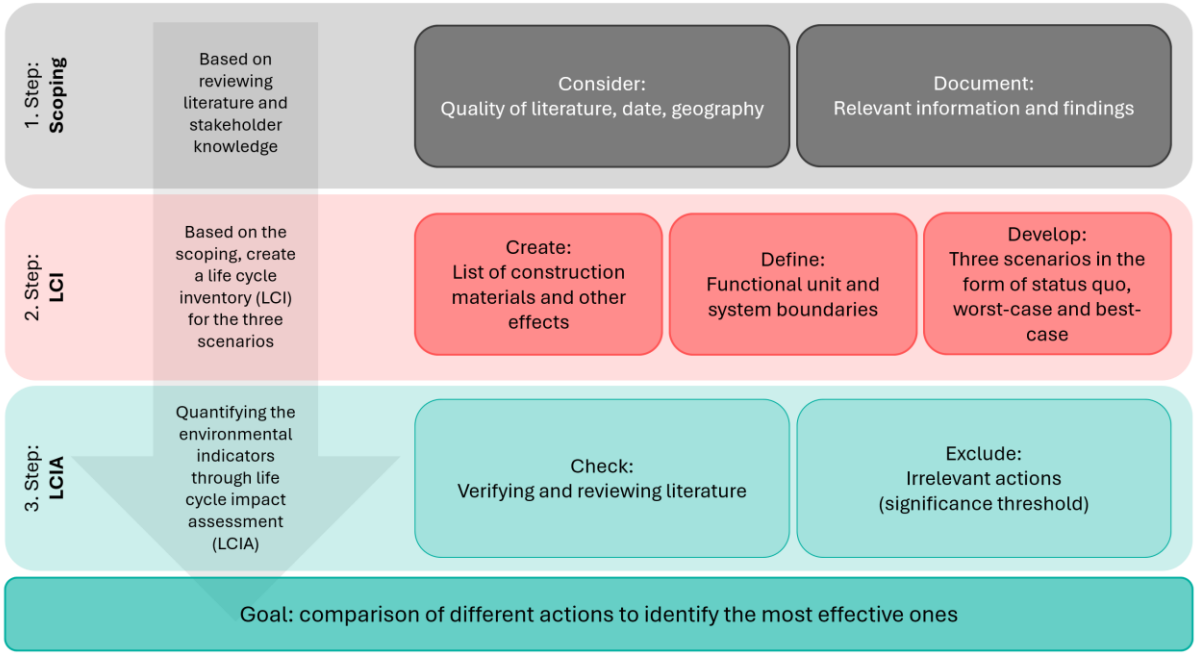


Figure 3.3: Summary of the methodology applied in the approach, including scoping, life cycle inventory (LCI) with scenario defining, and life cycle impact assessment (LCIA) as a three-step system.

In **scoping**, we define the action, its intended effects, and the parameters needed for quantification by reviewing literature and consulting stakeholders (e.g., municipal planners and project partners). We prioritize recent and context-relevant sources (Europe, especially Germany) and document the materials, processes, operating conditions, and other effects that the LCI must capture. This includes behavioral changes and acceptance of the actions. This step also identifies the functional unit and preliminary system boundaries, clarifies which operational indicators will be affected, and records data gaps and parameter ranges.

In the **LCI**, we formalize the functional unit and set system boundaries. We also define bills of materials as well as capture other effects to represent the action's efforts and benefits. The inventory includes material and energy flows, infrastructure elements where relevant, and quantified side effects (e.g., adoption rates, modal shifts, utilization factors). When literature is incomplete, we estimate quantities using stakeholder input and analogous studies and then derive per-material intensities from the constructed bills of materials. We select representative datasets and processes from widely used LCI databases (ecoinvent) to ensure transparency and reproducibility. In parallel, we define the scenarios that will be assessed. Scenario development with sensitivity analysis is a standard tool to explore future conditions and decision levers in sustainability contexts (Fauré et al. 2017; Skea et al. 2021).

We model **three scenarios** to analyze possible outcomes. The status quo (predictive) represents state-of-the-art industrial park and company operations without additional actions and addresses *what will happen* and *what if* no change is made (Lu et al. 2024). Two explorative scenarios capture uncertainty in execution quality and acceptance: a best-case scenario assumes high adoption and well-executed, market-ready options. A worst-case scenario assumes low adoption and conservative performance, reflecting

barriers and less favorable local conditions (Cluzel et al. 2014). We deliberately exclude prototype-stage technologies to keep the best-case grounded in near-term feasibility. Technologies still in prototype or patent stages may not be ready for implementation for several years or even decades, and it is uncertain whether they will ever reach market readiness (Torrisi et al. 2016; Bottai et al. 2025). To assess uncertainty, we vary influential parameters within documented ranges as a simplified sensitivity analysis (Marzooghi et al. 2022). Consequently, the defined scenarios serve as the basis for our sensitivity analysis. The varying parameters focus on key levers such as energy mix, technology shares, distances, utilization, lifetimes, and behavioral responses. Stakeholders co-develop the inventories and scenarios to ensure realism and local relevance.

In the **LCIA**, we translate the inventory into environmental impacts for each scenario under cradle-to-grave system boundaries, from raw-material extraction through end-of-life (Mirzaie et al. 2020). We report GWP, cumulative energy demand (CED), and raw material input (RMI) using established characterization methods and datasets (e.g., IPCC 2021 for GWP; Frischknecht et al. (2015) for CED; Mostert and Bringezu (2019) for RMI). Results are presented as absolute values and as changes relative to the status quo. This makes potential burden shifting visible (e.g., actions that reduce GWP and CED but raise RMI). The contrast between best- and worst-case outcomes highlights that benefits are not guaranteed and depend on local context, technology choice, and execution quality. Uncertainty increases the further a scenario projects into the future (Fauré et al. 2017). For decision support, collective scenarios can be defined to combine multiple actions and explore interdependencies and behavioral interactions. These scenarios may reveal cumulative benefits or diminishing returns when actions are implemented together.

3.3 Results

After defining the methodological background, the KREGI approach will be applied in the context of the KREGI project regarding developed categories, criteria, indicators, and actions. Additionally, the specific topics to be addressed and how the scenarios are defined will be elaborated. Finally, a practical and quantified example will be presented. The current results of the approach are summarized in Figure 3.4.

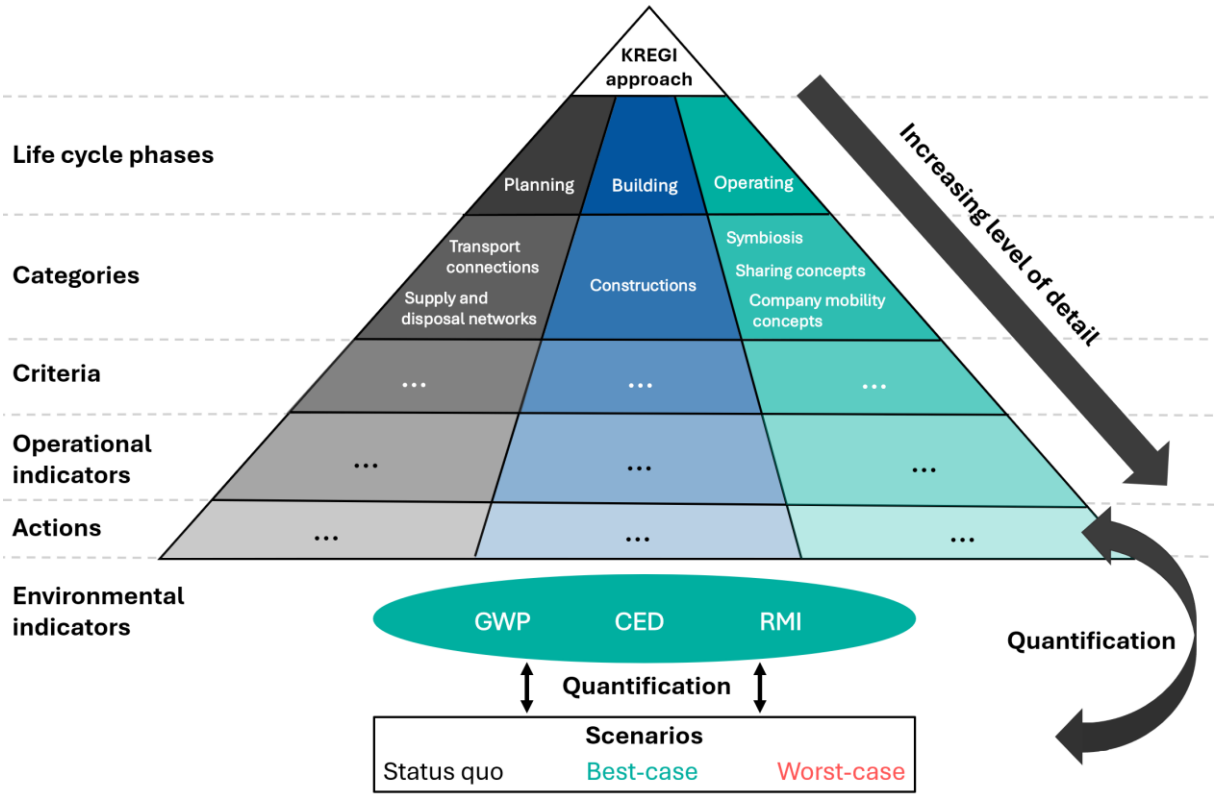


Figure 3.4: The current results of the KREGI approach include identified life cycle phases, specific categories, criteria, operational indicators, and actions. The resulting scenarios interact iteratively with these actions and are quantified with three environmental indicators: global warming potential (GWP), cumulative energy demand (CED), and raw material input (RMI).

3.3.1 Application of the approach within the KREGI project and first results

The approach evaluates and includes all life cycle phases of industrial parks (Adoue et al. 2015; Belaud et al. 2019), with a focus on industrial locations in Germany. The approach begins with the *planning* phase, where the design, boundaries, and local conditions of the industrial park are considered and assessed. This stage is within the responsibility of the municipality and addresses the influences of the planned location during site selection and defining the layout. Categories of criteria defined for this life cycle phase include *transport connections* and *supply and disposal networks*.

The next life cycle phase, involves construction of buildings and is therefore named *building* in our approach. The only category within this phase is *constructions*. While companies will plan and construct the buildings, the conditions are set by municipalities.

After planning potential locations and constructing buildings within the industrial park, companies enter the *operating* phase, which is the third life cycle phase. This phase focuses on implementing environmental benefits related to company operations and identifying possible synergies. Sharing concepts and enhancing symbiosis at the company level are evaluated under the category of *symbiosis*. Additional categories are *company mobility concepts* and *sharing concepts*, which address improvements and collaboration around mobility and infrastructure for employees.

The final life cycle phase is *end-of-life*. As the approach developed, it became evident that actions and indicators related to this phase are more effectively integrated into the other life cycle phases rather than treated as a separate phase. Consequently, aspects such as *adaptability*, *modular design*, and *reuse* are addressed during the *planning*, *building*, and *operating* of the industrial park.

The operational indicators were developed to measure whether the criteria are met, environmental indicators were defined to assess environmental impacts. To streamline information, only the most relevant environmental indicators regarding climate and resource efficiency were selected: GWP, CED, and RMI. The RMI is an input-oriented indicator that assesses raw materials used and extracted from nature, as adopted from Mostert and Bringezu (2019), and helps measure the reduction of material inputs. GWP directly addresses climate change, while RMI addresses resource depletion. The CED connects these two environmental challenges, highlighting that energy efficiency actions are essential and can be evaluated holistically, while the type of energy source (fossil or renewable) is captured by the GWP. By considering these three environmental indicators, potential burden shifting from actions can be identified. Variations of these three indicators in the form of raw material consumption, energy consumption and greenhouse gas emissions were, for example, also used as basis for defining an eco-efficient indicator for industrial symbiosis networks (Park and Behera 2014).

3.3.2 Quantification and application for actions

We quantify environmental impacts with a three-step process: scoping, LCI, and LCIA. In scoping, we reviewed peer-reviewed literature and consulted stakeholders to define each action and collect parameter ranges. However, we often lacked data for literature comparisons across all indicators, especially for RMI. In the LCI, we built bills of materials and documented side effects to represent both benefits and efforts. Where literature was incomplete, we estimated quantities using stakeholder input and analogous studies. In the LCIA, we calculated GWP, CED, and RMI with ecoinvent 3.10. Where database entries or RMI data were missing, we derived material-specific intensities from the constructed bills of materials rather than benchmarking against published values. Executing these steps required more detailed data on material use and on other effects (e.g., behavioral changes and user acceptance) to complete the quantification of all environmental indicators.

To exemplify the application of our approach, one action is quantified for the relevant aspects, and the following scenarios will be presented. As an example criterion, *reduction of individual mobility* falls under the category of *company mobility concepts*. The operating indicator *modal split* is influenced by the action *implementing a car sharing possibility by an established provider for employees and companies of the industrial park* (referred to as *implementing a car sharing station*). Therefore, this action addresses the micro level by covering individual employee mobility within companies, as well as the meso level through the interaction between multiple companies for car sharing. Additionally, the aspects, car size, fuel type, and efficiency gain enable the inclusion of nano level aspects

into the action. To assess the suitability of this action, the established requirements for actions will be verified, as summarized in Table 3.2.

Table 3.2: Aligning the six requirements for actions with the example of implementing a car sharing station.

Requirements for actions	How the requirement is fulfilled
#1: Innovation	Car sharing currently represents only a small fraction of mobility and is not considered mainstream (Meelen and Münzel 2023).
#2: Unambiguity	The action of *implementing a car sharing station* is considered unambiguous, as car sharing stations are well-known and the steps to implement are clear. Detailed decisions regarding the number of cars, types of cars, and placement should be made by the planners themselves. The success of the planning process is partly integrated into the defined scenarios.
#3: Effect on environmental impact	Car sharing has been evaluated in several studies for its potential to reduce environmental impacts related to material use, energy consumption, and greenhouse gas emissions, as noted in a review on car sharing (Arbeláez Vélez 2024).
#4: Measurability	The establishment of a car sharing station is measurable, as is its operation, which can be assessed using various indicators. As an operational indicator the change of modal split for the employees can be evaluated.
#5: Significance	Since environmental benefits are achievable, the significance of this individual action is met. When multiple actions are available and comparable, significance can be assessed based on the total potential environmental benefit. For example, if at least five percent of the total environmental benefits can be realized, the action could be considered significant.
#6: impact in the current time	The establishment of a car sharing station has an immediate effect on changing commuting behavior shortly after it is implemented.

All requirements are met and therefore, the action is deemed appropriate. To define the scenarios and apply the approach, background information for the assumptions is necessary, as detailed in Appendix B 1. The functional unit for each action is unique and for the action *implementing a car sharing station* is defined as *person kilometers of a full-time employee without home office in Germany per year (pkm/a)*. This specification allows for easy scaling for companies with varying employee numbers and work time shares per employee. The *modal split* serves as the operating indicator relevant to quantifying the action, specifically its change due to implementation.

In the status quo scenario, no car sharing station will be established in the industrial park, and the modal split will remain unchanged. Given that the research focus is on Germany, the modal split for Germany will be assumed (Statistisches Bundesamt 2022), along with the average vehicle fuel type share (Kraftfahrt-Bundesamt 2024). Also, the production and operation of vehicles, including their end-of-life considerations, are taken into account for a cradle-to-grave approach.

In the explorative scenarios, a car sharing station will be established. Assumptions for this action are primarily based on data and studies from Germany and the Netherlands (a neighboring country). The implementation of car sharing will lead to changes in three areas: work commuting, business trips, and shifts in private transport mode use, which will each be evaluated. Changes between best-case and worst-case scenarios are defined by action-specific parameters that depend on the action's boundary conditions. Accordingly, we do not use a universal set of sensitivity factors. Instead, we define scenario variables for each action in line with its system boundaries. We select parameters that reflect

levers the implementer can influence. For car sharing, for example, we include uncertainties and sensitivity in the adoption rate, the fleet's electrification share, the vehicle-size mix, efficiency gains of newer vehicles relative to older ones, and the utilization (load factor) of charging stations. When multiple sources report different values for the same parameter, we use the average of those values to approximate a realistic central estimate of the impacts.

In the best-case scenario, private cars for work commuting and personal use are optimally substituted with car sharing. This implies that the modal shift is primarily assumed to be occurring from abandoning individual cars rather than public transport. It is assumed that all shared cars used for work commuting and business trips will be battery electric vehicles (BEV) including an optimistic increase in efficiency compared to private cars. Additionally, an increase in the proportion of small, shared cars is expected compared to the current vehicle size mix in Germany.

The worst-case scenario differs from the best-case scenario by a suboptimal substitution of private cars for work commuting and personal use. In this case, the modal shift occurs more from public transport than from individual cars. It is assumed that half of the shared cars used for work commuting and business trips will be BEV, reflecting a pessimistic increase in efficiency compared to private cars. Additionally, a mild increase in the proportion of small, shared cars is expected compared to the current vehicle size mix in Germany.

These aspects are linked to processes from the LCA database ecoinvent, version 3.10, together with IPCC (2021) for GWP, CED from Frischknecht et al. (2015), and RMI adopted from Mostert and Bringezu (2019) as impact assessment methods. More details on the quantification for each aspect and the associated processes, including the detailed quantification for each process, can be found in Table B 12 and Table B 13 in Appendix B 2. Figure 3.5 summarizes the resulting environmental impact reduction of each scenario in comparison to the status quo scenario based on our assumptions. Environmental benefits are defined as positive outcomes, whereas disadvantages are defined as negative outcomes.

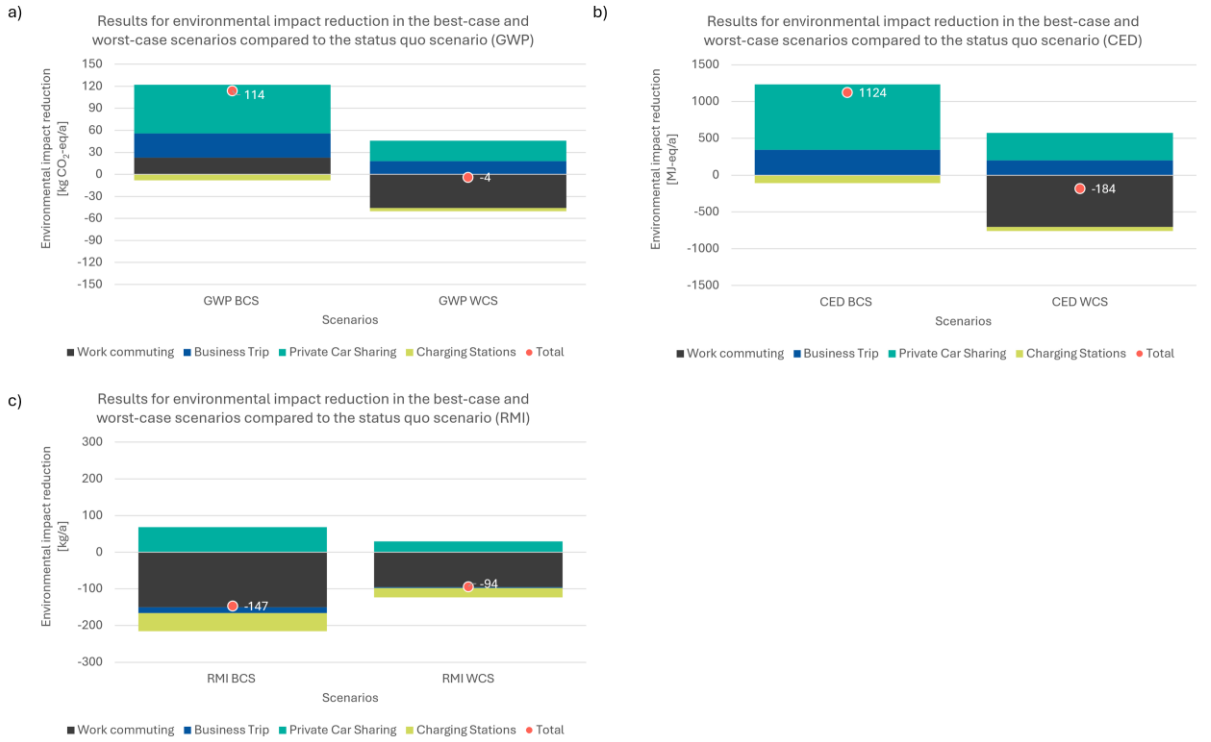


Figure 3.5: Results for impact reduction using the example of the action *implementing a car sharing station* in the best-case scenarios (BCS) and worst-case scenarios (WCS) compared to the status quo, including a comparison of a) GWP, b) CED, and c) RMI environmental impacts across all aspects.

In the best-case scenario, total benefits amount to +120 kg CO_2-eq/a (GWP) and +1,155 MJ-eq/a (CED), while RMI shows a disadvantage of −93 kg/a. In the worst-case, the net climate effect is marginal (+4 kg CO_2-eq/a), and both energy demand and material use worsen (−87 MJ-eq/a and −63 kg/a).

Private car sharing drives most of the gains, delivering the largest GWP and CED benefits in both scenarios (+70/+29 kg CO_2-eq/a; +919/+386 MJ-eq/a) and, uniquely, an RMI benefit (+63/+26 kg/a). This can be attributed to a reduction in car ownership and a shift away from car use. Business trips add smaller but consistent climate and energy benefits (+29/+13; +300/+123) alongside slight RMI disadvantages (−8/−5). Work commuting is highly sensitive to implementation quality: it benefits GWP and CED in the best-case (+31; +76) but has an RMI disadvantage (−106). In the worst-case, it has disadvantages for all environmental indicators (−34; −540; −67). Charging infrastructure imposes modest disadvantages across indicators (−10/−4; −140/−56; −42/−17).

These results highlight two decision levers. First, shifting from private cars to public transport yields larger net benefits than simply replacing combustion vehicles with BEVs. Figure 3.5 shows the RMI panel with a positive segment for private car sharing (benefit) and negative segments for work commuting and business trips (disadvantages), reflecting higher BEV material intensity where car use persists. Second, downsizing to smaller vehicle classes reduces impacts across GWP, CED, and RMI. Across scenarios, higher BEV shares correlate with GWP and CED benefits but RMI disadvantages, whereas smaller vehicles consistently improve all three indicators.

3.4 Discussion

The established KREGI approach could be a feasible way to address identified research gaps regarding possible evaluation of industrial parks and companies to answer the initial research questions. The evaluation of industrial parks and settling companies builds on quantifying actions for implementation, as demonstrated with the example of car sharing. By quantifying multiple actions' effects, municipalities and companies can gain an overview that helps decision-making. Defining and selecting the most effective actions is a first way to extend the approach to a decision-support tool.

Through a novel three-step evaluation system, multiple independent data sources are considered for final quantification and evaluation. System boundaries have been clarified to reduce bias and enable an objective evaluation of actions across three environmental indicators: GWP, CED, and RMI. The transparent definition of best-case and worst-case scenarios as scenario funnel demonstrates that varying conditions and assumptions may lead to a range of possible outcomes rather than guaranteeing a single value. This also includes various geographical literature and applications to demonstrate that real-world effects are expected to fall between both scenarios. These results can then be compared to a status quo without any implemented action to enable an ex-ante evaluation.

By covering planning, operation, building, and end-of-life, the approach spans all industrial park life-cycle phases and the CE nano, micro, and meso levels. The meso level is emphasized in planning and operation because industrial park-scale decisions (layout, shared utilities, mobility services) enable inter-company exchanges and often require municipal–company coordination. Planning assesses industrial park layout and benefits, partly shaped by municipal constraints. Operation focuses on symbiosis and sharing at the meso level and includes intra-company aspects. This phase also addresses micro-level actions such as employee mobility. The building phase includes the nano level by comparing materials, modeling buildings as material aggregates without defining specific designs. Macro-level CE insights (Kirchherr et al. 2017) can be added via cross-regional comparisons. End-of-life emphasizes adaptability to accommodate company turnover, favoring building reuse over new construction and is included in the former phases.

Applying the approach to the action of implementing a car sharing station further clarifies its understanding. The defined requirements for action selection have been verified. Details of the literature considered, and the assumptions made are shown in Appendix B 1. Appendix B 2 additionally presents information regarding the performed LCA. The results indicate that under favorable circumstances, benefits for GWP and CED can be achieved, although RMI increases concurrently. Poor implementation yields no environmental gains. Analyzing the scenarios reveals key levers and risks. BEVs raise RMI but lower GWP and CED. If GWP or CED are prioritized, increasing BEV share is beneficial, while if RMI is prioritized, implementation warrants caution. Downsizing to smaller vehicles consistently improves outcomes and should be prioritized. In the future, high-impact actions should be prioritized due to limited resources, which may lead to the exclusion of low-benefit actions. However, valuable aspects of complex actions may still offer advantages, such as the positive effects of private car sharing highlighted in the example presented.

Future users of our approach can use this example to orient themselves when conducting their own individual action evaluations.

Our applied example also illustrates that not every expectedly beneficial action yields benefits under any circumstance. Based on this, municipalities and companies can prioritize actions that guarantee benefits and offer higher advantages. The next step is to evaluate the interdependencies of other actions to develop a collective scenario. This collective scenario is defined by a coherent industrial park model and demonstrates the cumulative or diminishing benefits of actions, such as how discounted public transport tickets could mitigate the impact of implementing a car sharing station. This evaluation is also necessary when actions are added or removed from the evaluation. The definition of collective scenarios and the interdependencies of actions should be developed as closely as possible to the users, rather than through a generalized approach. This minimizes deviation from reality and leverages the detailed information that users have about their individual contexts and interdependencies. Consequently, this aspect is not directly integrated into the KREGI approach.

The applied action includes some limitations and considerations. The results are based on an average German use case, but conditions may vary in specific locations of industrial parks in Germany or internationally, potentially influencing the outcomes. For example, the modal split for each industrial park depends on public transport availability. Car sharing is more frequently used when public transport is insufficient (van der Linden et al. 2025). Uncertainties and variable conditions resulting from different circumstances in the application of actions are addressed through best-case and worst-case scenario, and additional aspects could be integrated into scenario definitions. For instance, different advertising strategies could target various user groups to increase acceptance for car sharing (van der Linden et al. 2025), which would be reflected in the best-case scenario. However, practical user acceptance will likely differ across locations and assumptions made here. If information derive from sources that consider different regions or countries, a weighting factor could also be used to account for the uncertainties of regional differences. Since the information for the car sharing example could be clearly derived from valid European sources, considering a weighting factor was not necessary in this case.

Furthermore, interactions with other actions such as utilizing local photovoltaic electricity production should be considered in a collective scenario as they may change the outcomes. This collective scenario could be built upon dynamic modeling. Literature indicates that car sharing can decrease car kilometers and thus reduce GWP (Nijland and van Meerkerk 2017). We only consider a reduction in kilometers driven for private car sharing. This is because work commuting and business trips typically involve a shift from private and company-owned vehicles, with an assumed increase in commuting car kilometers. Expanding the scope to include more detailed changes in all transport modes could alter results and enhance the benefits of this action. Additionally, comparing the car sharing to concepts like ride sharing could reveal further insights on reducing vehicle use and car kilometers (Ta et al. 2018; Ruch et al. 2021), highlighting complementary strategies or preferred options. Future applications could also consider prototypes or patents to expand the scope, as they may highlight additional improvement potential (Spreafico 2025).

However, these should be clearly marked to ensure comparability between the actions. Additionally, other influencing factors could be incorporated into the application case, such as the electricity mix, car lifetime, and the use of synthetic fuels, to broaden the understanding of uncertainty and sensitivity.

To further reduce barriers to using the approach, additional steps could be implemented. For example, a web tool could be developed to apply and test actions while including quantified effects. A similar tool has been created for identifying industrial symbiosis' in industrial parks (Lütje et al. 2021). Furthermore, additional case studies can help identify and implement improvements in future versions.

The number of indicators and actions should be kept below 100 (Cagno et al. 2023) to avoid overwhelming users with options. Small and medium enterprises (SMEs) may be challenged with the effort required for numerous actions, leading to reduced acceptance and inefficient measurement and implementation (Ormazabal et al. 2018; Dey et al. 2021; Cagno et al. 2023). This aspect could also be extended to municipalities. To address this, the significance threshold for the actions in the form of requirement for actions number five (significance) can be adjusted to include a limitation.

The defined scenarios present quantified actions for scientific, industrial, or municipal purposes and highlight potential improvements. This can serve as a foundation for implementing actions aimed at achieving resource- and climate-efficiency in industrial parks or company sites, potentially aiding in the formation of EIP. However, it is crucial to verify that theoretical benefits are realized in practice, as actual applications of concepts like circularity may differ significantly from their theoretical potential (Saadé et al. 2022). Additionally, success stories can inspire other industrial parks to adopt similar changes (Schlüter et al. 2023). This effect could also encourage individual companies to promote changes aimed at reducing environmental impacts. Consequently, the environmental benefits of successful implementation may be even greater when considering this factor, although quantifying this effect is challenging.

The approach can be extended by including weighting, aggregation or scoring methods to form an MCDM framework (Taherdoost and Madanchian 2023) and a following decision-support tool. For example, each action could be assigned a score based on its potential for reducing environmental impact. This scoring system can enhance usability and encourage companies to address environmental impacts while simplifying the evaluation process for actions. Additionally, municipalities and companies can evaluate their environmental performance, with municipalities potentially setting minimum scores for company acceptance in an industrial park. Based on this, municipalities can establish boundaries and thresholds for the design of industrial parks, such as through land-use plans that companies must adhere to. Further development is also needed for the weighting of the scoring system, especially concerning the balance between different environmental indicators.

The life cycle of an industrial park includes design, layout, commercialization, operation, and renewal (Adoue et al. 2015; Belaud et al. 2019). By considering all life cycle stages from the municipalities' perspective, our approach combines top-down and mixed

methods for planning an EIP (Paquin and Howard-Grenville 2012; Susur et al. 2019). The municipality is in our approach responsible for initiating, supporting, and overseeing commitments related to actions and their environmental benefits. According to Uusikartano et al. (2021) this gives the municipality roles as organizer, policymaker, and regulator, potentially leading to the appointment of a park manager employed by the municipality. This creates an incentive for companies to pursue environmental benefits and implement relevant actions. Additionally, policymakers can use the quantified actions as a basis for their decision-making and in defining future goals. For example, the most effective actions could be mandated in national regulations, allowing existing companies or industrial parks to receive a roadmap for the gradual implementation of these actions. Furthermore, current policies and implementations can be evaluated and compared using the KREGI approach to potentially reallocate resources toward more effective aspects.

Additional indicators beyond the environmental indicators could provide further insights. For a full evaluation of sustainability, also economic and social aspects could be added and for example the economic aspect could be considered within the selection of actions (Saadé et al. 2022). As another example, car sharing can enhance transportation equity among different groups and provide the benefits of car use without requiring ownership (van der Linden et al. 2025) and thereby accounting for social benefits. As additional environmental indicator, water use is a relevant environmental impact to consider, though quantifying different water types and assessing local water scarcity are essential (Boulay et al. 2018). Other significant environmental impacts of industrial processes, such as eutrophication, acidification, and photochemical oxidation (Park and Behera 2014), could be included in future adaptations of the approach. This would expand the approach's scope beyond climate and resource protection. Furthermore, circularity indicators could complement the environmental indicators (Saadé et al. 2022). Evaluating related R-strategies (Potting et al. 2017; European Commission 2020a) could offer additional perspectives on actions and comprehensively assess actions and indicators within the CE (Schöggl et al. 2020).

The ways in which each research question is addressed, along with unresolved issues and potential next steps, are summarized in Table 3.3.

Table 3.3: Alignment of KREGI contributions with the study's research questions and areas requiring further development.

Research question	Solution provided by the KREGI approach	Unresolved issues and next steps
How can an approach be designed to quantify environmental improvements through actions ex-ante, that can then be executed by companies and municipalities?	A three-step method (Scoping → LCI → LCIA) defines actions via six requirements, sets functional units and system boundaries, and quantifies status quo vs. best-/worst-case scenarios for ex-ante comparison. Stakeholder input complements literature and LCA data.	Future work should expand the action catalogue, verify the "significance" threshold and indicator weights with stakeholders. Also, strengthen sensitivity analysis, verify results ex post in the real-life laboratories, and formalize data-collection templates for reproducibility.
How can the effects of these actions be evaluated regarding their climate and resource efficiency?	Climate and resource efficiency is evaluated with three environmental indicators (GWP, CED, RMI), to reveal burden shifting. Scenario deltas vs. status quo provide comparative impacts.	The method could be expanded by an objective weighting scheme, improved verification of RMI data for some actions, optional inclusion of context-relevant indicators such as water scarcity or land use, and integration of cost-effectiveness metrics to support decision-making, and CE aspects such as R-strategies.
How can all life cycle stages in the form of planning, building and operation of an industrial park be incorporated in the approach?	The approach covers planning (transport connections; supply/disposal networks), building (constructions), and operation (symbiosis; company mobility; sharing), with end-of-life embedded within these phases.	Unresolved aspects include explicit quantification of end-of-life pathways of companies, building adaptability, and dynamic modeling of interdependencies between actions.
How can this approach include the CE evaluation at nano (products), micro (intra-company), and meso (inter-company and industrial park) level?	CE levels are operationalized: nano in the building phase (materials, design), micro in company operations (e.g., mobility concepts), and meso at industrial park scale (inter-company symbiosis, shared infrastructures).	Further work should present more actions across all levels, quantify synergies and conflicts in collective scenarios, validate transferability across different geographies and industrial park typologies, and expand to the macro level.

3.5 Conclusion & outlook

This work presents the KREGI approach as a methodology developed to assist municipal and company actors in selecting actions for location selection, inter-company improvements, and industrial park layout planning. It helps identifying feasible actions and quantifying them in scenarios for comparability in terms of climate and resource efficiency. The evaluation is structured around life cycle phases, categories, criteria, operational indicators, and resulting actions. Environmental effects are assessed using three environmental indicators in the form of GWP, CED, and RMI, covering the life cycle phases of planning, building, and operating while considering end-of-life.

As a practical application, municipal actors can evaluate companies as external stakeholders, or companies can evaluate possible sites internally. This would motivate companies to address their environmental footprint and could lead municipalities to set minimum scores for company acceptance in industrial parks. This could incentivize the pursuit of environmental benefits. The evaluation aspects for companies include the buildings to be constructed, symbioses to be emphasized, and mobility improvements for employees. To illustrate this approach, the action of *implementing a car sharing station* was evaluated. The results demonstrate that benefits are not achieved across all environmental indicators. For example, the RMI does not exhibit any advantages from the

implementation of the action, whereas both GWP and CED do show potential positive outcomes. Additionally, in the worst-case scenario, it may be entirely unfeasible to achieve any benefits. This underscores the potential outcomes associated with the use of this approach and emphasizes the importance of evaluating various actions and their effect within a span. It also transparently communicates uncertainties and sensitivities.

To enhance the approach, more actions need to be quantified, enabling comparison and selection of the most effective ones for recommendation. For example, a comparison with ride sharing could indicate which concept to prefer. The focus on relevant actions improves usability for municipalities and companies. Additionally, the interdependence of actions should be considered when defining collective scenarios, which can illustrate potential achievements in an industrial park when multiple actions are implemented. To facilitate this process, dynamic modeling of these collective scenarios could be implemented to enhance detail and automate the quantification across multiple actions. Furthermore, applications outside of Germany should be tested to determine whether the approach is usable as is or if modifications are needed. With adapted assumptions for the scenarios, the KREGI approach can be applied globally, as the methodology is not regionally limited. Existing actions can be modified to reflect regional key aspects, such as modal split or energy mix, when adapting to specific local contexts. If information comes from sources covering different regions or countries, a weighting factor could be applied to address uncertainties related to regional differences. Also, the level of detail for the quantification could be reduced to enhance the usability of the approach.

To transform our approach into a comprehensive framework, each action and the three environmental indicators must be weighted. Along with a scoring system, this will extend the approach into an MCDM framework and decision-support tool. To enhance usability, an online tool can complement the theoretical basis and present our results in a graphical user interface. Additionally, the approach could be expanded to include CE aspects. For example, CE indicators could supplement existing environmental indicators, along with an evaluation of related R-strategies. Also, the addition of complementary environmental indicators such as eutrophication, acidification, photochemical oxidation, water use, or land use could extend the evaluation of environmental impacts. By incorporating social and economic indicators, the approach could be expanded to evaluate not only environmental impacts but also serve as a comprehensive sustainability assessment tool.

4 Publication III: Extension and application of the approach toward a decision-support tool

Verkic, Benedikt; Nolte, Annalisa; Greiff, Kathrin; Araujo, Juliano B. (2026): A decision-support tool for prioritizing environmental actions with complementary circularity insights at company and industrial park levels. In *Cleaner Environmental Systems* 21, p. 100441. https://doi.org/10.1016/j.cesys.2026.100441

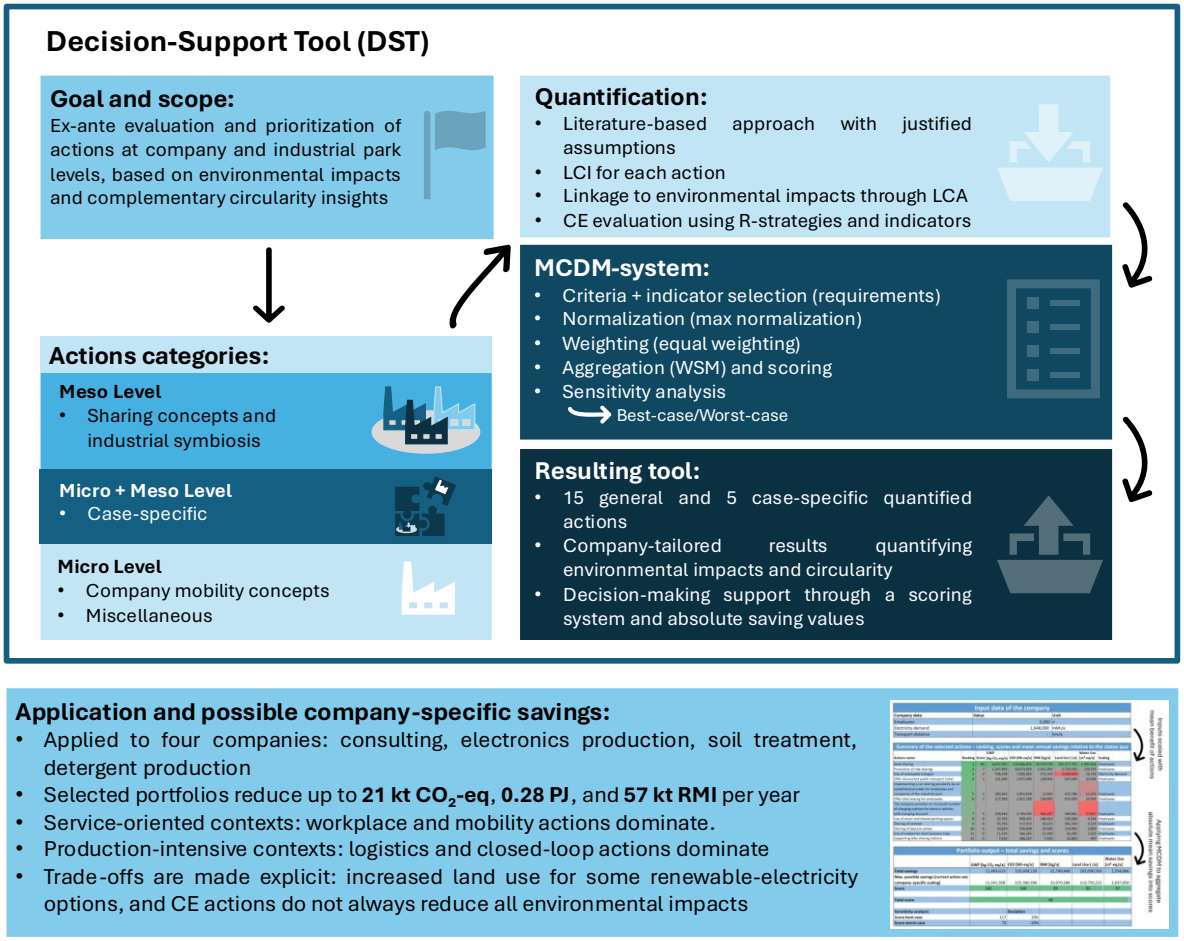


Figure 4.1: Graphical abstract of Publication III.

*This section is a reprint of **Verkic et al. (2026)**. The content is reproduced "as is" with the exception of formatting changes.*

This chapter summarizes Publication III, which addresses RQ3 and RQ4 by integrating the indicator base and the KREGI action- and scenario-based approach into a low-effort LCA-MCDM DST. In doing so, it operationalizes the previous methodological pillars and tests the integrated framework in four company case studies. The paper develops an LCA-MCDM framework that ranks operational actions at company and industrial-park levels by environmental performance, while treating circularity as a complementary, non-compensatory perspective. The DST uses five environmental indicators (GWP, CED, RMI, WU, and LU). Actions are mapped to R-strategies, and optional CE indicators (such as recycled content) can be displayed alongside the environmental results but are not aggregated

with them. To obtain composite scores, action effects are normalized via an action-based maximum for each indicator and company, equally weighted for all indicators by default, and aggregated via weighted sum method. Scores are expressed as “points” and are complemented by absolute changes in each indicator to retain interpretability. Uncertainty is represented through status-quo, best-case, and worst-case scenarios. The DST computes mean-based scores and additional scores for each scenario, producing simple bands that indicate how robust an action’s ranking is with respect to parameter and context uncertainty. The tool is implemented as an Excel tool that requires only a small set of company inputs (employees, electricity demand, transport activity) and a yes/no selection of applicable actions. It is applied to four cases: a consulting firm, an electronics manufacturer, a soil-treatment company, and a detergent producer. This explores how rankings and trade-offs differ between service-oriented and material- or energy-intensive contexts. The case studies illustrate both the practical usefulness of the framework for ex-ante prioritization based on prospective LCA results and its limitations, which are additionally discussed in detail in Chapter 5.

Abstract

Industrial activities account for 28 % of global greenhouse gas emissions, and many operational decisions at company (micro) and industrial park (meso) levels are taken without quantitative ex-ante assessment of their environmental and circularity impacts. This paper presents a low-effort decision-support tool (DST) that integrates life cycle assessment and multi-criteria decision-making to rank operational actions by environmental performance while assessing circularity as a complementary aspect. The DST requires only three readily available company inputs (number of employees, electricity demand, and transport distance), while 15 generic and 5 case-specific actions are pre-quantified for five environmental indicators. Methodologically, the DST contributes a generic ex-ante scoring tool that combines LCA results with core MCDM elements (normalization, weighting, aggregation) and adds a complementary circularity perspective. It produces a single environmental score per action and action portfolio, alongside circularity information based on R-strategies and optional circularity indicators. Applications to a consulting firm, an electronics manufacturer, a soil-treatment company, and a detergent producer show that selected action portfolios can reduce annual greenhouse gas emissions by up to 10 kt CO2-eq, cumulative energy demand by 148 TJ, and raw material input by 58 kt. The applications also reveal trade-offs, such as increased land use for some renewable electricity options. Workplace and mobility actions dominate in service-oriented contexts, whereas logistics and closed-loop product actions (e.g., refill packaging, internal PA 6.6 regranulation) are most effective in production settings. The DST's contribution is a micro–meso tool that can jointly inform environmental and circularity decisions across various sectors.

4.1 Introduction

Global CO_2 emissions from energy and industrial processes remain at record highs (IEA 2025), with industry responsible for roughly 28 % of total annual emissions (International Energy Agency 2023; Liu et al. 2023). Industrial processes are often concentrated within industrial parks, which cluster several companies, presenting significant opportunities for improvement (World Bank 2021; Shao et al. 2024). Circular economy (CE) strategies can reduce environmental impacts at both the meso level of industrial parks and the micro level of individual companies (Kristensen and Mosgaard 2020; Cagno et al. 2023).

Evaluation and performance-measurement frameworks are therefore essential to make CE manageable and to guide decisions (Baratsas et al. 2022; Simão et al. 2022; Cagno et al. 2023) across different levels and multiple environmental aspects (Cagno et al. 2023; Neri 2021; Harris et al. 2021). Among assessment methods, life cycle assessment (LCA) and multi-criteria decision-making (MCDM) are particularly relevant because combining them brings life-cycle environmental information into multi-criteria decisions (Ahluwalia and Nema 2007; Goulart Coelho et al. 2017; Ferrante et al. 2025). At industrial-park level, eco-industrial park (EIP) frameworks and indicator systems measure energy and material efficiency, emissions, and symbiotic exchanges (Valenzuela-Venegas et al. 2016; Huang et al. 2019a; World Bank 2021). CE-specific tools, such as circularity indices and maturity or readiness frameworks, extend this toolbox by focusing on resource loops and

organizational capabilities (Pigosso and McAloone 2021; Baratsas et al. 2022; Barros et al. 2024). Parallel work shows that circularity and environmental performance are related but distinct and can involve trade-offs between impact categories (Harris et al. 2021; Elia et al. 2024; Barros et al. 2024).

However, several recent reviews highlight that many of these methods and tools (i) focus on assessing existing systems, (ii) are data-intensive, and (iii) are not well suited to serve as low-effort ex-ante decision-support instruments for prioritizing concrete actions in companies and industrial parks (Valls-Val et al. 2022; Ferrante et al. 2025; Verma et al. 2025). Many corporate CE tools (e.g., circularity indices or readiness frameworks) are used mainly for ex-post monitoring or qualitative self-assessment and do not systematically integrate full life-cycle environmental impacts, especially at the level of operational actions (Baratsas et al. 2022; Chrispim et al. 2023; Barros et al. 2024). Reviews of CE and sustainability assessment for companies note that existing tools are often fragmented, heterogeneous in definitions and system boundaries, and difficult to apply in a low-effort way by practitioners (Valls-Val et al. 2022; Ferrante et al. 2025; Bais et al. 2025; Verma et al. 2025).

Recent reviews show that MCDM is widely used for sustainability assessment, including in combination with LCA, and that dozens of generic decision-support methods are already available (Lindfors 2021; Parolin et al. 2024). However, even where LCA–MCDM is applied at technology, product, or company/park level, the alternatives are usually technologies or system scenarios rather than reusable operational actions that companies and park operators can directly implement across micro and meso levels (Lindfors 2021; Parolin et al. 2024). These limitations can be summarized in five remaining gaps.

(i) most tools do not quantify the expected environmental effect of specific operational actions ex-ante at the company or park level because they either focus on products, provide retrospective evaluations, or aggregate impacts at a high level (Kravchenko et al. 2019; Harris et al. 2021; Elia et al. 2024); (ii) micro- and meso-level aspects are rarely integrated in a single decision-support framework that can account for both on-site aspects (e.g., mobility, energy use) and inter-company symbioses (e.g., shared infrastructure) (Singh et al. 2016; Fehrer and Wieland 2021; Harris et al. 2021; Elia et al. 2024; Barros et al. 2024); (iii) many existing tools and approaches require case-specific model building and detailed stakeholder weighting, which is challenging in practice (Lindfors 2021; Parolin et al. 2024; Ferrante et al. 2025); (iv) many also require detailed data, expert modeling and rely on highly compensatory aggregation without making assumptions about compensability explicit, which limits their usability as low-effort tools for practitioners needing quick guidance (Lindfors 2021; Valls-Val et al. 2022; Ferrante et al. 2025); and (v) few frameworks jointly consider circularity and environmental impacts at the action level and explicitly address potential trade-offs (Saidani et al. 2019; Corona et al. 2019; Kristensen and Mosgaard 2020; Valls-Val et al. 2022; Barros et al. 2024).

To address these gaps, we propose a decision-support tool (DST) that operates at the level where companies make decisions: specific operational actions. Our tool is ex-ante in the sense that it is applied before implementation to compare alternative actions under

scenario-based LCA assumptions, rather than to monitor realized performance ex-post. The DST has three main components. First, it includes a set of pre-quantified actions representing typical micro- and meso-level interventions (e.g., workplace and mobility, logistics, sharing and symbiosis). Second, it embeds a scoring system that combines life-cycle-based environmental information with MCDM to produce a single environmental performance score per action and per action portfolio. Third, it adds a complementary circularity perspective by mapping actions to R-strategies and allowing users to add context-specific CE indicators, which are reported alongside the environmental score but not aggregated with it. In practice, this circularity perspective helps users distinguish between actions that combine high environmental performance with strong circularity characteristics and those where circularity and environmental impacts diverge. CE indicators are not integrated into the environmental MCDM score to avoid compensating high impacts with high circularity aspects and because circularity metrics do not necessarily correlate with environmental performance (Harris et al. 2021; Elia et al. 2024; Sewenet et al. 2026).

The DST builds on the KREGI (climate and resource protection in commercial and industrial areas) project, which developed an action-oriented approach for resource and climate protection in industrial and commercial areas (Verkic et al. 2025b). The KREGI approach defines action concepts, operative indicators, best-/worst-case scenarios, and allows for quantifying actions using LCA. In that work, the approach was illustrated with a single exemplary action (car sharing), but no generic action catalog was developed. In this paper, we use these KREGI elements as a basis but extend them by adding normalization, weighting and aggregation into a single score and an explicit circularity perspective. Thereby we transform the building blocks into a complete decision-support workflow with action ranking and portfolio scores.

Methodologically, the DST advances existing LCA–MCDM approaches in several ways. First, it operationalizes ex-ante environmental assessment at the level of concrete operational actions spanning both micro/meso levels, rather than at the level of individual technologies or products. Second, it newly defines a pre-quantified action library (15 general and 5 case-specific actions) scaled to specific companies using three readily available inputs (number of employees, electricity demand, and transport distance). Thereby it drastically reduces the data and modeling burden typically associated with LCA–MCDM tools. Third, it integrates a separate but linked circularity perspective: each action is mapped to at least one R-strategy and can be associated with simple CE indicators (e.g., recycled content, reuse cycles), which are reported alongside the environmental score but not aggregated with it. Fourth, it represents uncertainty through scenario-based sensitivity bands around mean-based scores, consistent with recommendations to explicitly address uncertainty in MCDM-based sustainability assessments using scenarios and other simple sensitivity approaches, rather than relying solely on data-intensive probabilistic models (Wulf et al. 2019; Lindfors 2021; Parolin et al. 2024). The DST primarily targets companies, with potential extensions to park operators, municipalities, and researchers.

In summary, the main research question is:

How can a low-effort decision-support tool be developed to help companies prioritize actions that reduce environmental impacts while evaluating circularity as a complementary aspect?

To operationalize this question, we formulate five sub-research questions (SRQ). SRQ 1–3 address the design of the DST, SRQ 4 tests its performance in application, and SRQ 5 examines the design of the action set for future extensibility:

- **SRQ 1 (Evaluation):** How can environmental and circularity indicators be selected and operationalized so that diverse actions at the micro/meso levels can be evaluated consistently within a single DST?
- **SRQ 2 (Normalization, weighting & aggregation):** Which normalization, weighting, aggregation, and uncertainty-representation methods are suitable to produce a single, interpretable environmental score per action while preserving information on trade-offs across indicators?
- **SRQ 3 (Usability):** What functional design and data requirements allow the DST to remain low-effort (minimal input variables, short time-to-decision) without compromising validity and transparency?
- **SRQ 4 (Effectiveness in application):** How does the DST perform when applied to different company types (service and production) and levels (micro and meso), and what patterns of high-impact actions and trade-offs emerge from these case studies?
- **SRQ 5 (Action set design & extensibility):** Which methodological requirements enable consistent selection and definition of actions so that the DST remains comparable across applications while allowing case- and company-specific extensions of the action set?

In the subsequent Section 4.2, the tool's purpose and methods are outlined. Section 4.3 shows the results of the DST, which is applied to four case study companies. The results are discussed in Section 4.4, and a conclusion is given in Section 4.5.

4.2 Methodology of the decision-support tool

Building on the KREGI approach Verkic et al. (2025b), we adopt KREGI's operative indicators and best-/worst-case scenario logic as quantified LCA inputs and apply them to develop and pre-quantify an initial action set of 20 actions. We then extend this basis by (i) broadening the environmental indicator set, (ii) defining an action-based max normalization, (iii) specifying a default weighting scheme, (iv) aggregating via a weighted sum into a single environmental score at action and portfolio level, and (v) integrating circularity and scenario-based uncertainty analysis as complementary components. The DST integrates LCA information into an MCDM workflow to prioritize actions that aim to reduce environmental impacts at the micro/meso levels. CE evaluation is integrated through R-strategies

and user-defined CE indicators. The DST is implemented as an Excel-based tool and the template is provided as supplementary materials (SM) 2+3.

The method sequence follows established MCDM–LCA practice: goal and scope definition; theoretical framework; criteria and indicator selection; data normalization; weighting; aggregation and scoring as well as uncertainty and sensitivity analysis. This is adapted from Goulart Coelho et al. (2017) and Torkayesh et al. (2022), and aligned with OECD guidance on composite indicators (Nardo et al. 2005; OECD 2008). Appendix A provides detailed background on the MCDM components, including the justification for their selection and the steps used to develop each. Figure 4.2 provides an overview of the resulting workflow, distinguishing components adopted from KREGI from those newly designed in this paper. A program flow chart illustrating the DST steps from a user perspective is provided in Figure 4.3.

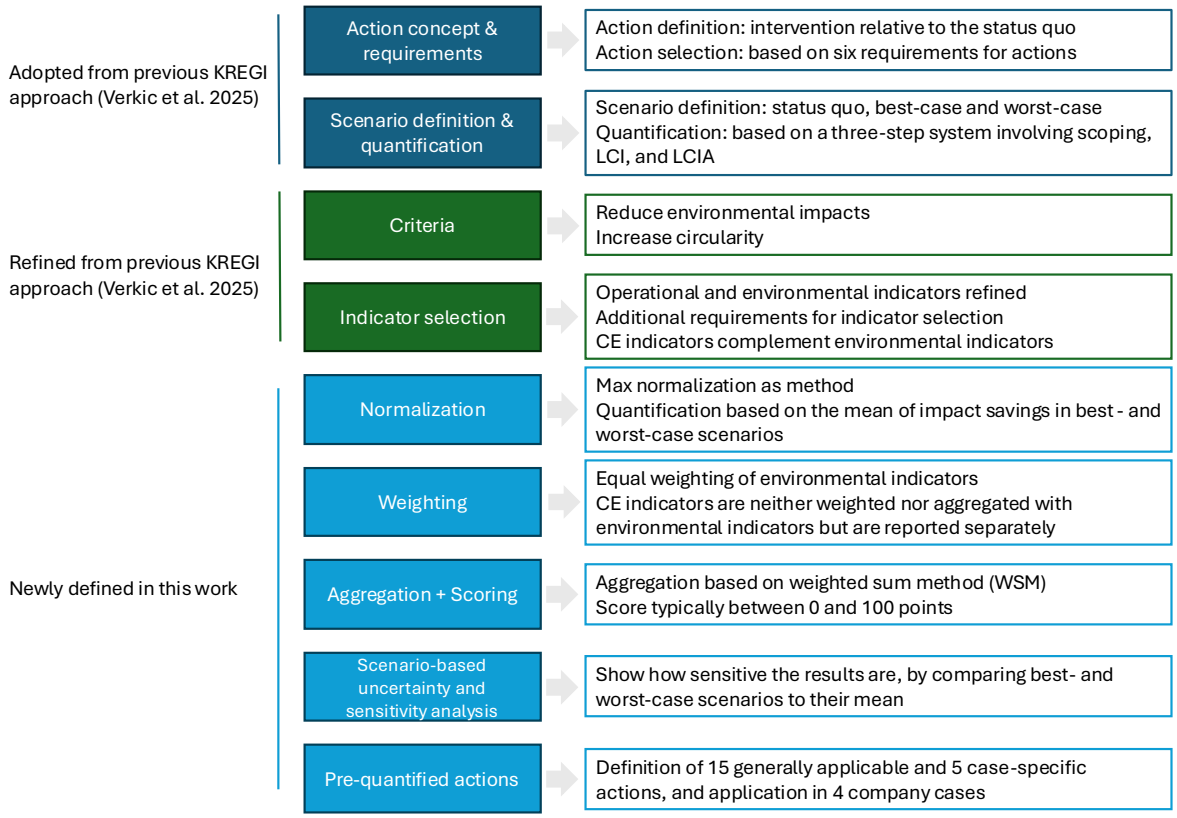


Figure 4.2: Methodology summary for the DST. Definition, selection and quantification of actions and the scenarios adopted from Verkic et al. (Verkic et al. 2025b). Criteria and indicator selection are refined. Normalization, weighting, scoring, and sensitivity analysis are newly defined here.

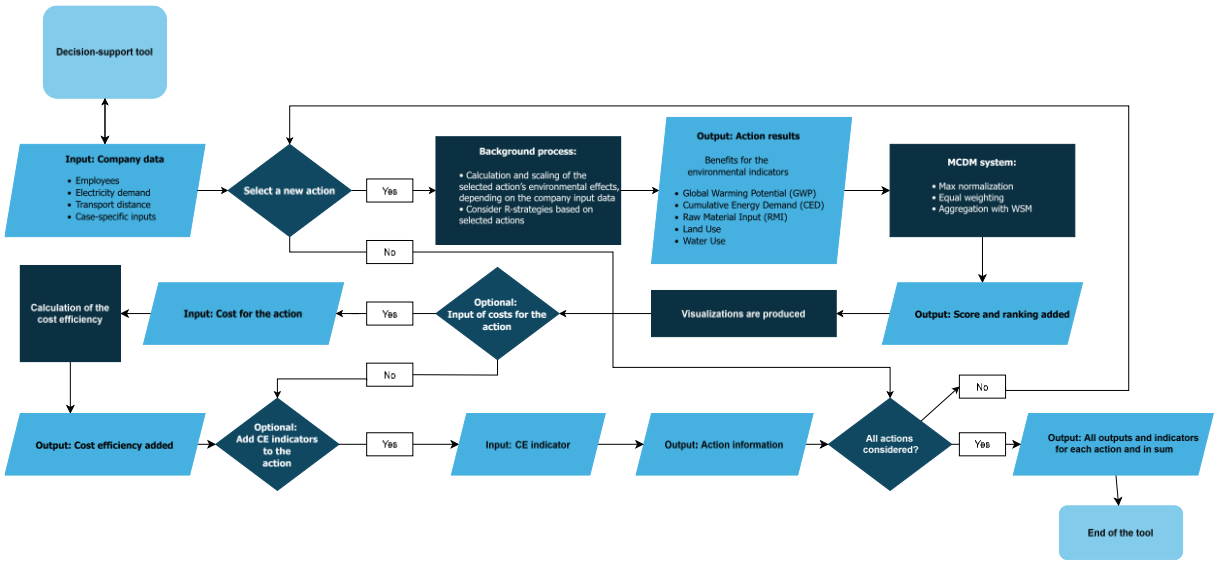


Figure 4.3: Program flow chart of the DST to visualize the concept and application.

4.2.1 Theoretical framework and scope

Following Gan et al. (2017), the theoretical framework guides method selection and design choices to address the gaps identified in Section 4.1 and SRQ 1-3. The purpose is to provide a holistic, ex-ante evaluation of environmental impacts and circularity at micro/meso levels.

Spatially, the scope covers company operations and inter-company sharing and industrial symbiosis at the industrial-park level, reflecting the role of EIPs. Temporally, the tool targets the pre-planning and early design stages, when actions can be selected before costly modifications are implemented (Schlegl et al. 2019).

The environmental assessment adopts a life-cycle perspective from resource extraction to end-of-life, consistent with LCA practice. From a sustainability perspective, environmental performance is prioritized, acknowledging that increases in circularity do not necessarily reduce environmental impacts (Harris et al. 2021; Elia et al. 2024). An option to include economic outcomes as user input on costs per action is available for cost–benefit discussions. These cost data are reported alongside the environmental scores. They are not normalized, weighted or aggregated with the environmental indicators and therefore do not influence the ranking of actions.

4.2.2 Actions: definition and quantification

Addressing SRQ 1 and SRQ 5, the DST treats *actions* as operational interventions that are intended to reduce environmental impacts and may increase circularity. Action definition follows the KREGI requirements (Verkic et al. 2025b), which specify six requirements that ensure consistency and extensibility of the action set: innovation, unambiguity, effect on environmental impact, measurability, significance, and impact in the current time. In this paper, we apply these requirements to develop and pre-quantify an initial action set of 20 actions. In other contexts, users can add actions that are based on the same requirements and quantify them with the same workflow. The additional actions can then be integrated into the DST and compared.

Action quantification follows a three-step workflow adopted from the KREGI approach: (i) literature review and derivation of benchmarks, (ii) stakeholder input where appropriate, and (iii) LCA-based calculation of indicator deltas. For each action a, company i, and indicator k, we quantify two scenarios $s \in \{\text{best,worst}\}$ relative to the status quo (baseline). We denote the baseline impact as $I_{i,k}^{\text{base}}$ and the scenario value as $I_{i,k}^{a,s}$ for $s \in \{\text{best,worst}\}$. The scenario-specific reduction is according to equation 1

$$\Delta I_{i,k}^{a,s} = I_{i,k}^{\text{base}} - I_{i,k}^{a,s} \quad (1)$$

where positive values indicate improvement. While best-case and worst-case scenarios are quantified individually, all subsequent normalization, weighting, aggregation, and scoring use the mean of the effects (see equation 2)

$$\bar{\Delta} I_{i,k}^{a} = \frac{\Delta I_{i,k}^{a,\text{best}} + \Delta I_{i,k}^{a,\text{worst}}}{2} \quad (2)$$

Best-/worst-cases are used exclusively for uncertainty analysis in Section 4.2.7.

The current DST implementation includes 15 generally applicable and 5 case-specific actions, which are applied to four case-study companies in Section 4.3. The four case-study companies were purposively selected to cover a service-only context (consulting) and three production-intensive contexts (electronics, soil treatment, and detergents), so that the full range of general and possible case-specific actions could be illustrated. The generally applicable actions are broadly usable across company types and constitute the core of the DST, while the case-specific actions illustrate how users can add tailored options and benchmark them against the general set (SRQ 5). Appendix C 3 documents each action with preconditions, data inputs, scaling rules, and quantified effects, providing the necessary transparency for extension.

4.2.3 Criteria and indicator selection

Addressing SRQ 1 (evaluation) and SRQ 3 (usability), the DST organizes indicators into three types (operative, environmental and CE indicators), which correspond to different roles in the decision model. Operative indicators (e.g., modal split, electricity intensity) capture the implementation state of actions and serve as inputs to the LCA quantification. Environmental indicators quantify impacts and form the basis of the composite environmental score.

To balance holistic coverage with ease of use (Dale and Beyeler 2001; Zhu et al. 2010; Cagno et al. 2023), all indicators in the tool are required to meet four conditions, synthesized from the indicator and composite-index literature:

- Relevance: Indicators must be relevant to assessing company performance on the intended dimension (environmental or circularity) (Valenzuela-Venegas et al. 2016; Baratsas et al. 2022). Relevance is verified through their established use in comparable assessment models and/or a scientifically validated linkage to environmental or circularity outcomes.
- Unambiguity: Indicators must be clearly and consistently defined to avoid misunderstandings (OECD 2008; Baratsas et al. 2022; Struck 2023). Clarity is supported

by action descriptions and fact sheets that specify the definition, units, data sources, and measurement rules.

- Measurability: Indicator data must be available or measurable in a cost-effective and straightforward manner (Valenzuela-Venegas et al. 2016; Baratsas et al. 2022). Preference is given to data aligned with recognized reporting standards (e.g., GRI); justified alternatives are accepted.
- Coherence: Indicator use must be coherent across actions and contexts, employing common concepts, classifications, and definitions (Nardo et al. 2005; OECD 2008).

The original KREGI approach used global warming potential (GWP), cumulative energy demand (CED), and raw material input (RMI) as environmental indicators (Verkic et al. 2025b). To better represent environmental resources, the DST adds water use and land use, consistent with resource-focused perspectives such as MIPS (Liedtke et al. 2014) and with common practice in industrial symbiosis and EIP assessment (Verkic et al. 2025a). Indicator definitions and characterization factors follow established sources: GWP uses IPCC (2021) characterization, CED follows Frischknecht et al. (2015), RMI uses characterization factors from Mostert and Bringezu (2019), and water use and land use are based on the Environmental Footprint method recommended by the European Commission (European Commission 2021). Measurability is ensured via LCI data and the operative indicators, while coherence is maintained through consistent system boundaries and background datasets as detailed in Appendix C 3.

Circularity is represented in two complementary ways. First, each action is mapped to one or more R-strategies following Potting et al. (2017) and summarized in Table 4.1. This mapping is shown in the action fact sheets and lists, as well as in a portfolio summary, so that users can see which high-circularity strategies are implemented in their action portfolio. Second, users can assign simple, user-selected CE indicators to actions (e.g., share of secondary material or closed-loop share). These CE indicators are defined per action and reported alongside the environmental scores at action-level and for the executed portfolio as additional columns in the action ranking in the tool. They are not included in the environmental scoring equations, i.e. they are not normalized, weighted, or aggregated with the environmental indicators. This design avoids compensating high environmental impacts with increased circularity and reflects the fact that CE indicators do not always correlate with environmental performance. Some actions are strongly linked to circularity (e.g., recycling actions that close the loop), whereas others (e.g., mobility actions) are not, but can contribute to narrowing the loop (Bocken et al. 2016). This provides a structured CE lens for qualitative interpretation, prioritization, and reporting, and allows high-circularity actions to be compared with more generic ones.

Table 4.1: Actions are assigned to categories and to R-strategies based on the 9R framework by Potting et al. (2017).

CE-level	Category	Action	Mapped R-strategy
Micro	Company mobility concepts	Offer discounted public transport ticket	Rethink
		Use of e-bikes for short business trips	
		Offer bike leasing for employees	
		Promotion of ride sharing	
		Use of BEV as company vehicles for business trips	
		Company provides an increased number of charging stations for EVs with charging discount	No direct link
	Miscellaneous	Use of electric trucks in operational transport	Rethink
		Use of renewable energies	
Meso	Sharing concepts & industrial symbiosis	Implementing a car sharing possibility by an established provider	
		Supporting bike sharing stations	
		Supporting e-scooter sharing stations	
		Use of smart and shared parking spaces	
		Sharing of daycare center	
		Sharing of canteen	
		Desk sharing	
Micro + meso	Case-specific	Use of a shared storage to increase load of transports	
		Refill concentrate plastic pouch instead of conventional plastic bottle	Reuse
		Treatment of soil instead of landfill	Recycle
		Refill plastic pouch made of secondary materials	
		Closed-loop blending of PA 6.6 regranulate in injection molded housings	

4.2.4 Normalization

Addressing SRQ 2, normalization in the DST makes heterogeneous environmental indicators comparable and links action-level effects to the company-specific improvement potential. We adopt max normalization for each environmental indicator, based on the mean effect of actions and scaled by company inputs. This reflects the decision focus on the company-specific improvement potential: each action's effect is expressed relative to the total potential that could be achieved if all applicable actions were implemented. Defining $M_{i,k}$ as the total mean potential of all actions ensures that splitting actions into smaller units does not artificially inflate scores and that portfolio sums remain interpretable.

For company i and indicator k, A_i is the set of applicable actions. The company-specific maximum achievable mean reduction for indicator k, $M_{i,k}$, is defined as the total potential across all applicable general actions and any user-added actions as shown in equation 3:

$$M_{i,k} = \sum_{a \in A_i} \bar{\Delta} I_{i,k}^{a} \quad (3)$$

For each action a, the normalized mean effect is calculated according to equation 4

$$e_{i,k}^{a} = \frac{\bar{\Delta} I_{i,k}^{a}}{M_{i,k}}, \quad (4)$$

and scenario-specific normalized effects for sensitivity analysis are calculated according to equation 5

$$e_{i,k}^{a,\text{best}} = \frac{\Delta I_{i,k}^{a,\text{best}}}{M_{i,k}}, e_{i,k}^{a,\text{worst}} = \frac{\Delta I_{i,k}^{a,\text{worst}}}{M_{i,k}}. \quad (5)$$

By construction, $e_{i,k}^{a}$ adds up to at most 1 across all actions for a given indicator. Importantly, we allow negative normalized values if $\Delta I_{i,k}^{a} < 0$ (e.g., if not all environmental indicators inherit an advantage). Allowing negatives and not relying on categorical scaling preserve information about harmful effects and potential trade-offs, in keeping with recommendations to avoid masking uncertainty or value conflicts in composite indices (Freudenberg 2003; OECD 2008).

4.2.5 Weighting

Addressing SRQ 2 and SRQ 3, weighting reflects the relative importance of environmental indicators and is designed to remain simple and transparent. By default, environmental indicators receive equal weights $w_k = 1/K$ (with $w_k \geq 0$ and $\sum_k w_k = 1$). Equal weighting is adopted for three reasons. First, in the ex-ante, cross-sector context addressed here, robust preference information for trading off GWP, CED, RMI, land use, and water use is typically unavailable and heterogeneous across companies and stakeholders (Nardo et al. 2005; OECD 2008). Using participatory weighting processes or deriving statistical weights (e.g., PCA, BOD) would contradict the low-effort and generally applicable nature of the tool. Second, the composite-indicator and MCDM literature often adopts equal weighting as a default when no robust preference or empirical information is available, and recommends that sensitivity to alternative weights be acknowledged and, where possible, explored (Nardo et al. 2005; OECD 2008; Singh et al. 2009; Gan et al. 2017; Pizzol et al. 2017; Odu 2019).

Third, equal weighting facilitates communication and avoids giving a false impression of precision where underlying preferences are uncertain (Nardo et al. 2005; OECD 2008). In the case studies, equal weighting is used as the default, even though it implies full compensability between fundamentally different impacts (Gan et al. 2017; Pizzol et al. 2017), which is in practice not always the case. Section 4.4 therefore reports an illustrative climate-focused weighting scenario to show how alternative weights affect action rankings. CE indicators are not weighted or aggregated with environmental indicators, in line with evidence that increased circularity does not necessarily reduce environmental impacts and to avoid compensation between the two dimensions (Harris et al. 2021; Elia et al. 2024).

4.2.6 Aggregation and scoring

Addressing SRQ 2, aggregation in the DST generates interpretable scores for action prioritization while remaining compatible with the normalization and weighting design. This choice is driven by the properties of the normalized effects and the intended output: some $e_{i,k}^{a}$ can be zero or negative (if an action worsens an indicator), and the tool requires a single, interpretable score. We aggregate normalized marginal effects using the weighted sum method (WSM), a linear aggregation procedure widely used in MCDM (e.g., (Odu 2019)). We use WSM because this aggregation is linear, it can handle zero and negative values, and the resulting score can be interpreted as the weighted contribution of all

actions to the company-specific improvement potential. In contrast, geometric aggregation (e.g., weighted product) is not robust to zero or negative values, and non-compensatory multi-criteria methods typically require more detailed preference information and yield rankings (Nardo et al. 2005; OECD 2008; Gan et al. 2017), which is less suited to our communication and portfolio-design goals. The use of linear aggregation in sustainability assessments has been successfully applied to condense large indicator sets into single sustainability scores and to analyze trade-offs among structural alternatives (Sánchez-Garrido et al. 2022). However, WSM assumes additive, independent effects and can misestimate combined outcomes.

This results in a mean-based environmental score for each action a at company i, as given inequation 6

$$S_i^a = 100 \cdot \sum_{k=1}^{K} w_k \cdot e_{i,k}^a. \quad (6)$$

This typically yields scores between 0 and 100 points per action. For the portfolio of executed actions A^{exec}, the mean-based environmental score is calculated according to equation 7:

$$S_i^{\text{env}} = 100 \cdot \sum_{k=1}^{K} w_k \cdot \left(\sum_{a \in A^{\text{exec}}} e_{i,k}^a \right). \quad (7)$$

This linear aggregation implies that portfolio scores are obtained by summing the normalized marginal effects of selected actions and therefore assumes that these effects are additive and independent. The tool does not explicitly model synergies, overlaps, or saturation effects between actions. Such interactions are instead discussed qualitatively in the actions coherence notes and in the limitations (Section 4.4).

In addition to normalized scores, the tool reports absolute, unnormalized environmental deltas $\bar{\Delta} I_{i,k}^a$ per action and for the executed portfolio to support expert interpretation. Scores are expressed as “points” rather than percentages to avoid implying a normative 100 % optimum, since the tool does not include all conceivable actions and is intended for relative prioritization within a given context.

4.2.7 Scenario-based uncertainty and sensitivity analysis

Addressing SRQ 2, the DST incorporates a structured, scenario-based uncertainty and sensitivity analysis to assess how scores respond to uncertainty in action effects. For each action, we compute best- and worst-case normalized effects $e_{i,k}^{a,\text{best}}$ and $e_{i,k}^{a,\text{worst}}$ using the same normalization bases $M_{i,k}$ derived from mean potentials. Scoring is based on the mean value $\bar{\Delta} I_{i,k}^a$, while best and worst cases form explicit bands around this mean. Scores for these scenarios are given by equation 8:

$$S_i^{a,\text{best}} = 100 \cdot \sum_{k=1}^{K} w_k \; e_{i,k}^{a,\text{best}}, S_i^{a,\text{worst}} = 100 \cdot \sum_{k=1}^{K} w_k \; e_{i,k}^{a,\text{worst}} \quad (8)$$

This scenario-based approach is deliberately simple so that it can be implemented with the limited data typically available in ex-ante company applications.

Because normalization uses the mean-based reference, scores from the uncertainty analysis can exceed 100 or fall below 0. This combines evaluation of input data sensitivity

(Goulart Coelho et al. 2017) and a scenario analysis which is a core tool in future-oriented LCA frameworks (Olsen et al. 2018; Moshrefi et al. 2022). In the case studies (Section 4.3), we use these bands to discuss the robustness of action rankings and portfolio scores. This scenario-based uncertainty analysis provides a simple sensitivity check on how scores change under best- and worst-case assumptions about action effects. We treat uncertainty in indicator weights by exploring the sensitivity of scores and rankings to alternative hypothetical weight sets (equal vs. climate-focused weights) in Section 4.4.

4.3 Results: application in case studies

We apply the DST to four company cases to demonstrate its applicability and cross-level usability, a need highlighted in recent literature (Valls-Val et al. 2022; Ferrante et al. 2025). We illustrate how action priorities and trade-offs vary across micro and meso levels for a consulting firm (service-oriented, without production), an electronics site (production-intensive with internal recycling options), a soil-treatment company (production-oriented with significant material flows), and a detergent manufacturer (production-intensive with options for external recycling).

For all cases, action effects are quantified for best- and worst-case scenarios, using the mean for scoring. Sensitivity analysis reports scenario bands relative to the mean-based scores. Appendix C 2 and Appendix C 3 provide the underlying scaling rules and case-specific assumptions.

In the case studies, we present portfolio results assuming that all beneficial actions from the current action set are implemented, to highlight the maximum potential savings within this set. In practice, companies can also choose to implement only a subset of actions in line with their constraints. Because normalization uses the company-specific maximum achievable mean reduction $M_{i,k}$ as reference (Eq. 3), one point of score corresponds to different absolute savings in different companies. Scores are therefore not quantitatively comparable across companies because they are intended to rank actions and portfolios within a given company relative to its own improvement potential.

Values originate from the same workflow for all cases: pre-quantified action effects from Appendix C 3 are scaled by company-specific inputs (employees, energy demand, transport distances).

4.3.1 Case study 1 – consulting company

To illustrate a service-only context, we consider a consulting company as first case study, with approximately 3,500 employees (PricewaterhouseCoopers GmbH). For modeling, 3,000 full-time equivalents (FTE) are assumed (see Appendix B). The company provides office-based services, does not operate its own fleet, and has relatively low energy demand per employee (22 kWh/m^2·a (Bagherian et al. 2021)) with average gross area per workplace of 28 m^2 (Stolze and Ricci 2022)).

Input data of the company

Company data	Value	Unit
Employees	3,000	n
Electricity demand	1,848,000	kWh/a
Transport distance	-	km/a

Inputs scaled with mean benefit of actions

Summary of the selected actions – ranking, scores and mean annual savings relative to the status quo

Actions name	Ranking	Score	GWP [kg CO_2-eq/a]	CED [MJ-eq/a]	RMI [kg/a]	Land Use [-/a]	Water Use [m^3-eq/a]	Scaling	R-Strategy
Desk sharing	1	44	1,287,692	22,425,884	2,315,619	7,728,435	300,854	Employees	Rethink
Promotion of ride sharing	2	29	1,167,000	16,674,450	1,351,500	5,743,500	124,230	Employees	Rethink
Use of renewable energies	3	4	708,338	7,685,065	572,104	- 5,699,629	78,706	Electricity demand	Rethink
Offer discounted public transport ticket	4	3	141,000	1,875,300	148,500	625,500	10,500	Employees	Rethink
Offer bike leasing for employees	5	3	127,500	1,817,100	138,000	615,000	10,500	Employees	Rethink
Implementing a car sharing possibility by an established provider for employees and companies of the industrial park	6	2	280,903	2,852,828	- 13,983	425,188	- 21,445	Employees	Rethink
Use of smart and shared parking spaces	7	1	22,759	569,441	188,363	128,288	4,548	Employees	Rethink
Sharing of canteen	8	1	35,795	517,413	43,221	181,354	4,229	Employees	Rethink
Sharing of daycare center	9	1	24,834	358,608	29,389	124,460	2,800	Employees	Rethink
Use of e-bikes for short business trips	10	0	11,520	166,365	12,300	56,280	1,022	Employees	Rethink
Supporting bike sharing stations	11	0	7,626	106,357	7,353	32,869	497	Employees	Rethink

Applying MCDM to aggregate absolute mean savings into scores

Portfolio output – total savings and scores

	GWP [kg CO_2-eq/a]	CED [MJ-eq/a]	RMI [kg/a]	Land Use [-/a]	Water Use [m^3-eq/a]
Total savings	3,814,967	55,048,810	4,792,366	9,961,245	516,441
Max. possible savings (current action set; company-specific scaling)	4,182,105	58,139,340	4,806,349	16,100,956	537,886
Score	91	95	100	62	96
Total score	89				
Sensitivity analysis:		**Deviation**			
Score best-case	124	40%			
Score worst-case	53	-40%			

Figure 4.4: Results of the DST for case study 1: inputs, action savings, and scores.

The actions portfolio (Figure 4.4) attains a total score of 89 points, with sub-indicator scores of 91 (GWP), 95 (CED), 100 (RMI), 62 (land use), and 96 (water use). In absolute terms, the portfolio saves about 3.8 kt CO_2-eq, 55 TJ and 4.8 kt RMI per year, plus substantial land- and water-use reductions. The high subscores for GWP, CED, RMI and water indicate that the portfolio exploits a large share of the improvement potential represented by the current action set in this context.

Action-level effects are heterogeneous but dominated by employee-scaling actions. “Desk sharing” ranks first (score 44) and accounts for the majority of savings, consistent with the large office footprint. “Promotion of ride sharing” ranks second (score 29) with substantial additional gains. “Use of renewable energies” ranks third (score 4), but carries a noticeable land-use penalty. The net effect of using renewable energies remains positive given the modest electricity demand of the site and the strength of other actions. Additional workplace and mobility actions contribute smaller gains. The uncertainty analysis yields a best-case portfolio score of 124 (+40 %) and a worst-case score of 53 (-40 %), reflecting substantial scenario uncertainty around a high mean-based performance.

4.3.2 Case study 2 – electronics industry

As case study 2, we consider a company in the electronics industry to examine how plastic recyclate can be reintegrated into internal company cycles as a case-specific action. The focus is on polyamide (PA) 6.6, of which approximately 10,000 t were produced in

2020 (Phoenix Contact 2022). Around 6,000 employees (5,145 FTE) work at the site (Phoenix Contact). The average specific electricity intensity of the site is approximated at 0.49 kWh/kg (Mena Ledezma and Posada Correa 2023).

Input data of the company

Company data	Value	Unit
Employees	5,145	n
Electricity demand	6,860,000	kWh/a
Transport distance	-	km/a
Mass of waste PA 6.6	60	t/a

Inputs scaled with mean benefit of actions

Summary of the selected actions – ranking, scores and mean annual savings relative to the status quo

Actions name	Ranking	Score	GWP [kg CO_2-eq/a]	CED [MJ-eq/a]	RMI [kg/a]	Land Use [-/a]	Water Use [m^3-eq/a]	Scaling	R-Strategy
Desk sharing	1	37	2,208,392	38,460,391	3,971,287	13,254,267	515,965	Employees	Rethink
Promotion of ride sharing	2	25	2,001,405	28,596,682	2,317,823	9,850,103	213,054	Employees	Rethink
Use of renewable energies	3	4	2,629,438	28,527,893	2,123,719	- 21,157,715	292,167	Electricity demand	Rethink
Closed-loop blending of PA 6.6 regranulate in injection molded housings	4	4	183,423	3,122,237	69,672	- 2,569	218,426	Mass of waste PA 6.6	Recycle
Offer discounted public transport ticket	5	3	241,815	3,216,140	254,678	1,072,733	18,008	Employees	Rethink
Offer bike leasing for employees	6	3	218,663	3,116,326	236,670	1,054,725	18,008	Employees	Rethink
Implementing a car sharing possibility by an established provider for employees and companies of the industrial park	7	2	481,749	4,892,600	- 23,981	729,198	- 36,779	Employees	Rethink
Use of smart and shared parking spaces	8	1	39,031	976,592	323,043	220,013	7,800	Employees	Rethink
Sharing of canteen	9	1	61,388	887,363	74,124	311,021	7,253	Employees	Rethink
Sharing of daycare center	10	1	42,590	615,012	50,402	213,450	4,801	Employees	Rethink
Use of e-bikes for short business trips	11	0	19,757	285,316	21,095	96,520	1,753	Employees	Rethink
Supporting bike sharing stations	12	0	13,078	182,402	12,611	56,371	852	Employees	Rethink

Applying MCDM to aggregate absolute mean savings into scores

Portfolio output – total savings and scores

	GWP [kg CO_2-eq/a]	CED [MJ-eq/a]	RMI [kg/a]	Land Use [-/a]	Water Use [m^3-eq/a]
Total savings	8,140,729	112,878,953	9,431,140	5,698,116	1,261,308
Max. possible savings (current action set; company-specific scaling)	8,770,371	118,179,211	9,455,121	27,613,140	1,298,087
Score	93	96	100	21	97
Total score	81				
Sensitivity analysis:		**Deviation**			
Score best-case	127	57%			
Score worst-case	35	-57%			

Figure 4.5: Results of the DST for case study 2: inputs, action savings, and scores.

The actions portfolio (Figure 4.5) attains a total score of 81 points, with sub-indicator scores of 93 (GWP), 96 (CED), 100 (RMI), 21 (land use), and 97 (water). Annual savings amount to about 8.1 kt CO_2-eq, 113 TJ, and 9.4 kt RMI, plus substantial water use and some land use reductions.

Action-level results are heterogeneous and reflect the dominant scaling by employees, complemented by energy demand and the targeted closed material loop. “Desk sharing” ranks first (score 37) and accounts for the largest share of absolute savings, followed by “Promotion of ride sharing” (score 25). “Use of renewable energies” ranks third (score 4), improving GWP, CED, RMI, and water while carrying a heavy land-use burden. The net effect remains positive given the site’s modest electricity demand and the strength of other actions. The case-specific recycling circularity action (“Closed-loop blending of PA 6.6 regranulate in injection-molded housings”) ranks fourth, yielding incremental benefits with a negligible land-use burden. Additional workplace and mobility actions contribute smaller gains. Uncertainty analysis indicates a best-case score of 127 (+57 %) and a worst-case score of 35 (-57 %), revealing large scenario uncertainty around a high mean-based performance.

4.3.3 Case study 3 – soil treatment

The company in case study 3 specializes in mechanical treatment of excavated soil and seeks a site near construction activities to minimize transport. Some parameters remain uncertain due to pending approvals and contractor selection.

Input data of the company

Company data	Value	Unit
Employees	6	n
Electricity demand	13,500,000	kWh/a
Transport distance	343,500	km/a
Mass of soil	100,000	t/a

Inputs scaled with mean benefit of actions

Summary of the selected actions – ranking, scores and mean annual savings relative to the status quo

Actions name	Ranking	Score	GWP [kg CO_2-eq/a]	CED [MJ-eq/a]	RMI [kg/a]	Land Use [-/a]	Water Use [m^3-eq/a]	Scaling	R-Strategy
Treatment of soil instead of landfill	1	51	197,789	611,341	57,513,692	9,674,359	778,871	Mass of soil	Recycle
Use of a shared storage to increase load of transports	2	1	71,429	1,030,956	42,627	193,715	2,293	Mass of soil	Rethink
Use of electric trucks in operational transport	3	1	274,953	2,638,329	33,287	- 490,673	- 15,617	Transport distance	Rethink
Desk sharing	4	0	2,575	44,852	4,631	15,457	602	Employees	Rethink
Promotion of ride sharing	5	0	2,334	33,349	2,703	11,487	248	Employees	Rethink
Offer discounted public transport ticket	6	0	282	3,751	297	1,251	21	Employees	Rethink
Offer bike leasing for employees	7	0	255	3,634	276	1,230	21	Employees	Rethink
Implementing a car sharing possibility by an established provider for employees and companies of the industrial park	8	0	562	5,706	- 28	850	- 43	Employees	Rethink
The company provides an increased number of charging stations for electric vehicles with charging discount	9	0	637	5,499	- 613	880	- 115	Employees	/
Sharing of canteen	10	0	72	1,035	86	363	8	Employees	Rethink
Use of smart and shared parking spaces	11	0	46	1,139	377	257	9	Employees	Rethink
Sharing of daycare center	12	0	50	717	59	249	6	Employees	Rethink
Use of e-bikes for short business trips	13	0	23	333	25	113	2	Employees	Rethink
Supporting bike sharing stations	14	0	15	213	15	66	1	Employees	Rethink

Applying MCDM to aggregate absolute mean savings into scores

Portfolio output – total savings and scores

	GWP [kg CO_2-eq/a]	CED [MJ-eq/a]	RMI [kg/a]	Land Use [-/a]	Water Use [m^3-eq/a]
Total savings	551,021	4,380,852	57,597,433	9,409,603	766,307
Max. possible savings (current action set; company-specific scaling)	5,725,668	60,522,432	61,777,403	9,900,276	1,357,047
Score	10	7	93	95	56
Total score	52				
Sensitivity analysis:		**Deviation**			
Score best-case	53	2%			
Score worst-case	52	-2%			

Figure 4.6: Results of the DST for case study 3: inputs, action savings, and scores.

The actions portfolio (Figure 4.6) achieves a total score of 52 points, reflecting high progress in resource- and land-related indicators and modest progress in climate- and energy-related indicators. In absolute terms, the portfolio saves roughly 0.55 kt CO_2-eq, 4.4 TJ, and 58 kt RMI per year, with major land- and water-use reductions. Relative to case-specific maximum potentials, sub-indicator scores are about 10 (GWP), 7 (CED), 93 (RMI), 95 (land), and 56 (water).

"Treatment of soil instead of landfill" ranks first (score 51) and dominates portfolio performance as case-specific circular action of type Recycle. "Use of a shared storage to increase load of transports" (score 1) further improves performance by increasing logistics efficiency in a case-specific way. "Desk sharing" and other employee-scaling actions add

comparatively small but positive contributions, reflecting the small share of employee-related impacts in this soil- and logistics-dominated case.

If the renewable-electricity action is added, GWP, CED, RMI, and water use approach their maxima, but land use becomes strongly negative due to land occupation by ground-mounted photovoltaic (GM-PV). This results in a negative mean-based action score and highlights a pronounced trade-off that users must consider. For the portfolio configuration analyzed here (excluding that non-beneficial action), the uncertainty analysis yields narrow bands (best case 53 points, worst case 52 points), suggesting robust mean-based results.

4.3.4 Case study 4 – detergent manufacturer

The fourth case is a detergent producing and packaging company representing an energy-intensive manufacturing context with significant material flows. The headquarters site in Düsseldorf-Holthausen has 6,000 employees (5,145 FTE) (Henkel AG & Co. KGaA 2025b). The company operates its own fleet, e.g., for production, warehouse, and sales (Henkel AG & Co. KGaA 2025a). Yearly transport distances are estimated based on the number of employees operating and the site's road network (Henkel AG & Co. KGaA 2025b), and electricity demand is estimated based on a public report on the site's electricity network (Reitze et al. 2024).

Input data of the company

Company data	Value	Unit
Employees	5,145	n
Electricity demand	2,060,000,000	kWh/a
Transport distance	8,212,500	km/a
Detergents produced	100,000,000	n/a

Inputs scaled with mean benefit of actions

Summary of the selected actions – ranking, scores and mean annual savings relative to the status quo

Actions name	Ranking	Score	GWP [kg CO_2-eq/a]	CED [MJ-eq/a]	RMI [kg/a]	Land Use [-/a]	Water Use [m^3-eq/a]	Scaling	R-Strategy
Refill concentrate plastic pouch instead of conventional plastic bottle	1	8	3,821,000	49,457,000	2,009,000	17,233,500	1,327,000	Detergents produced	Reuse
Desk sharing	2	6	2,208,392	38,460,391	3,971,287	13,254,267	515,965	Employees	Rethink
Promotion of ride sharing	3	5	2,001,405	28,596,682	2,317,823	9,850,103	213,054	Employees	Rethink
Offer discounted public transport ticket	4	1	241,815	3,216,140	254,678	1,072,733	18,008	Employees	Rethink
Offer bike leasing for employees	5	0	218,663	3,116,326	236,670	1,054,725	18,008	Employees	Rethink
Implementing a car sharing possibility by an established provider for employees and companies of the industrial park	6	0	481,749	4,892,600	- 23,981	729,198	- 36,779	Employees	Rethink
The company provides an increased number of charging stations for electric vehicles with charging discount	7	0	546,475	4,715,135	- 525,402	754,741	- 98,796	Employees	/
Sharing of canteen	8	0	61,388	887,363	74,124	311,021	7,253	Employees	Rethink
Use of smart and shared parking spaces	9	0	39,031	976,592	323,043	220,013	7,800	Employees	Rethink
Sharing of daycare center	10	0	42,590	615,012	50,402	213,450	4,801	Employees	Rethink
Refill plastic pouch made of secondary materials	11	0	364,000	12,610,000	431,000	- 16,000	134,000	Detergents produced	Recycle
Use of e-bikes for short business trips	12	0	19,757	285,316	21,095	96,520	1,753	Employees	Rethink
Supporting bike sharing stations	13	0	13,078	182,402	12,611	56,371	852	Employees	Rethink

Applying MCDM to aggregate absolute mean savings into scores

Portfolio output – total savings and scores

	GWP [kg CO_2-eq/a]	CED [MJ-eq/a]	RMI [kg/a]	Land Use [-/a]	Water Use [m^3-eq/a]
Total savings	10,059,343	148,010,958	9,152,348	44,830,640	2,112,918
Max. possible savings (current action set; company-specific scaling)	806,314,165	8,778,359,135	648,232,363	44,846,640	89,983,893
Score	1	2	1	100	2
Total score			21		
Sensitivity analysis:		**Deviation**			
Score best-case	27	27%			
Score worst-case	16	-27%			

Figure 4.7: Results of the DST for case study 4: inputs, action savings, and scores.

The actions portfolio (Figure 4.7) attains a total score of 21 points, with sub-indicator scores of 1 (GWP), 2 (CED), 1 (RMI), 100 (land use), and 2 (water). In absolute terms, annual savings amount to 10 kt CO_2-eq (GWP), 148 TJ-eq (CED), 9.2 kt (RMI), 44.8 million land use units, and 2.1 million m^3-eq (water).

"Refill concentrate plastic pouch instead of conventional plastic bottle" ranks first (score 6) as case-specific action and is the main driver of portfolio performance, delivering especially large savings in RMI, land use, and water use. "Desk sharing" ranks second (score 5) and makes a major contribution due to the large employee base. Among mobility actions, "Promotion of ride sharing" (score 2) and "Offer discounted public transport ticket" (score 2) provide additional moderate gains. The second case-specific action, "Refill plastic pouch made of secondary materials", yields smaller net benefits with a minor land-use burden. Both packaging actions explicitly target circularity through recycling and allow decision makers to distinguish these circular packaging actions from purely energy- or mobility-related actions.

Energy-related actions in this case illustrate strong trade-offs. “Use of renewable energies” substantially improves GWP and CED and slightly improves RMI and water use but is heavily penalized in land use due to the GM-PV worst-case, producing a strongly negative mean-based action score. “Use of electric transport vehicles” similarly reduces GWP and CED but increases land and water use under the adopted electricity-mix assumptions, resulting in a negative net score. The uncertainty analysis yields a best-case portfolio score of 27 (+27 %) and a worst-case score of 16 (-27 %), indicating moderate uncertainty around a relatively low mean-based performance.

4.3.5 Summary and comparison of the case studies

The four case studies reveal consistent patterns in how structural drivers shape portfolio performance, action rankings, and uncertainty, and they collectively address SRQ 4. Within the present pre-quantified action set, service-oriented and mixed contexts are dominated by actions that scale with employees (workplace and mobility). Production- and material-intensive contexts derive most gains from meso-level interventions that alter logistics of material flows and from closed-loop actions that enhance circularity.

The service-oriented consulting case attains near-maximal sub-indicator scores (particularly for GWP, CED, RMI and water) and a high portfolio score. This reflects that employee- and workspace-centric actions are consistently beneficial and involve few structural trade-offs. The electronics-industry case combines both profiles: employee actions underpin high scores and robustness, while the case-specific PA 6.6 closed loop adds gains. Because normalization is company-specific and based on each firm’s total mean potential across the current action set, these high scores indicate that, in these two contexts, most of the improvement potential represented by the present catalog of actions is exploited. They do not imply that these companies are better in an absolute sense than the soil-treatment or detergent cases. Across all cases, renewable-electricity actions illustrate an important caveat: under some implementations (e.g., GM-PV in the worst-case scenario), land use penalties can outweigh climate/energy benefits in equal-weight scoring, highlighting the value of context-appropriate design.

In the production-oriented soil-treatment case, case-specific actions that change soil use and logistics strongly improve RMI, land, and water, while electrification and renewable-electricity options introduce trade-offs between climate/energy and land/water. At the detergent manufacturer, high site energy intensity magnifies land-occupation burdens under the adopted renewable-electricity implementation, so the renewable-energy action is strongly negative despite GWP/CED gains. Consequently, even when only beneficial actions are selected, the soil-treatment and detergent cases achieve lower scores than the consulting and electronics cases, because a larger share of their theoretical improvement potential lies in actions that are either outside the current action set or involve strong trade-offs.

Overall, the applications show that:

- Total scores and rankings are highly context-dependent and can be dominated either by employee-scaled actions (service/mixed contexts) or by case-specific material/logistics actions (production/material-intensive contexts).
- Circularity-oriented actions such as refill packaging and soil treatment, which address Recycle, can both enhance circularity and even yield the highest environmental benefits. Yet this is not guaranteed and trade-offs (e.g., increased energy use or land occupation) must be explicitly evaluated.
- Excluding non-beneficial actions and prioritizing low-variance actions can narrow uncertainty bands and stabilize portfolios, which may improve the robustness of decisions.
- Separating CE reporting from the environmental score clarifies where circularity actions also deliver environmental gains and where they lead to trade-offs.

From a CE perspective, within the current pre-quantified action set, the R-strategy mapping shows that the generally applicable actions are predominantly Rethink actions, while case-specific actions introduce additional Reuse and Recycle strategies. In practice, users can therefore use the DST not only to select environmentally effective actions, but also to design portfolios with an explicit mix of R-strategies (e.g., ensuring that at least one Reuse or Recycle action is implemented) and to report circularity-relevant metrics alongside environmental results.

4.4 Discussion

4.4.1 Overview of key findings and positioning

The case applications show that action priorities and trade-offs are strongly context-dependent and that energy-related actions can yield large climate and energy benefits but also land- and water-use burdens.

Compared with existing CE and EIP tools, which often provide retrospective and aggregated indicators at company or park level (e.g., (UNIDO 2016; Zhao et al. 2017; Baratsas et al. 2022; Cagno et al. 2023)), the DST offers an ex-ante, action-level micro–meso perspective for ranking and portfolio design with minimal input data. By operationalizing composite-indicator guidance (Nardo et al. 2005; OECD 2008) in an action-based, company-oriented format, the DST fills the gap between detailed LCA studies and high-level CE frameworks and links CE indicators more directly to everyday decision processes in companies and industrial parks.

The four case studies also highlight generic challenges of ex-ante sustainability decision-making at company and park levels that are relevant regardless of the specific assessment tool used. First, action priorities are highly context-dependent: service-oriented cases are dominated by workplace and mobility actions, whereas production- and material-intensive cases are driven by logistics and closed-loop interventions, so generic “best actions” do not exist. Second, several actions that appear beneficial from a

single-indicator perspective (e.g., GWP) reveal strong trade-offs when assessed across indicators, most notably renewable-electricity and electrification options that reduce climate impacts but substantially increase land and/or water use. Third, scenario bands show that uncertainty in action effects can be large for some interventions, implying that robust decisions require combining tool results with expert judgment rather than relying on point scores alone.

4.4.2 Addressing SRQ 1: evaluation

The chosen environmental indicator set (GWP, CED, RMI, water use, land use) is unambiguous, measurable, and coherent with LCA practice, and covers environmental resources in line with MIPS (Liedtke et al. 2014) and common EIP indicators (Verkic et al. 2025a). Actions span internal company actions (e.g., mobility, fleet, energy) and inter-company sharing/symbiosis (shared infrastructure), reflecting the micro–meso emphasis in CE and eco-industrial development (Kristensen and Mosgaard 2020; Cagno et al. 2023). In two of four case studies, desk sharing, a meso-level action, is the highest-scoring action, and in a third case it ranks second.

CE is represented in the DST by mapping actions to R-strategies and by allowing users to attach simple CE indicators to each action. These CE attributes are displayed next to the environmental scores in the action ranking and are summarized at portfolio level, but they are not normalized, weighted, or aggregated with the environmental indicators. This avoids compensating high environmental impacts with high circularity and is consistent with evidence that circularity does not guarantee impact reduction (Harris et al. 2021; Elia et al. 2024). In practical terms, the CE information is used to (i) identify actions that combine high environmental scores with strong circularity characteristics, (ii) highlight actions where circularity and environmental performance diverge, and (iii) design portfolios that reflect both environmental and CE ambitions (e.g., a minimum number of Reuse or Rethink actions). The case-specific, CE-oriented actions illustrate that such a separate but linked CE view is needed: some deliver both circularity and environmental benefits, while others involve trade-offs that become visible when CE attributes are examined alongside the environmental scores.

4.4.3 Addressing SRQ 2: normalization, weighting, and aggregation

Normalization follows established guidance for composite indicators (Ebert and Welsch 2004; Nardo et al. 2005; OECD 2008; Gan et al. 2017). We adopt max normalization at the indicator level anchored in the mean effect of actions (the average of best- and worst-case scenario reductions) and scaled by company inputs. Dividing by this basis yields normalized values that can be interpreted as contributions to the company-specific improvement potential.

Weighting uses equal default weights to minimize effort and avoid arbitrary preference assumptions (Gan et al. 2017; Paradowski et al. 2021; Kühnapfel 2021). Although equal weighting is debated (Pizzol et al. 2017; Torkayesh et al. 2022), it is widely used in practice (Gan et al. 2017) and is seen as appropriate for a generally usable, low-effort tool. Participatory/data-driven methods or pre-weighting of environmental indicators could be

tested where effort and data availability permit (Goulart Coelho et al. 2017; Gan et al. 2017; Angelo et al. 2017).

The case studies highlight the sensitivity of results to the indicator set and equal weighting. In the soil-treatment and detergent cases, the renewable-energy action receives a negative mean score because land and water burdens outweigh GWP and CED savings. Not implementing this action keeps GWP and CED scores low and leaves part of their improvement potential unused. This shows that aggregate scores must be interpreted together with indicator-level results and that alternative weighting schemes may be appropriate where climate or energy indicators are prioritized.

To illustrate the effect of alternative weights, we tested a hypothetical "climate-focused" weighting scenario in Case Study 3, in which GWP and CED each receive an adjusted weight of 0.35, while RMI, land use, and water use share the remaining weight of 0.10 each. Under equal weighting, "treatment of soil instead of landfill" is the highest-scoring action (51 points), whereas "use of renewable energies" obtains a strongly negative mean-based score (-38 points) because land-use and water-use burdens dominate its climate and energy benefits. With the climate-focused weights, actions that primarily reduce GWP and CED, such as "use of renewable energies", gain score relative to the equal-weight baseline and move to first place with a positive net score (27 points), closely followed by "treatment of soil instead of landfill" (26 points). This example shows that rankings are sensitive to corporate priorities and that different weighting schemes can yield markedly different results.

Aggregation uses WSM to produce a single environmental score per action and portfolio. WSM is transparent, compatible with zero and negative values, and widely used (Nardo et al. 2005; Gan et al. 2017). CE indicators remain separate to avoid double counting and compensation. Uncertainty analysis then compares best- and worst-case scores against mean-based scores.

4.4.4 Addressing SRQ 3: usability

The tool is deliberately designed as low-effort: all general actions scale with a small set of readily available company inputs (employees, energy demand, self-operated transport distances). Defaults and operative indicators limit data burden and reduce opportunities for strategic manipulation. Clear indicator definitions, action fact sheets, and explicit normalization, weighting, and aggregation rules support transparency and traceability (Nardo et al. 2005; OECD 2008). As low-effort assessment tools can support awareness and decision-making in firms (Bais et al. 2025), we expect that our dual reporting of scores and absolute deltas will simplify communication compared to stand-alone LCA or material flow analysis (Jerome et al. 2022) and may help non-experts grasp priorities.

4.4.5 Addressing SRQ 4: effectiveness in application

In the consulting case, employee-scaled actions dominate and yield near-maximal sub-indicator scores and relatively narrow uncertainty bands. In the electronics case, the same pattern appears, supplemented by a case-specific closed loop (PA 6.6 regranulation) that adds targeted benefits. In the soil-treatment and detergent cases, case-specific

circularity actions yield positive scores, whereas electrification and renewable-electricity options introduce climate- and energy-related trade-offs. These patterns suggest that the DST can help identify high-impact actions across micro and meso levels, reveal trade-offs, and expose uncertainty ranges that matter for decisions.

4.4.6 Addressing SRQ 5: action set design and extensibility

Following OECD (2008) and Valenzuela-Venegas et al. (2016), we define inclusion criteria for actions and indicators to improve transparency and comparability. When new actions (e.g., context-specific or nano-level) are added, normalization bases update automatically, preserving comparability while shifting scores as the total potential changes. CE indicators remain user-defined, and an optional economic view can be added without affecting environmental scoring.

At present, most generally applicable actions target employee mobility and workplace aspects, while production-related and material-efficiency actions appear mainly as case-specific additions. This focus limits coverage for material- and energy-intensive sectors but also illustrates how, within one category, the DST can highlight a few hotspot actions (e.g., desk sharing, ride sharing) that deliver most of the benefits, while others add little.

4.4.7 Methodological reflections and limitations

Nevertheless, several limitations remain.

1. The current parameterization reflects German and European contexts (e.g., electricity mix, commuting modal split). Applications elsewhere should adapt scenario assumptions, which can influence the results of actions.
2. Dynamic interactions among actions (e.g., substitution between e-bikes and electric vehicles for business trips) are not modeled and are only indicated via coherence notes in the action descriptions. Because portfolio scores under the WSM aggregation are obtained as the sum of normalized marginal effects, they implicitly assume additive and independent action effects. This can over- or underestimate combined outcomes when actions are based on the same improvement potential (e.g., changes in modal split) or are synergetic. This static, additive treatment is consistent with conventional LCA practice but can be complemented by system dynamics integrated LCA approaches that explicitly model feedback loops, time delays, and dynamic interactions between technical and behavioral variables where such dynamics are critical (Yi et al. 2023). Portfolio scores should therefore be interpreted as approximations: where strong interactions are expected, users should adapt the underlying changes and complement the DST with case-specific analysis and qualitative assessment (Günther et al. 2020).
3. To keep effort low and limit strategic manipulation, the tool relies on a small set of required inputs and default assumptions. This design entails a speed–precision trade-off: the resulting scores provide rapid guidance for prioritization but should not be interpreted as precise forecasts of realized environmental performance.

This would require case-specific adjustments, LCAs or detailed studies beyond the scope of the DST.

4. Results for production-intensive cases are sensitive to the equal-weighting choice, especially when land-intensive renewable options are considered.
5. No systematic usability assessment (e.g., structured surveys) was conducted

4.4.8 Practical implications and future work

Despite these limitations, the case applications suggest that the DST can provide useful support in practice. In all four cases, the required inputs were available from existing company data, so a first action ranking could be generated without additional data collection. The resulting rankings and scenario bands were used to structure internal discussions about which actions to examine in more detail and where targeted LCAs or feasibility studies would be needed before implementation. Industrial parks and municipalities can use the approach to explore shared infrastructures and symbiosis concepts (Zhu et al. 2010; UNIDO 2016; World Bank 2021), complementing broader frameworks with an action-level perspective while recognizing that the DST does not replace detailed planning tools.

In feedback discussions, company and municipality representatives expressed positive views on the approach. For example, they stated that 'the simple action overview and scores are understandable' and it is 'a good way to communicate trade-offs to non-expert colleagues'. Several also noted that some results were unexpected and led to internal discussions about adjusting initial implementation priorities, although detailed follow-up decisions are beyond the scope of this paper.

Integrating the tool with broader frameworks (e.g., all KREGI categories) can align company-level choices with industrial park-wide objectives. Researchers can extend the methodology to nano and macro CE levels, add new actions and indicators, and test alternative weighting and aggregation schemes or multi-layer sustainability integration (environmental–economic–social). Future work should: (i) expand case applications to build benchmarks; (ii) test alternative weighting, aggregation and sensitivity approaches, including probabilistic sensitivity analysis where data permit; (iii) adapt scenarios for non-European contexts; and (iv) integrate social and economic dimensions for comprehensive sustainability assessment (Singh et al. 2009).

4.5 Conclusion

This paper presented a DST that ranks operational actions by environmental performance and evaluates circularity as a complementary dimension. The DST provides a multi-level and action-level prioritization with a single interpretable environmental score and a separate view on circularity-related trade-offs.

The environmental indicator set (GWP, CED, RMI, land use, water use) enables consistent evaluation of diverse actions at company and industrial-park levels. The chosen normalization, weighting, and aggregation scheme yields a single score per action and portfolio while preserving information on harmful effects and trade-offs. Implementing the tool

with a small set of readily available company inputs keeps data requirements low and calculations transparent and traceable.

Applications to a consulting firm, an electronics manufacturer, a soil-treatment company, and a detergent producer demonstrate that the DST is applicable across diverse organizational contexts and that action priorities are strongly context-dependent. In service-oriented and mixed settings, workplace and mobility actions underpin high scores and relatively narrow uncertainty bands. In production- and material-intensive settings, logistics and case-specific closed-loop actions can deliver substantial resource- and land-related improvements but may introduce trade-offs in climate- and energy-related indicators. Circularity-focused actions such as refill packaging and internal PA 6.6 regranulation can enhance circularity and reduce environmental impacts, but this is not guaranteed.

In practical terms, the tool can help companies identify and prioritize high-impact actions from a pre-quantified general action set, add and compare case-specific actions, and communicate expected environmental benefits through a simple score plus absolute savings. Because normalization is based on the company-specific maximum achievable mean reduction for each indicator, the aggregated environmental scores are strictly intra-organizational. They are intended only for ranking actions and portfolios within a given company or industrial park and must not be used to compare the resulting environmental scores of different organizations or sites.

Industrial park operators and municipalities can use the approach to support infrastructure planning, company selection, and the design of symbiosis concepts at industrial park level. The current implementation is limited by the number of case applications, the European parameterization, and simplifying assumptions about interactions between actions. With broader application and methodological extensions (e.g., alternative weighting/aggregation and additional indicators), the DST could evolve into a more robust component of decision-making.

5 Synthesis & comprehensive discussion

This section synthesizes the main results of the three papers, places them in the context of existing research and shows how they jointly address the overall aim of the thesis. Beyond summarizing the individual papers, this chapter highlights the added value of integrating them into a single methodological framework. While each publication contributes a specific element, their combination creates a structured workflow for ex-ante environmental decision-support that is not found in existing CE or IE assessment approaches. The framework is structured along the three methodological pillars: the indicator base for industrial and urban symbiosis and EIPs, the KREGI evaluation approach for actions and scenarios, and the DST. To make the cumulative logic explicit at the start of this synthesis, Table 5.1 summarizes what each publication contributes and how its output is used in the next step.

Table 5.1: Publications I–III contributions and reuse in the cumulative framework.

Publication	Main purpose	Key output for dissertation	What is reused in the next step
I	Build CE-aware environmental indicator base (RQ1)	Scoping review for structured indicator landscape; indicator-to-R-strategy mapping; compact indicator core identification	Core indicators + CE/R-strategy mapping logic used in II and III
II	Ex-ante action-based evaluation method (RQ2)	KREGI approach: action requirements + life-cycle-phase/CE-level structure + 3-step prospective LCA workflow; scenario logic; car-sharing example	KREGI workflow + scenario structure used to build/quantify the broader action library in III
III	Low-effort DST and behavior across cases (RQ3–RQ4)	DST: LCA-MCDM scoring; pre-quantified action library; scenario bands; circularity shown as complementary aspect; four case studies	Integrated tool + cross-case insights used for thesis-level synthesis, discussion, and outlook

5.1 Integrated synthesis of main findings

The three papers of this thesis form successive layers of one integrated framework, as outlined in Section 5.1.4. This section synthesizes the main findings of these three methodological layers with a focus on their interaction and on how they jointly respond to the research gaps identified in Section 1.2.3.

5.1.1 Environmental indicators for industrial and urban symbiosis and eco-industrial parks

Publication I conducts a scoping review of environmental indicators used in studies on industrial and urban symbiosis, EIPs and related meso-level CE aspects, and identifies 624 comprehensive indicators. The indicators cluster mainly into a few dominant categories: material, waste and water; environment and emissions; energy; and a smaller group related to symbiosis and sharing. Within these categories, use is highly uneven: a relatively small core of indicators is applied frequently, while many others appear only once or in very specific contexts. Across the reviewed literature, a limited set of energy-, climate-, material-, waste-, and water-related indicators dominates practical assessment,

even though the overall indicator landscape remains fragmented, as also reported in the literature (Guinée 2002; Frischknecht et al. 2015; Valenzuela-Venegas et al. 2016; Zhao et al. 2017; Hauschild et al. 2018; Dong et al. 2022).

A distinctive contribution of Publication I is the explicit mapping of indicators to R-strategies. This mapping shows that indicators aligned with Rethink and Reduce are particularly common (e.g., avoided primary materials, improved resource productivity, reduced energy use), while Reuse and Recycle are also well represented. In contrast, indicators directly associated with strategies such as Refuse, Refurbish, Remanufacture or Repair appear only rarely in industrial- and urban-symbiosis contexts. This mirrors broader analyses of CE conceptualizations and metrics, which consistently find that higher-order strategies such as Refuse, Rethink, Reduce, and Reuse are referenced far less often than Recycle (and, in some cases, Recover-oriented options) in both definitions and practice (Kirchherr et al. 2017; Potting et al. 2017; Schöggl et al. 2020).

Building on these results, this cumulative thesis uses the scoping review as the empirical basis for defining the environmental indicator core of the integrated framework. For the framework developed here, the findings from Publication I support two main design choices. Guided by work on central LCIA and energy-system impact categories and on input-oriented resource indicators (Liedtke et al. 2014; Frischknecht et al. 2015; Hauschild et al. 2018; Baumgärtner et al. 2021), this thesis adopts a compact core set of environmental indicators: GWP, CED, RMI, WU, and LU. Together, these five indicators capture climate and energy burdens, material use, and two key "MIPS-type" resource categories (water and land) (Liedtke et al. 2014; Frischknecht et al. 2015; Hauschild et al. 2018; Baumgärtner et al. 2021) in a way that remains manageable for practical application.

Second, and as discussed in detail in Section 1.2.2, the thesis treats circularity and environmental impacts as complementary but distinct dimensions. Circularity indicators and R-strategies are used to structure and interpret interventions at nano, micro and meso levels, whereas LCA-based environmental indicators provide the quantitative basis for scoring and comparison. By keeping these dimensions separate, the framework avoids compensatory aggregation between circularity metrics and environmental pressures and helps to keep rebound and burden-shifting risks visible.

Overall, Publication I both reflects and extends existing work by quantifying indicator use frequencies, revealing gaps in R-strategy coverage and providing a structured, CE-aware indicator base for subsequent methodological developments. In the cumulative framework, this indicator base underpins the choice of the five core environmental indicators used in KREGI/DST (GWP, CED, RMI, WU, and LU). This selection is supported by Publication I's scoping review (457 sources and 624 clustered indicators), which shows that some energy-, climate-, material-, waste-, and water-related indicators form the repeatedly used core in meso-level industrial symbiosis and EIP assessments.

5.1.2 Methodological approach to evaluate improvements for companies based on actions and scenarios

Publication II develops the KREGI approach as an ex-ante, action- and scenario-based method to evaluate environmental improvements from actions in industrial parks and companies. It structures actions along the life cycle of industrial parks and distinguishes three phases: planning (e.g., site selection, transport access, energy and infrastructure strategies), building (e.g., building design, construction materials, flexibility) and operation (e.g., mobility concepts, shared services and infrastructure, industrial symbiosis applications). This life cycle framing builds on prior work that applies life cycle thinking to industrial park development and argues for considering all phases (from design and layout through commercialization, operation, and renewal) in planning and evaluation (Adoue et al. 2015; Belaud et al. 2019). It also aligns with recent low-carbon CE frameworks that emphasize systemic transformations and demand-side actions before substitution and end-of-pipe solutions (Zhang et al. 2026). KREGI operationalizes this by linking each phase to criteria, operational indicators and concrete actions.

A core contribution of Publication II is the explicit definition and selection of actions: they must be innovative relative to the status quo, clearly defined, measurable, environmentally relevant, and significant within the current planning horizon. This addresses a gap in the industrial symbiosis literature, where case studies often lack a common framework for comparing exchanges and relating them to broader network dynamics (Chertow and Ehrenfeld 2012; Boons et al. 2017). KREGI then quantifies these actions via a three-step prospective LCA procedure that is applied ex-ante (scoping, LCI, LCIA) under status-quo, best-case and worst-case scenarios for GWP, CED and RMI. This is consistent with best practices in prospective and policy-relevant LCA (Guinée 2002; International Organization for Standardization 2006; Fauré et al. 2017; Arushanyan et al. 2017; Hauschild et al. 2018).

Scenario analysis is used to capture uncertainty and contextual variability. For each action, a status-quo, best-case and worst-case scenario are modeled, representing different levels of adoption, performance and boundary conditions. This is particularly important for actions that depend on behavioral change (e.g., mobility concepts) or on uncertain technologies (e.g., electrification, renewable energies). The use of a small set of discrete scenarios, rather than full probabilistic modeling, reflects the need for a simple and communicable representation of uncertainty and is consistent with how scenario analysis is used in policy-oriented futures and future-oriented LCA frameworks (Skea et al. 2021; Moshrefi et al. 2022; Bosco et al. 2025). A comparable distinction between “alternatives” and “scenarios” is made in recent water-sector frameworks for symbiotic CE solutions (Bosco et al. 2025). In these frameworks, alternatives denote technical or organizational configurations that actors can choose or adjust, while scenarios describe broader contextual developments beyond their control (e.g., regulation or energy mix), and are used to test the robustness of alternatives under different plausible futures (Bosco et al. 2025).

The car-sharing action illustrates how KREGI operates in practice and how its results align with existing shared-mobility studies. In KREGI, substitution patterns between modes and different shares of combustion and electric vehicles, including charging infrastructure, are explicitly modeled. Under favorable conditions, car sharing reduces GWP and CED at industrial-park level, but increases RMI. Under less favorable substitution patterns, net environmental benefits can be small or even negative. This is consistent with the nuanced picture reported in the car-sharing LCA literature (Nijland and van Meerkerk 2017; Amatuni et al. 2020; Arbeláez Vélez 2024).

Within the cumulative framework, these features of the KREGI approach provide the methodological basis for quantifying actions consistently across companies and industrial parks. Compared with indicator-based scoring methods for EIPs, which compute composite performance indices from fixed indicator sets (Zhao et al. 2017; Qiu and Luo 2021; Babkin et al. 2023), KREGI delivers a richer picture of how concrete actions alter environmental indicators under different assumptions and scenarios. It therefore complements existing frameworks by adding an ex-ante, action-specific and scenario-based layer to industrial-park evaluation and by making the links between life-cycle phases, CE levels and environmental outcomes explicit. In the integrated thesis framework, KREGI thus acts as the quantitative bridge between the indicator base from Publication I and the LCA-MCDM DST in Publication III.

5.1.3 Decision-support tool

Publication III builds on the indicator base from Publication I and the KREGI approach from Publication II to develop a low-effort, quantitative DST that ranks actions at company and industrial-park level by environmental performance. Circularity is additionally treated as a complementary, non-compensatory perspective. The DST uses five environmental indicators (GWP, CED, RMI, WU, and LU) and maps each pre-quantified action to relevant R-strategies, so that circularity information can be displayed alongside environmental results without being numerically aggregated into a single score. This design avoids compensation effects in which high circularity scores could mask increased environmental burdens or vice versa and allows users to see clearly where circular strategies and environmental benefits align or diverge. Environmental scoring is based on pre-quantified action effects and requires only a small set of company-specific inputs (e.g., number of employees, electricity demand, transport activity) plus a simple yes/no selection of applicable actions, which makes the tool usable under typical SME-type data and capacity constraints.

At the core of the DST is a deliberately simple LCA-MCDM design. For each company and indicator, action effects are normalized via an action-based maximum, defined as the sum of mean effects of all applicable actions, so that scores are anchored to the improvement potential represented by the current action set and are not sensitive to arbitrary changes in the range of underlying values. All five environmental indicators are given equal weight by default, as a transparent choice under heterogeneous and often unknown stakeholder preferences. This follows common practice in the composite-indicator and sustainability-indicator literature, which notes that equal weighting is often adopted

when no sound empirical basis or consensus on alternative weighting schemes is available (Nardo et al. 2005; OECD 2008; Gan et al. 2017). Equal weighting is not a neutral or scientifically determined choice, but a value-based assumption that should be made transparent and treated carefully in interpretation (Pizzol et al. 2017). Aggregation uses a simple weighted sum, but unlike standard 0-1 normalization it allows negative normalized values so that detrimental effects in single indicators remain visible. This design responds to concerns that certain normalization and aggregation schemes can distort results or hide trade-offs between indicators (Goulart Coelho et al. 2017; Gan et al. 2017). More generally, it reflects the point made in the MCDM literature that weighting and aggregation choices are core modeling decisions that differentiate methods and strongly influence evaluation outcomes (Taherdoost and Madanchian 2023). Scores are expressed as "points" and are complemented by absolute changes in each indicator to retain interpretability.

Recent work on normalization in EF methods shows that normalization choice can strongly influence single scores and sometimes even outweigh weighting effects, especially when reference inventories are incomplete or misaligned (Laurentiis et al. 2023). Comparable MCDM studies also demonstrate that different ranking algorithms can lead to markedly different orders even with the same data and weights (Zournatzidou et al. 2025). Against this backdrop, the DST's internal, action-based normalization and straightforward weighted-sum aggregation are intentionally conservative design choices that keep the reference system within the company/action set. It also avoids importing hard-to-control biases from external normalization schemes, at the cost of limiting cross-company comparability.

Uncertainty is represented through the status-quo, best-case and worst-case scenarios defined in the KREGI approach. The DST computes a mean-based score (using the average of best- and worst-case effects) and additionally scores for each scenario, using the same normalization basis, which yields simple scenario bands around each action's environmental score and around portfolio scores. These bands indicate how robust an action's ranking is to parameter and context uncertainty and are in line with using exploratory, non-probabilistic scenarios to represent uncertainty in policy-oriented futures and future-oriented LCA (Fauré et al. 2017; Skea et al. 2021; Moshrefi et al. 2022).

Because the DST builds portfolio scores by additively aggregating action effects, some portfolios may include overlapping or dependent actions, which can lead to double-counting or infeasible combinations. To address this without increasing the data burden or changing the low-effort scoring logic, this dissertation complements scoring with a qualitative interaction-screening layer (mutual exclusivity, overlap, dependency, synergy/rebound flags). The screening is documented and discussed in Section 5.5 and is used as a portfolio plausibility check rather than a quantitative correction.

Publication III applies the DST in four company case studies (a consulting firm, an electronics manufacturer, a soil-treatment company and a detergent producer) to explore how the framework behaves in different organizational and sectoral contexts. In the consulting company, actions related to workspace use (e.g., desk sharing) and employee

mobility emerge as high-leverage levers for GWP and CED reductions. This pattern reflects the importance of office buildings and commuting in service-oriented organizations (Kim et al. 2016; Harris et al. 2020; Stolze and Ricci 2022). In the electronics and detergent cases, the highest-scoring portfolios combine generic company-wide actions, such as mobility, building-related aspects, and renewable electricity, with sector-specific actions that target core production processes. This aligns with several organizational GHG-accounting and OLCA studies showing that major environmental hotspots often arise both from production-related processes and from generic activities such as purchased energy, buildings, and transport (WBCSD 2004; UNEP 2015; Ahmed et al. 2026). In the soil treatment company, actions targeting treatment processes and logistics dominate the environmental improvement potential, consistent with LCA-type studies that identify material handling and transport as central drivers in soil management systems (Magnusson et al. 2015; Hale et al. 2021).

Scenario bands reveal differences in robustness across actions and sectors. In the consulting case, high scores combined with relatively narrow bands indicate robust environmental benefits under different assumptions. In production-intensive cases, some actions, particularly renewable energy and electrification options, exhibit wide bands that span positive and negative composite scores. This reflects both their sensitivity to scenario assumptions and the equal-weighting choice in the composite scoring. These findings are consistent with LCA-extended energy system studies that find decarbonization pathways improve climate-related indicators while increasing resource use and land-related impacts (Junne et al. 2020; Baumgärtner et al. 2021). Similar context-dependent patterns are reported in sector-specific decision tools for water reuse, where reclaimed water can be clearly preferable in some combinations of treatment technology, distance and energy mix but not in others (Kalboussi et al. 2022).

Existing LCA-MCDM and related multi-criteria tools for supporting decisions (Torkayesh et al. 2022; Balali and Yunusa-Kaltungo 2025; Ferrante et al. 2025; Kadrić et al. 2026) are methodologically complex, data- and computation-intensive, and generally developed for specific sectors or levels. In contrast, the DST developed in this thesis deliberately trades such complexity for accessibility and generic applicability, using a simple scoring design that can be applied across sectors under low data availability. Implemented as an Excel tool and relying on a pre-quantified library of actions, it avoids case-by-case modeling and extensive data collection. Yet it still provides structured, quantitative rankings and makes trade-offs and uncertainties visible through individual-indicator effects and scenario bands. In doing so, it fills a gap between purely qualitative CE tools and full bespoke LCA-MCDM studies. The tool supplies a practical, LCA-based decision aid that can be embedded into broader CE, EIP and regulatory planning processes. Figure 5.1 summarizes the resulting environmental score potential per indicator for the four company case studies, illustrating how the improvement opportunities are distributed differently across GWP, CED, RMI, LU and WU.

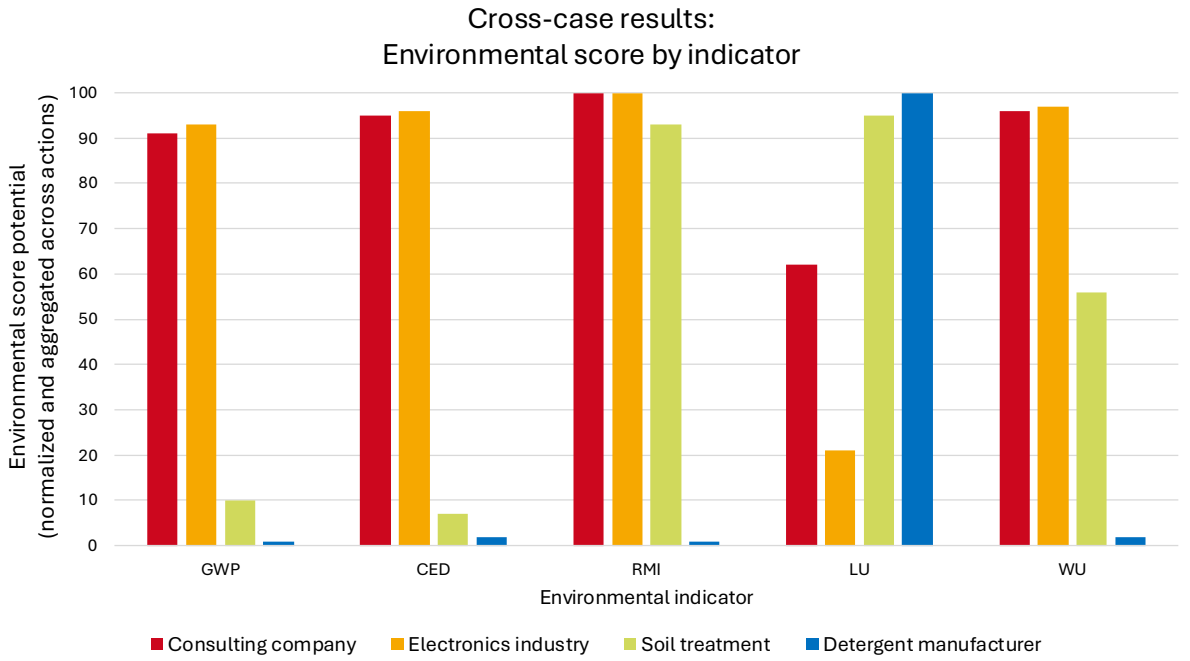


Figure 5.1: Cross-case environmental score potential by indicator. Aggregated normalized environmental scores (potential improvement) for each environmental indicator (GWP, CED, RMI, LU, and WU) are shown for the four company case studies (consulting company, electronics manufacturer, soil-treatment company, detergent manufacturer).

5.1.4 Added value of integrating the indicator base, KREGI approach and DST

Taken together, Publications I–III form an integrated framework whose combined value exceeds what each methodological pillar could provide in isolation. Applying a common indicator base, a consistent action- and scenario-based quantification (KREGI approach), and a unified LCA-MCDM scoring scheme (DST) across the four company case studies yields substantial but differently distributed environmental improvement potentials. Because normalization uses company-specific maximum saving potentials, points are intra-organizational and must not be used for benchmarking between companies.

In the consulting and electronics cases, reductions in GWP and CED dominate the achievable improvement, while in the soil-treatment case the largest relative gains occur in RMI, LU and WU. For the detergent manufacturer, the aggregated normalized indicator potentials are highly uneven (GWP = 1, CED = 2, RMI = 1, LU = 100, WU = 2), so LU dominates the composite score and therefore the action ranking. As a result, actions that perform well in GWP and CED but have large LU burdens (e.g., renewable-electricity options with high land-use demand) can receive low or even negative composite scores, and LU becomes the decisive indicator for prioritization. These differences and patterns arise not from arbitrary methodological changes between cases, but precisely because the same indicator set, action quantification logic and scoring design are consistently applied in heterogeneous organizational and sectoral contexts. To make these cross-case findings easier to transfer beyond the four case studies, the following short “rules of thumb” summarize the main patterns observed across contexts (see also Figure 5.1):

- In service-oriented contexts, workspace-use and employee-mobility actions tend to dominate the improvement potential for GWP and CED.

- In material- and energy-intensive contexts, logistics- and process-focused actions tend to become more important in the ranking.
- Renewable-energy and electrification actions can reduce GWP and CED but may increase LU and WU, so these trade-offs should be checked explicitly.
- Actions with wide scenario bands should be treated as “data-sensitive” and may require local data refinement before investment decisions.

The indicator base from Publication I ensures that evaluation focuses on a compact set of environmental indicators that are both widely used in industrial- and urban-symbiosis and EIP assessments and conceptually well aligned with CE. Building on this, the KREGI approach developed in Publication II translates these indicators into a structured chain that links environmental criteria, operational indicators and concrete actions along industrial-park life-cycle phases and CE levels. It also quantifies action effects via prospective LCA used ex-ante under status-quo, best-case and worst-case scenarios. Publication III then extends these pre-quantified action effects in a simple but explicit LCA-MCDM framework. The actions are implemented in the DST, so that companies and industrial parks can obtain action- and portfolio-level scores, scenario bands and CE information with low data and capacity requirements.

This chain covers the entire path from indicator selection to practical decision-support, which is rarely provided in existing approaches. Existing EIP indicator systems and international frameworks define extensive indicator lists and benchmarks and are mainly applied ex-post to classify or compare industrial parks (Huang et al. 2019a; World Bank 2021). However, these standards focus on setting performance requirements and do not provide detailed action-level, ex-ante evaluation methods for prioritizing specific actions at a given site. In parallel, academic work has proposed multi-criteria sustainability assessment models for industrial parks that can be used for both ex-post assessment and proactive exploration of scenarios (Le Tellier et al. 2022). Yet even these models are not designed as operational tools for ranking individual improvement actions or portfolios at specific parks. Corporate CE tools such as MICRON and Circular Flow focus on company-level circularity indicators and reporting, with MICRON in particular being built around GRI-based indicators (Baratsas et al. 2022; Barros et al. 2023; Chrispim et al. 2023). However, these and other corporate CE assessment tools integrate life-cycle environmental impacts only to a limited extent and generally do not provide low-effort, action-by-action prioritization support for practitioners (Baratsas et al. 2022; Barros et al. 2023; Valls-Val et al. 2023; Chrispim et al. 2023; Bais et al. 2025). The framework developed in this thesis complements these approaches by supplying a generic, LCA-based scoring layer that quantifies environmental effects of concrete actions and portfolios at micro and meso levels, without aggregating circularity and impact information into a single index.

Methodologically, the integration also offers a template for future ex-ante EIP and CE assessment tools. It shows how an empirically derived, CE-aware indicator base can be linked to a life-cycle- and scenario-based action evaluation method and then to a low-effort quantitative scoring instrument that presents trade-offs and uncertainties transparently. Because the same core indicators and pre-quantified actions are used across micro

and meso levels, different actors (such as companies, industrial-park operators, municipalities and consultants) can base their discussions on a shared set of numbers and concepts rather than on fragmented, case-specific metrics. The reusable action library implies that once an action has been modeled robustly through the KREGI-DST combination, it can be transferred to many contexts with limited additional effort, as long as key contextual parameters (e.g., energy mix, mobility patterns, technology characteristics) are adapted.

At the same time, the pre-quantified action effects are not universal constants. They depend on key background assumptions and modeling choices, for example the electricity mix, the renewable technology option (e.g., rooftop vs. ground-mounted PV), and mobility substitution patterns. The best-case and worst-case scenarios provide a transparent range, but they represent simplified plausibility bounds rather than statistical confidence intervals. Therefore, transferring the action library to new regions, sectors, or future years requires recalibrating the most influential parameters and, where needed, re-quantifying specific actions. In practical use, the DST should be applied for screening and prioritization, while high-investment or highly context-sensitive actions should be validated with a more detailed, project-specific follow-up assessment.

The integrated framework also connects to, and can be embedded in, broader planning and regulatory processes. For example, multi-level frameworks for IED 2.0, highlight the need for robust, LCA-supported indicators and quantitative tools to assess CE-related actions at installation, industrial-area, supply-chain and territorial levels, but do not themselves provide generic, ready-to-use scoring schemes (Vázquez Calvo et al. 2025). The framework developed here can supply such scores and trade-off analyses as input for the assessment and selection stages of industrial-symbiosis roadmaps (Knoebl et al. 2025; Krzeminski et al. 2026) or for circularity plans and permits under IED 2.0 (European Parliament and Council 2024). Similarly, macro-level reviews of CE and climate mitigation underline that there is still limited quantified evidence on CE-climate synergies and a lack of detailed, sector- and company-level case studies to inform policy and modeling (WBCSD 2024; Oni et al. 2026; Magalar et al. 2026). The quantified improvement potentials and scenario bands generated by the KREGI-DST framework can serve as bottom-up inputs or case evidence for refining such scenarios.

At the same time, IAM-linked tools such as PREMISE show how different mitigation pathways can be translated into scenario-specific background databases by systematically transforming key sectors (power generation, fuels, cement, steel, road transport) in ecoinvent on the basis of IAM projections (Sacchi et al. 2022). In future work, the action- and scenario-based KREGI-DST framework could be combined with such IAM-driven prospective LCI databases to analyze how different global decarbonization pathways influence the relative performance of company- and park-level action portfolios. This could especially be relevant for future energy uses.

Beyond methodology, the integration has practical advantages for governance and collaboration in industrial regions. Planning sustainable transitions in industrial clusters often requires coordination between different actors such as municipalities, park

operators, firms, energy and transport providers and civil society (Boons et al. 2017; Susur et al. 2019; Greiving et al. 2022; Knoebl et al. 2025). By providing a shared indicator base, an action catalog and quantified environmental effects, the framework offers a common language and evidence base for such multi-stakeholder dialogues. Stakeholders can use it to explore different combinations of actions, to discuss trade-offs (e.g., between GWP and LU for renewable-energy options) and to co-develop industrial-park development pathways aligned with climate and CE goals under realistic data and capacity constraints.

In summary, the added value of integrating the indicator base, the KREGI approach and the DST lies in providing (i) a coherent methodological chain from indicators to decisions; (ii) a reusable, generally applicable library of pre-quantified actions for micro- and meso-level application; and (iii) a low-effort but transparent scoring tool that can be embedded into existing CE, EIP and regulatory frameworks. Together, these elements help bridge the gap between high-level CE and EIP concepts and the day-to-day prioritization of concrete environmental actions in companies and industrial parks. However, reusing the pre-quantified action library requires periodic updates and context-specific parameter adaptation, so results should be interpreted as screening-oriented rankings, especially when transferring the framework to other regions or future energy systems.

Table 5.2 additionally summarizes the added value of the integrated framework compared to a standard LCA or CE indicators alone, as well as its limitations.

Table 5.2: Added value of the integrated framework compared with standalone LCA and standalone CE approaches.

Framework improvements vs. standalone LCA	Framework improvements vs. standalone CE indicators / R-strategies	Framework limitations
Enables fast screening and ranking of many operational actions without building a new LCI model for each company and each option.	Quantifies environmental impacts (e.g., GWP, energy and resource use), so higher circularity is not assumed to be environmentally better.	Relies on pre-quantified action effects and assumptions, so key parameters and scenario ranges must be adapted for other regions or future years.
Provides a pre-quantified action library and a consistent scoring logic, so results are comparable across actions within one company or industrial park.	Makes circularity visible (R-strategy mapping and optional CE indicators), but does not mix it into the environmental score, so trade-offs and burden shifting remain visible.	Can only prioritize actions that are included in the catalog, so relevant sector-specific actions may be missing and the potential is bounded by the current action set.
Makes uncertainty visible through a simple scenario band (status quo / best-case / worst-case), which many single LCA results do not communicate clearly to practitioners.	Supports action prioritization in a CE context by linking actions and R-strategies to quantified environmental performance, instead of relying on circularity aspects only.	Represents uncertainty with discrete scenarios and does not model interactions or rebound effects, so high-investment actions should be validated with a project-specific follow-up assessment.

5.2 Answers to the research questions and hypothesis

This section consolidates how the three papers address the four specific RQs and the MRQ of the thesis, and it revisits the central hypothesis in light of the findings.

5.2.1 RQ1 - Indicator basis for industrial and urban symbiosis

Publication I answers RQ1 by providing an empirical overview of which environmental indicators are used to assess industrial symbiosis, urban symbiosis, EIPs, and related meso-level CE initiatives. It is based on a scoping review of 457 sources and identifies 624 distinct environmental indicators after clustering. A central finding is that the indicator landscape is highly fragmented, while a relatively small and robust core of indicators is used repeatedly across contexts. This robust core is dominated by energy-, climate-, material-, waste-, and water-related metrics, which indicates what practitioners and researchers most often consider "decision-relevant" in real applications.

This confirms and extends earlier observations of heterogeneous indicator systems for EIPs and industrial symbiosis, where energy, emissions, and resource use emerge as central themes (Valenzuela-Venegas et al. 2016; Elia et al. 2017; Dong et al. 2022). Each indicator is also mapped to one or more R-strategies, revealing good coverage of high-circularity strategies such as Rethink, Reduce, Reuse and Recycle, but limited coverage of others like Refuse, Refurbish or Remanufacture, which is consistent with broader CE indicator reviews (Elia et al. 2017; Saidani et al. 2019; Pascale et al. 2021).

For this cumulative dissertation, Publication I provides the justification for fixing a compact five-indicator environmental core (GWP, CED, RMI, WU, LU) as the consistent evaluation backbone for the subsequent KREGI quantification and the DST scoring layer. This directly supports the MRQ because a fixed, evidence-based indicator core reduces repeated case-by-case indicator selection effort and enables low-effort ex-ante comparison and prioritization of actions under realistic data and capacity constraints. At the same time, the R-strategy mapping provides a structured circularity perspective that can be reported alongside environmental results without assuming that higher circularity automatically implies lower environmental impacts.

5.2.2 RQ2 - Scenario-based action evaluation approach

Publication II answers RQ2 by developing the KREGI approach as a generic, action- and scenario-based method for ex-ante evaluation of environmental improvement actions in companies and industrial parks. Its central contribution is to translate the indicator core into a practical, reusable workflow that links (i) criteria and operational indicators to (ii) clearly defined actions and (iii) quantified environmental effects under explicit scenarios.

Methodologically, KREGI defines actions as targeted interventions beyond the status quo and requires that actions meet clear inclusion requirements (e.g., unambiguous definition, action effect, relevance in the planning horizon). It structures actions along industrial-park life-cycle phases (planning, building, operation) and across CE levels (nano, micro, meso), which supports consistent organization of heterogeneous actions in one framework. The quantification follows a three-step prospective LCA procedure (scoping, LCI, LCIA) and models each action under status-quo, best-case, and worst-case scenarios to represent contextual variability and parameter uncertainty. In Publication II, this quantification is demonstrated for the indicators GWP, CED, and RMI, while Publication III

later extends the same logic to the full five-indicator core by adding LU and WU for the DST scoring.

A key insight from the detailed car-sharing example is that results can depend strongly on behavioral assumptions and substitution patterns, and that trade-offs across indicators can occur even for seemingly “green” actions. This example illustrates why the scenario logic is not just an add-on, but a necessary component for robust ex-ante decision support in real organizational settings.

For the cumulative dissertation, the main added value of KREGI is that it produces standardized, scenario-based action effects that can be reused as input for the DST without requiring end users to build a full LCI model for each action and company. This directly supports the MRQ because it operationalizes “low effort” at the method level: action comparison becomes feasible under realistic data and capacity constraints while still keeping uncertainty visible through scenario ranges.

In relation to existing work, KREGI complements ex-post industrial symbiosis and EIP assessments by providing an explicit ex-ante action evaluation procedure that is consistent across life-cycle phases and organizational levels and is designed for comparing concrete future actions rather than describing current performance only.

5.2.3 RQ3 - LCA-MCDM design for low-effort scoring

Publication III answers RQ3 by defining how pre-quantified LCA results for actions are converted into simple, transparent multi-indicator scores that can be applied under limited data availability. The DST operationalizes this by using five environmental indicators (GWP, CED, RMI, WU, LU) and by scoring actions based on their pre-quantified effects.

Methodologically, the scoring follows three core steps: normalization, weighting, and aggregation. First, action effects are normalized using an action-based maximum per indicator and company, so scores are anchored to the improvement potential represented by the applicable action set. Second, indicators are equally weighted by default, which is a transparent choice when stakeholder preferences are heterogeneous or unknown. Third, results are aggregated with a weighted-sum scoring method that allows negative values, so trade-offs and detrimental effects in single indicators remain visible. To retain interpretability, the tool complements point scores with absolute changes for each indicator.

Uncertainty is represented through consistent status-quo, best-case, and worst-case scenarios for each action, resulting in simple scenario bands around action and portfolio scores. This provides decision-makers with an immediate robustness signal, especially for actions whose performance depends strongly on contextual parameters (e.g., energy mix or behavioral substitution effects).

A short sensitivity example in the case applications illustrates that rankings can change under alternative weighting priorities, so weights should be treated as a decision assumption rather than a “neutral” truth. At the same time, the default equal-weighting design supports comparability and ease of use across actions within the same company or industrial park.

For the cumulative dissertation, the main added value of this LCA–MCDM design is that it turns the KREGI action quantifications into a low-effort prioritization output without requiring users to perform action-by-action LCI modeling themselves. This directly supports the MRQ because it enables decision-relevant relative rankings of actions under realistic data and capacity constraints while keeping trade-offs and uncertainty visible. In addition, circularity information is reported as a complementary dimension via R-strategy mappings and optional CE indicators rather than being merged into the environmental score, which helps avoid hiding burden shifting behind a single composite index.

5.2.4 RQ4 - Framework behavior, robustness and sensitivity

Publication III answers RQ4 by testing the integrated framework in four contrasting company contexts (consulting, electronics manufacturing, soil treatment, detergent production) and comparing how action rankings and indicator trade-offs behave across these settings. Across all four applications, the framework produces coherent rankings and identifies a small set of high-leverage actions per company, but the ranking patterns are strongly context-dependent. In service-oriented contexts, actions related to workspace use and employee mobility dominate improvement potential for GWP and CED, whereas in material- and energy-intensive contexts, logistics- and process-focused actions become more important. A recurring cross-case insight is that renewable-energy and electrification actions can reduce climate- and energy-related impacts while increasing LU and WU, and these trade-offs are visible in the multi-indicator results.

A key robustness element is the scenario-band representation (status quo, best case, worst case), which shows how stable an action's score and rank are under uncertain assumptions. Actions with narrow bands can be interpreted as robust candidates, while actions with wide bands should be treated as data-sensitive and checked with better local data before major decisions. The case applications further show that rankings can change under alternative indicator weights, so weighting should be understood as an explicit decision assumption rather than a neutral default.

For the cumulative dissertation, these observations provide the empirical "reality check" needed for the MRQ: they demonstrate that the framework can support low-effort ex-ante prioritization, while making context dependence, trade-offs, and uncertainty visible rather than hiding them in a single deterministic score. At the same time, the results also clarify the limits of generalizability: rankings are reliable as relative comparisons within a company/industrial park and the given action set, but they should not be interpreted as universal "best actions" across all contexts.

5.2.5 Answering the main research question and revisiting the hypothesis

The MRQ (Section 1.3) asks how a generic, low-effort ex-ante framework can be developed and critically assessed that enables companies and industrial parks to prioritize environmental improvement actions under realistic data constraints in a CE context, while making trade-offs and uncertainties explicit. Taken together, Publications I–III provide an integrated answer by linking a structured indicator basis, scenario-based action quantification, and an LCA–MCDM scoring tool into one consistent workflow. Publication I

establishes a CE-aware indicator basis and motivates a compact five-indicator core (GWP, CED, RMI, WU, LU) that keeps the assessment manageable while remaining decision-relevant. Publication II operationalizes this indicator basis through the KREGI approach, which defines actions via explicit inclusion requirements and quantifies action effects ex-ante using prospective LCA under status-quo, best-case, and worst-case scenarios. Publication III converts these action effects into low-effort, multi-indicator scores in the DST and tests the resulting rankings across four contrasting company contexts, while reporting circularity as a complementary dimension rather than mixing it into the environmental score.

Overall, the results support the methodological hypothesis within the scope of this dissertation: the integrated framework generates decision-relevant relative rankings of actions and action portfolios under typical data and capacity constraints, and it makes key trade-offs and uncertainty visible through multi-indicator reporting and scenario bands. At the same time, the applications confirm important boundary conditions: results are ex-ante and therefore indicate potential rather than realized improvements, and composite scores depend on the chosen indicator set, equal weighting, additive aggregation, the action catalog, and context-specific parameterization. These limitations (see Section 5.5) do not invalidate the approach, but they define how it should be used in practice: as a transparent screening and prioritization tool that guides follow-up analysis for high-investment or highly sensitive actions.

5.3 Methodological contributions and scientific positioning

The methodological contributions of this thesis can be summarized along three coupled pillars: (i) a structured, CE-aware environmental indicator base for industrial and urban symbiosis, (ii) a scenario-based action-evaluation approach (KREGI) that applies prospective LCA to portfolios of actions across industrial-park life-cycle phases, and (iii) a low-effort LCA-MCDM scoring design that aggregates action effects into composite environmental scores while keeping circularity indicators separate. Together, these pillars form an integrated framework for ex-ante environmental decision-support at micro and meso levels and position the work at the intersection of IE, CE assessment and decision-analytic methods.

Indicator base for industrial and urban symbiosis

Publication I advances the state of research by transforming a scattered indicator landscape into a coherent, CE-aware basis for meso-level environmental assessment in industrial and urban symbiosis and EIPs. Earlier works, such as Valenzuela-Venegas et al. (2016), compiled indicators for EIPs, while other reviews focused on CE indicators more broadly without a specific industrial-symbiosis context (Elia et al. 2017; Saidani et al. 2019; Pascale et al. 2021). In contrast, Publication I systematically screens the literature, clusters the resulting indicators into 624 comprehensive indicators across five methodologically motivated groups. Publication I also introduces relative use-rate metrics to distinguish a robust core of widely used indicators from a long set of rarely used ones, while mapping each indicator to one or more R-strategies.

For the cumulative framework, these results are used to define the compact core of five environmental indicators (GWP, CED, RMI, LU and WU) that underpin the KREGI approach and the LCA-MCDM DST. This choice reflects patterns identified in Publication I, where energy-, climate- and resource-related metrics dominate, and aligns the framework with established concepts such as CED in LCA and MIPS-type resource indicators (Liedtke et al. 2014; Frischknecht et al. 2015; Hauschild et al. 2018; Baumgärtner et al. 2021). The explicit mapping to R-strategies also highlights under-represented strategies such as Refuse, Refurbish and Remanufacture, indicating where future indicator development could better support high-circularity interventions at industrial-park scale. In this way, Publication I provides an empirically grounded indicator base that both reflects current assessment practice and guides the design of the subsequent methodological pillars.

Scenario-based action-evaluation approach (KREGI)

Publication II introduces the KREGI approach as a generic action- and scenario-based prospective LCA methodology designed for ex-ante evaluation of actions in industrial parks and companies. Most industrial symbiosis and EIP studies evaluate realized synergies ex-post using LCA, MFA or eco-efficiency indicators (Park and Behera 2014; Marinelli et al. 2021; Dong et al. 2022). By contrast, ex-ante and prospective LCA applications to date are predominantly conducted at the level of individual technologies or sectors, often focusing on emerging technologies at specific TRL stages, rather than on portfolios of operational interventions at micro- and meso-scale (Cucurachi et al. 2018; Buyle et al. 2019; Arvidsson et al. 2024). The SIMPL approach is a recent example of such technology-focused work which integrates future scenario development into prospective inventory modelling through a sequence of steps that are well suited for small-scale LCAs of emerging technologies (Langkau et al. 2023). KREGI broadens the application and addresses this gap by structuring actions along the planning, construction and operation phases of industrial parks, linking them to CE levels and defining clear requirements for action selection (innovation beyond the status quo, unambiguous definition, measurable environmental effect, significance and relevance within the current planning horizon).

Methodologically, the KREGI approach applies a reusable three-step prospective LCA procedure that is used ex-ante (scoping, LCI, LCIA) to each action and models status-quo, best-case and worst-case scenarios with respect to GWP, CED and RMI. This design translates recommendations for ex-ante and scenario-based LCA from technology-level studies into a micro-meso context (Guinée 2002; Fauré et al. 2017; Hauschild et al. 2018). It thereby adopts scenario concepts from energy- and water-sector sustainability studies and enables the environmental consequences of actions (such as mobility concepts, shared infrastructure, or circular product options) to be quantified before implementation (Fauré et al. 2017; Skea et al. 2021; Bosco et al. 2025). The car-sharing case illustrates how behavioral and technological uncertainties can be represented via discrete scenarios. It also shows how the KREGI approach captures both environmental benefits and burden shifting across indicators, complementing existing LCA studies on shared mobility (Nijland and van Meerkerk 2017; Amatuni et al. 2020; Arbeláez Vélez 2024).

Within the cumulative thesis, the KREGI approach provides the quantitative backbone for the action library used in the DST. By applying the same ex-ante LCA logic across diverse actions and contexts, it ensures that pre-quantified action effects are consistent and comparable, thereby enabling screening and prioritization without requiring each company to perform full bespoke LCAs. The KREGI approach thus operationalizes the indicator base from Publication I at action level and forms the bridge between conceptual indicator work and the decision-support layer of Publication III.

LCA-MCDM scoring design for low-effort use

Publication III specifies an LCA-MCDM framework that is deliberately optimized for low-effort application while remaining consistent with guidance on composite indicators, CE performance assessment and LCA weighting. Reviews of CE assessment methods show that LCA remains the most widely used method for LCIA of circular systems, with MCDM approaches as the main complementary family of methods (Ferrante et al. 2025; Verma et al. 2025). These reviews also highlight that such integrated assessment approaches are often complex, data-intensive and resource-demanding, which poses challenges especially for organizations with limited technical and data capacities (Ferrante et al. 2025; Verma et al. 2025). In contrast, the DST combines the pre-quantification KREGI action approach with an internal, action-based max normalization (using the sum of mean effects of all applicable actions as reference for each indicator and company), equal weighting of five environmental indicators and weighted-sum aggregation that allows negative normalized values. These choices are motivated by known issues of other normalization methods (e.g., sensitivity to outliers and instability when adding new data) and by the need to keep trade-offs and detrimental effects visible for decision-makers (Nardo et al. 2005; OECD 2008; Pizzol et al. 2017; Goulart Coelho et al. 2017; Taherdoost and Madanchian 2023).

Recent work on EF normalization and MCDM methods shows that both normalization choices and ranking algorithms can strongly affect single scores and rankings (Laurentiis et al. 2023; Zournatzidou et al. 2025). Against this background, the decision to use internal normalization and simple weighted-sum aggregation keeps the reference system within the company and action set. This also avoids importing hard-to-control biases from external normalization schemes and complex MCDM algorithms, at the cost of limiting cross-company comparability.

Publication III additionally separates circularity information from environmental scoring by mapping actions to R-strategies and allowing optional CE indicators to be displayed without being aggregated numerically with the environmental indicators. This design choice is grounded in the conceptual distinction between CE, circularity and sustainability outlined in Section 1.2.2. It responds directly to concerns that treating circularity metrics and environmental impacts as a single compensatory index can hide rebound and burden-shifting effects (Corona et al. 2019; Harris et al. 2021; Elia et al. 2024; Sewenet et al. 2026). Uncertainty is represented through scenario bands derived from KREGI's status quo, best-case and worst-case results. This is consistent with the use of exploratory scenarios as a communicable way to capture uncertainty in policy-relevant futures and

future-oriented LCA studies (Fauré et al. 2017; Skea et al. 2021; Moshrefi et al. 2022). Implemented as an Excel tool with a small set of company inputs, the DST thus extends the LCA-MCDM literature by offering a generic, reusable scoring design tailored to low-effort use.

Integrated positioning within IE and CE assessment

Beyond the three individual pillars, the thesis contributes an integrated framework that connects indicator selection, ex-ante action quantification and decision-analytic scoring in a coherent way to address several gaps in the existing literature. International EIP frameworks and standards provide criteria and indicators for industrial park performance and are mainly used for ex-post assessment, classification and benchmarking (Huang et al. 2019a; World Bank 2021). Existing corporate CE tools, such as MICRON, Circular Flow and related maturity frameworks, mainly provide ex-post circularity indices or qualitative readiness scores (Pigosso and McAloone 2021; Baratsas et al. 2022; Barros et al. 2023; Chrispim et al. 2023; Bais et al. 2025). They rarely integrate full life-cycle environmental impacts or offer a generic, low-effort, ex-ante ranking of concrete actions (Chrispim et al. 2023; Bais et al. 2025). OLCA broadens the view to entire organizations and has often been applied mainly for analytical, comprehensive environmental profiling, with managerial and stakeholder-oriented uses still less common in practice (Ahmed et al. 2026).

The framework developed in this thesis complements these approaches by supplying a modular but coherent method that (i) is grounded in an empirically derived indicator base specifically for industrial and urban symbiosis, (ii) evaluates concrete actions via scenario-based prospective LCA applied ex-ante across micro and meso levels, and (iii) aggregates results into interpretable environmental scores with explicit treatment of uncertainty and circularity. It thereby provides a methodological “missing link” between high-level IE/CE policy frameworks and detailed, case-specific LCAs or MCDM studies. Multi-level frameworks for IED 2.0 emphasize that environmental permits BAT information exchange should support CE transitions at installation, industrial-area, supply-chain and territorial levels (Vázquez Calvo et al. 2025). Yet they do not themselves offer generic tools for ranking concrete actions. Additionally, industrial symbiosis roadmaps and self-assessment tools provide process guidance and qualitative ecosystem mapping (Knoebl et al. 2025; Krzeminski et al. 2026). Building on this, the developed KREGI-DST framework adds a standardized, low-effort LCA-MCDM layer that these approaches currently lack. The framework can supply the environmental scores and trade-off analyses needed in these assessment and selection stages.

The thesis also aligns with recent calls in the CE and climate-policy literature for integrated approaches that connect circular strategies, life-cycle-based environmental assessment and policy frameworks. Oni et al. (2026) and Magalar et al. (2026) for example, argue that achieving carbon neutrality requires linking CE actions to quantified emission reductions in sectoral and national pathways. Sewenet et al. (2026) conceptualize CE as an economic paradigm, circularity as its measurable expression and sustainability as the overarching normative objective. By treating circularity primarily as a structuring concept and providing an LCA-based environmental pillar that can later be combined with social

and economic assessments, this thesis operationalizes that distinction at micro and meso levels. Similar integration of a CE indicator dashboard with an LCA-based method has been explored at the urban scale, where a structured set of 27 CE indicators is combined with an urban metabolic LCA framework (Papageorgiou et al. 2025). Yet the present framework focuses specifically on company and industrial-park contexts and is designed for low-effort use.

Digitalization and Industry 4.0 developments offer further context for positioning the framework. Studies on digital tools for industrial symbiosis and CE show that web-based platforms and data-driven methods can support opportunity identification and assessment (Lütje et al. 2021; Verma et al. 2025; Bahmutsky et al. 2025). However, reviews of firm-level CE assessment tools and digital sustainability solutions highlight that such tools remain relatively scarce and often tailored to specific sectors or contexts (Bais et al. 2025; Verma et al. 2025). The DST's structure (indicator base, action database, parameter sets, scenario logic and scoring) could be embedded in such digital environments, where it would provide a ready-made environmental scoring layer that benefits from improved data availability without sacrificing transparency. In this sense, the thesis offers both a conceptual and a technical foundation for future digital implementations of ex-ante environmental decision-support in industrial and CE contexts.

Summary of key methodological contributions

In summary, the main methodological contributions of this thesis are:

- A systematic scoping, clustering and categorization of indicators for industrial and urban symbiosis and EIPs into 624 comprehensive indicators, resulting in a robust, CE-aware core set centered on GWP, energy use, material and waste flows, WU, and LU.
- An explicit conceptual and quantitative mapping of environmental indicators to R-strategies, clarifying the relationship between industrial-symbiosis/EIP assessment and CE strategies and highlighting under-represented R-strategies such as Refuse, Refurbish and Remanufacture.
- Development of the KREGI approach as a generic, scenario-based prospective LCA methodology that is used ex-ante along industrial-park life-cycle phases and CE levels, combined with clear action-selection requirements and a reusable three-step quantification procedure.
- Introduction of a pre-quantified library of actions for domains such as mobility, workspace use, energy supply and selected circular product options, which can be scaled and recombined for different companies and industrial parks using status-quo, best-case and worst-case scenarios.
- Design of an LCA-MCDM scoring framework that uses action-based max normalization, equal weighting of five environmental indicators and weighted-sum aggregation with allowance for negative scores, thereby linking scores to company-specific improvement potentials while keeping trade-offs explicit.

- Conceptual and practical separation of circularity information (R-strategy mapping and optional CE indicators) from environmental scoring, avoiding compensatory aggregation between circularity metrics and environmental impacts and making rebound and burden-shifting risks visible.
- Implementation of the framework in a low-effort Excel-based DST and empirical application in four diverse company contexts, demonstrating that the approach can generate decision-relevant action and portfolio rankings under realistic data and capacity constraints.

Compared to existing approaches, the framework goes beyond EIP indicator systems and international EIP guidelines (which mainly provide ex-post classification and benchmarks) by offering an operational ex-ante, action-level evaluation method for planning and redesign. It complements corporate circularity tools and maturity frameworks by supplying a quantitative, LCA-based scoring scheme for concrete actions while keeping circularity as a separate dimension. It also extends the LCA-MCDM literature by providing a generic, low-effort scoring design based on a reusable library of pre-quantified actions and a simple normalization and weighting scheme that remains transparent under realistic data constraints. Taken together, these contributions position the thesis as a methodological link between high-level IE/CE frameworks and detailed, case-specific LCAs, enabling ex-ante prioritization of environmental actions at micro and meso levels in a way that is both conceptually rigorous and practically applicable.

5.4 Practical implications

This section summarizes the main practical implications of the framework for different stakeholder groups: companies, industrial park operators, municipalities and regional planners, policy makers, consultants and service providers, and tool developers. In many respects, it responds to issues documented in the literature, such as the difficulty SMEs face in devoting time and resources to complex assessment tools and the need for scalable, low-burden performance-measurement frameworks (Ormazabal et al. 2018; Cagno et al. 2023). It also addresses calls in the EIP literature for more systematic decision-support methods and tools to guide EIP planning and the broader transition from conventional industrial parks to EIPs (Adoue et al. 2015; Belaud et al. 2019; Susur et al. 2019). Another issue it addresses is the difficulty of linking CE ambitions to measurable environmental outcomes (Elia et al. 2017; Harris et al. 2021; Elia et al. 2024).

Overall, the framework is designed as a screening and prioritization tool for companies, industrial parks and municipalities that want to identify high-impact environmental actions under data, time and capacity constraints. It does not replace detailed, project-specific LCAs or optimization models.

Companies and SMEs

For companies, the DST offers a way to structure environmental and CE management around a portfolio of pre-defined, quantified actions. This is particularly relevant for organizations that are under increasing pressure from EU regulatory frameworks but lack the internal resources to conduct comprehensive LCA or to design their own indicator

frameworks. In practice, companies can use the DST as a first screening tool to answer questions such as: “Given our current employee numbers, transport activity and energy demand, which actions have the largest potential to reduce GHG emissions and resource use?” or “If we implement only three actions in the next planning cycle, which ones should we choose to maximize environmental benefits?”.

In addition, the DST allows users to enter approximate cost information for each action and to compute a simple economic-efficiency indicator, such as cost per environmental score point. This provides a first indication of which actions are not only environmentally effective but also relatively cost-efficient. In this way, the tool supports more informed discussions in strategy, investment and sustainability committees by enabling companies to screen actions both in terms of environmental improvement and rough cost effectiveness before engaging in more detailed financial analyses. This responds to recent research indicating that firms are increasingly seeking to integrate sustainability and green technologies into their core strategies and business models (Pavesi et al. 2025). However, integrating these technologies is fundamentally a strategic innovation challenge, which makes it difficult to translate high-level intentions into concrete operational choices (Pavesi et al. 2025). Additionally, in sectors that already use mass-balance chain-of-custody certification to introduce recycled or bio-based feedstocks (Chen et al. 2026), the framework in this thesis can serve as a complementary layer. This can be done by quantifying the ex-ante life-cycle effects of such actions on indicators like GWP, energy use and resource extraction instead of relying only on certified content claims.

The action- and scenario-based results can feed into existing management systems and reporting processes. For example, the quantified impacts of actions on GWP and energy use could be integrated into carbon management plans, science-based target pathways or ISO 14001 environmental programs. They can also complement narratives in sustainability reports and GRI disclosures. In contrast to the largely qualitative, narrative descriptions of sustainability initiatives that dominate much current corporate reporting (Kassier 2024; Bais et al. 2025), the DST provides quantitative estimates of potential improvements, including uncertainty ranges. This enhances credibility and allows internal and external stakeholders to understand the relative significance of different possibilities. The action- and scenario-based results can also be combined with human resource and incentive systems, for example through management by objectives for department heads with variable pay tied to environmental performance targets (Marrucci et al. 2024). This design is consistent with broader evidence on green human resource management (HRM) and green compensation as levers for improving firms’ environmental performance (Adu Sarfo et al. 2024).

Many SMEs operate with limited financial and managerial resources, shortages of staff skills, and a lack of time, which makes it difficult for them to adopt complex sustainability and CE performance measurement tools (Ormazabal et al. 2018; Dey et al. 2021; Cagno et al. 2023; Ferasso et al. 2024). The DST can lower this entry barrier by providing a simpler assessment that requires only limited input data and is easier to apply in such constrained settings. This also responds directly to the recommendations of the ACTION guide, which emphasizes the need to simplify CE tools, to provide training and support for

potential users and to develop assessment approaches that are also applicable to service-oriented organizations (Chrispim et al. 2023). Recent OLCA applications in SMEs confirm both the need and the difficulty of such assessments (Ahmed et al 2026). SMEs could use the tool in combination with support from industrial park operators, municipal agencies or consultants to quickly identify a small set of high leverage actions and to build incremental improvement plans without large up-front analytical investments. These design choices directly address barriers that were empirically observed in a study of ten Swedish water-intensive and bio-based companies of different sizes (Chrispim et al. 2025). In that study, interviewees frequently cited lack of knowledge and mindset about CE tools, the time required for assessments, small company size, customers mainly requesting CO_2 data, and the perception that CE assessments are not a current priority as reasons for not carrying out CE-specific assessments (Chrispim et al. 2025).

Industrial park operators

For industrial park operators, the KREGI approach and the DST can play a central role in managing and communicating environmental performance at industrial park level. Operators can use action catalogs and quantifications to propose packages of actions to companies, to demonstrate the expected benefits of shared infrastructure or symbiosis initiatives. An action catalog could also be the basis to justify investments in park level projects, such as shared mobility services, park wide renewable energy systems or common waste treatment facilities. The scenario results can help operators manage expectations by clarifying that environmental outcomes depend on uptake and implementation quality.

Implementation-oriented industrial symbiosis literature emphasizes that such processes benefit from a clear, phase-wise roadmap (Knoebl et al. 2025; Krzeminski et al. 2026). The KREGI approach and the DST can provide quantitative input for the feasibility, selection and realization stages of such roadmaps by supplying life-cycle-based environmental scores and trade-off information for candidate symbiosis actions and park-level initiatives. Furthermore, industrial park operators can use the framework to define minimum environmental performance expectations or optional "enhanced performance" packages for companies seeking to locate or expand in the park. For example, the operator could specify that companies are expected to implement at least a certain number of actions from a set associated with a minimum environmental score, analogous to how green building certification schemes define bundles of actions (U.S. Green Building Council 2019; DGNB 2020). In this way, the framework can contribute to the governance and branding of EIPs, including in regions undergoing major structural change, such as the Rhenish coal-mining area in Germany (Greiving et al. 2022).

Municipalities and policy makers

Municipalities and regional planners can use the framework as an analytical extension to existing guidance on EIPs and industrial park planning. EIP frameworks and standards define prerequisites and performance indicators for parks (Huang et al. 2019a; World Bank 2021), but they focus on setting performance requirements and do not provide detailed decision-analytic methods for prioritizing specific actions at specific sites. By applying KREGI and the DST on proposed industrial park developments, municipalities can

quantitatively compare different layout options, mobility configurations or energy infrastructures with respect to their environmental effects. This can inform LU planning, transportation planning and infrastructure investments. For example, Drofenik et al. (2025) show that targeted energy-transition changes (coal phase-out, renewable electricity, efficiency) can raise a national circularity index and that corporate photovoltaic and efficiency investments can increase a company's index.

Furthermore, municipalities can use the quantitative results to design incentive schemes for companies, for example reduced land prices, tax breaks or support for companies that commit to implementing a certain set of high-impact actions. In the specific context of IED 2.0, environmental permits are expected to move beyond a narrow compliance focus to actively support CE transformation (European Parliament and Council 2024; Vázquez Calvo et al. 2025). Yet competent authorities currently lack operational tools and indicators to translate this ambition into day-to-day permitting practice (Vázquez Calvo et al. 2025). The action- and indicator-based results of this thesis could therefore be used not only by companies and park operators but also as input to circularity plans and other CE-related permits. This could help authorities to quantify expected environmental improvements of proposed actions in a simple and transparent way. At the same time, IAM-based climate policy studies increasingly integrate CE strategies into mitigation pathways, but they still lack material-level granularity and detailed representation of supply-chain sectors (Magalar et al. 2026). The quantified improvement potentials and trade-offs generated by the KREGI approach and the DST could therefore be used as bottom-up inputs or case-study evidence to inform more realistic CE assumptions in IAM scenarios. For example, it could be used for defining material-efficiency pathways or evaluating combinations of CE policies in specific sectors.

From a policy and funding perspective, the framework offers insights into which types of actions merit particular attention in support programs or regulations. The case studies indicate, for example, that actions related to building use (desk sharing), employee mobility and certain sector specific circular actions (such as soil treatment or refill packaging) can provide substantial environmental benefits. These action fields link directly to key European Green Deal objectives, including decarbonizing industry through CE strategies, delivering secure and affordable clean energy, and advancing sustainable and smart mobility systems (Ozcelik et al. 2025). This is also consistent with broader analyses of mitigation potentials in buildings, transport and materials sectors (Zhong et al. 2021; Harpprecht et al. 2024; Muessel et al. 2025; Peng et al. 2025), but the framework offers more granular quantification for industrial parks and companies. Funding bodies could use these insights to design programs that specifically support the uptake of such actions, for instance by subsidizing planning processes, infrastructure or technology investments that enable them.

Furthermore, the indicator-based and action-focused results can inform the evolution of EIP standards and national CE strategies. If certain indicators and actions are repeatedly shown to be impactful and widely applicable, they could be integrated into criteria for EIP certification, CE roadmaps or sectoral decarbonization plans (Huang et al. 2019a; World Bank 2021). Because CE initiatives that cut CO_2 via improved waste management span

multiple sectors and are difficult to measure, they are rarely reflected in national climate strategies, which reinforces the need for an operational, action-level tool (Baskaran and Byun 2025).

Consultants and service providers

For consultants and service providers, the framework and DST offer a structured backbone for advisory services. They can start from the indicator base, action catalog and scoring logic and adapt these to specific sectors or regions, increasing consistency and comparability across projects. The DST's scenario and scoring outputs also provide an accessible communication tool for discussing trade-offs and priorities with non-expert stakeholders.

Tool developers and digitalization

There are also practical implications for tool developers and digitalization efforts. While the current DST is implemented in a spreadsheet environment, the underlying structure (indicator base, action database, parameter sets, scenario logic and scoring) could be embedded in web-based platforms (Lütje et al. 2021; Papamichael et al. 2022) or in more advanced decision-support and modeling environments (Papamichael et al. 2022; Balali and Yunusa-Kaltungo 2025; Pollet et al. 2025). LCA configurators in the construction application show that such digital implementations can substantially accelerate design iterations and support both comparative and absolute assessments (Campo Gay et al. 2024). As an illustrative heavy-industry example, Mining 4.0 shows how increased sensor use and data integration can enable more timely and data-rich decision-making in industrial operations (Clausen et al. 2022). Such systems could integrate additional data sources, for example corporate reporting data, real-time energy consumption data or geographic information systems, to automate parts of the input and update process. They could also enable anonymized benchmarking between companies or industrial parks, showing how a given site's action portfolio compares to others in terms of environmental benefits and CE strategies. The literature on digital tools for identifying industrial symbiosis opportunities suggests that web-based platforms can effectively support networking and opportunity identification (Lütje et al. 2021). Recent work argues that additional digital technologies such as big data analytics and machine learning can substantially improve data collection, integration and analysis in LCA-based assessments of circular processes (Verma et al. 2025; Bahmutsky et al. 2025). At the same time, the actual uptake of such data-science-based approaches remains limited, even though scholars highlight that drawing on digital data sources and AI- or blockchain-based verification can enhance the transparency and confirmability of sustainability assessments (Bais et al. 2025; Verma et al. 2025; Agarwal et al. 2025; Bahmutsky et al. 2025). A similar approach could be taken for action-based environmental evaluation. In parallel, Belhadi et al. (2022) develop a self-assessment tool that quantifies how well CE and Industry 4.0 practices are integrated in organizations, grounding the model in dynamic capabilities theory and operationalizing it via a graph-theoretic approach. Such a framework could be combined with the LCA-based scoring scheme developed here, so that companies and supply chains

obtain, in a single integrated view, both their organizational readiness for circular and digital practices and the expected environmental performance.

Multi-stakeholder processes and industrial-region transitions

Finally, the framework can serve as a basis for multi-stakeholder dialogue in industrial regions. This need is particularly acute in sustainable transition planning for industrial clusters, where coordination between multiple actors such as municipalities, companies, park operators, energy and transport providers, and civil society is typically required (Boons et al. 2017; Susur et al. 2019; Greiving et al. 2022; Knoebl et al. 2025). Such collaborations are not only technical and organizational processes, but are strongly shaped by how individual business to business actors experience the circular solution and by how these experiences influence their willingness to collaborate, to change routines and to invest in new circular offerings (Alkki et al. 2025). By providing a common set of indicators, a catalog of actions and quantifications of their environmental effects, the framework offers a shared language and evidence base for such stakeholder dialogues. Stakeholders can use it to explore different combinations of actions to discuss trade-offs (for example between GWP and LU) and to co-develop pathways for industrial park development that are aligned with climate and CE goals.

5.5 Critical appraisal and limitations

The three methodological pillars developed in this thesis jointly provide a coherent framework for ex-ante environmental evaluation and prioritization of actions at company and industrial-park levels. At the same time, this framework is subject to several limitations and boundary conditions. Recognizing these is important both for the scientific interpretation of the results and for their practical use. The key limitations are:

- Coverage of environmental indicators only; economic and social aspects are not integrated quantitatively.
- Results are ex-ante and scenario-based, and therefore indicate potential rather than actually realized environmental reductions.
- Composite scores depend on indicator choice, equal weighting, and additive aggregation.
- The action catalog and parameterization are limited (current European conditions, application on selected sectors).
- Interactions among actions and rebound effects are not modeled explicitly.

The following subsections elaborate these limitations and their implications.

Scope of the assessment

A first set of limitations concerns the scope of the assessment. The indicator base and the subsequent KREGI approach and LCA-MCDM developments deliberately focus on environmental performance. Economic and social aspects are only treated qualitatively or, in the case of the DST, via optional cost inputs. Consequently, the framework does not provide a full sustainability assessment in the sense of integrating environmental, economic and social pillars as advocated in the sustainability assessment literature (Singh

et al. 2009; Wulf et al. 2019; Battiston et al. 2025; Sewenet et al. 2026). It cannot answer whether a given action portfolio is economically viable, socially acceptable or equitable, and it does not address distributional effects.

At company level, waste-management work such as the Sustainable Circularity Performance (SCP) model proposes a set of six KPIs, with two indicators for each of the environmental, economic, and social dimensions (Battiston et al. 2025). These KPIs are aggregated into a synthetic score (KPI0) that allows triple-bottom-line circularity performance to be evaluated for specific waste-generating processes (Battiston et al. 2025). In contrast, this thesis focuses on environmental indicators across many action types and sectors, leaving integrated economic and social assessment to future work. The advantage of this restriction is analytical reliability and transparency under low data availability, but it means that the environmental rankings produced by the framework must be complemented by economic and social analyses in practical decision-making. Similar patterns are seen at city scale, where most urban waste assessments omit social and circularity aspects or treat them only partially, highlighting that multi-dimensional frameworks are still methodologically demanding and relatively rare (Toboso-Chavero et al. 2025). In this context, life cycle costing (LCC) could be methodologically coupled with the existing LCA-based framework to quantify economic impacts of actions over consistent system boundaries and functional units and to derive simple cost-effectiveness metrics (e.g., cost per unit of environmental improvement) alongside the environmental scores.

Other holistic questionnaire-based micro level CE tools also fall short on several qualitative criteria, including transferability, credibility, confirmability, fit, and generality (Bais et al. 2025). These tools often overlook firm-specific conditions and do not make trade-offs between circular practices and other performance dimensions transparent to users (Bais et al. 2025).

Ex-ante, scenario-based nature and uncertainty

A second limitation relates to the nature of ex-ante, scenario-based results. Actions are quantified using scenario-based prospective LCA applied ex-ante with status-quo, best-case and worst-case scenarios, and the scoring scheme is anchored in the mean of best- and worst-case effects. As emphasized in the prospective and ex-ante LCA literature, scenarios are used to explore how systems might develop under different assumptions, rather than to forecast one guaranteed future (Arushanyan et al. 2017; Fauré et al. 2017; Cucurachi et al. 2018; Buyle et al. 2019; Arvidsson et al. 2024; Bosco et al. 2025). The framework therefore supports relative comparison and prioritization of actions within a given context, but it does not guarantee that the modeled savings will be realized in practice. Implementation barriers, behavioral responses, technological change, or interactions among actions may all cause realized performance to deviate from the scenario results. For practitioners, the DST should thus be seen as a screening and structuring tool that narrows down promising options, not as a substitute for detailed project-level LCA or financial analysis.

Closely related is the treatment of uncertainty. The framework represents uncertainty and variability through discrete best- and worst-case scenarios and uses these to construct

score bands around mean-based values. This is consistent with the use of exploratory scenarios in sustainability and energy assessments, where several internally consistent futures are compared qualitatively without assigning probabilities (Fauré et al. 2017; Skea et al. 2021). However, this approach does not quantify statistical uncertainty or cover the full space of possible parameter combinations. Correlations among parameters, long-term learning effects, macro-economic feedbacks or rebound effects are not explicitly modeled. As a result, the scenario bands should be interpreted as envelopes of plausibility rather than confidence intervals, and robustness assessments should be complemented with qualitative knowledge about local conditions. Complementary to scenario variation, uncertainty in technological implementation can also be addressed by modeling variants of an action as separate options. For example, distinguishing between "renewable electricity from photovoltaic systems" and "renewable electricity from wind power" rather than treating renewable electricity as a single generic action. This narrows uncertainty for each option and supports more specific decisions, such as the induced LU burden for photovoltaic systems.

Indicators, weighting and aggregation

A further limitation concerns indicator selection, weighting and aggregation. The framework uses a compact set of five environmental indicators (GWP, CED, RMI, WU, LU) and equal weighting with additive aggregation, which simplifies application. This is in line with recommendations for composite indicators under heterogeneous or unknown preferences (Nardo et al. 2005; OECD 2008; Pizzol et al. 2017). However, this choice omits other impact categories such as toxicity or biodiversity and implicitly assumes that all included indicators are equally important, which may not match sector- or region-specific priorities. The case studies show that equal weighting can materially influence ranking. For example, renewable-energy options that perform well in GWP and CED but poorly in LU may obtain negative composite scores. Decision-makers should therefore test alternative weighting schemes by conducting sensitivity analyses where feasible (Freudenberg 2003; Pizzol et al. 2017; Wulf et al. 2019). In this thesis, beyond equal weighting, only one alternative weighting scheme (a climate-focused scenario in the soil-treatment case) is tested. This example shows that rankings may change under other weighting choices, but such alternatives are not systematically explored here.

The use of additive aggregation through a weighted sum allows compensation between indicators. While negative normalized values and separate reporting of CE information avoid overly optimistic scores, compensation still means that poor performance in one environmental indicator can be offset by good performance in another. This is a fundamental property of compensatory aggregation, which assumes substitutability between components, and it has been explicitly problematized in both the composite-indicator and sustainability-assessment literature (Freudenberg 2003; Munda 2012). The MCDM literature similarly distinguishes explicitly between compensatory, non-compensatory, and partially compensatory approaches, in which negative performance on some attributes can be compensated by positive performance on others (Taherdoost and Madanchian 2023). In some decision contexts, non-compensatory or partially compensatory methods are more appropriate, but they usually entail higher model complexity and data

requirements (Cinelli et al. 2020; Greco et al. 2025). Recent analyses of alternative normalization sets show that external normalization can itself introduce substantial biases (Laurentiis et al. 2023). Different production-, consumption-, and planetary-boundary-based normalization references can shift which impact categories dominate single scores, and incomplete or misaligned inventories (e.g., ecotoxicity) can artificially exaggerate certain categories (Laurentiis et al. 2023).

Action catalog and context specificity

Another limitation concerns the pre-defined action catalog and contextual parameterization. The KREGI approach and the DST currently cover fifteen generally applicable actions and five case-specific actions for soil treatment, electronics and detergent packaging. These actions represent important domains such as mobility, workspace use, energy supply, sharing concepts and selected circular product strategies. Yet, they do not exhaust the space of possible interventions across all sectors. The improvement potentials computed in the case studies are therefore bounded by the current action set. Other, not yet modeled actions could be more effective in particular contexts. In addition, many parameter values used in the action quantifications, such as electricity mixes, commuting patterns, building characteristics and waste-treatment options, reflect mostly conditions in Germany or, more broadly, Europe. Applying the framework in other regions without adjusting these parameters can lead to biased results, particularly for energy-related actions where grid compositions and technology portfolios differ. Even within Europe, ongoing decarbonization and changes in transport systems will affect the relative performance of actions over time. While the methodological structure of the framework is transferable, its parameterization must be periodically updated and adapted to local contexts. To make these transfer requirements actionable (rather than purely cautionary), the following protocol summarizes what must be adapted first when applying the framework in a new regional or sectoral context.

1. **Keep the structure fixed**
   Maintain the core logic (indicator set, separation of environmental scoring and circularity descriptors, scenario-band concept, and scoring approach) to preserve internal consistency.
2. **Update background-system parameters**
   Adapt key background assumptions used in action quantification to the target context (e.g., electricity supply mix, fuel supply, transport conditions, and waste-treatment routes) and if necessary to the target reference year.
3. **Recalibrate scaling inputs**
   Re-check how organization-specific inputs (e.g., employees, electricity demand, transport activity) scale each action's effects and ensure unit consistency.
4. **Re-derive scenario ranges**
   Define context-specific best-/worst-case ranges for the most influential parameters (e.g., adoption rates, substitution patterns, or energy supply assumptions) using local data or expert input.

5. **Re-quantify affected actions where needed**
   If technologies/infrastructures differ significantly, reiterate the KREGI three-step quantification for the affected actions and add technology-specific variants as separate actions.
6. **Document and plausibility-check**
   Document all adapted parameters and compare a small subset of actions against either a bespoke LCA or published regional reference studies to confirm plausibility.

Action interactions

The framework also simplifies or omits interactions among actions. Action effects are assumed to be additive when portfolios are constructed. Dynamic interactions, for example, between mobility actions and parking requirements, or between renewable-electricity procurement and electrification of transport, are only reflected qualitatively in scenario assumptions and action descriptions. This simplification is necessary to keep the DST manageable and usable by non-experts, but it implies that portfolio scores may over- or underestimate combined effects when actions are strongly interdependent. Similarly, potential rebound effects, where efficiency gains or circular strategies lead to increased activity, are not modeled explicitly. This applies both to classical energy-efficiency rebound (Mashhadi Rajabi 2022; Karakaya et al. 2024; Jarvis and King 2024) and to CE rebound, where reuse, recycling or product-lifetime extension can expand markets and partly offset expected environmental and sustainability benefits (Figge and Thorpe 2019; Camana et al. 2021; Castro et al. 2022; Zerbino 2023). Conceptual analyses of efficiency, sufficiency, and consistency strategies show that efficiency improvements within established technology corridors can be offset by increased consumption or by technology lock-ins (Rudolf and Schmidt 2025). As a result, efficiency strategies on their own cannot guarantee that absolute environmental impacts fall to acceptable levels (Rudolf and Schmidt 2025).

To increase interpretability and reduce the risk of double counting, the framework can be complemented by an interaction screening that qualitatively classifies pairwise relationships between actions and flags portfolios that likely contain overlaps, dependencies, or conflicts. The screening does not change the underlying LCA results or the LCA–MCDM scoring, but serves as a plausibility check and documentation layer for decision-makers. Five interaction types can be distinguished: (1) Mutual exclusivity (actions cannot be implemented simultaneously), (2) Overlap / double-counting risk (actions affect the same activity driver so additive aggregation may overestimate or underestimate savings), (3) Dependency (one action is a prerequisite for another), (4) Synergy (combined implementation plausibly increases effectiveness beyond additivity), and (5) Rebound risk (action may trigger behavioral or market responses that reduce net savings). For each relevant action pair, an interaction code, a qualitative severity (low/medium/high), and a short justification (e.g., “same baseline variable,” “shared infrastructure,” “behavioral response plausible”) can be documented. A possible evaluation and handling scheme is summarized in Table 5.3.

Table 5.3: Qualitative action-interaction codes and recommended handling rules for action portfolios (plausibility layer; no modification of underlying LCA results or the additive LCA–MCDM scoring logic).

Code	Meaning	Practical handling in a portfolio
MX	Mutual exclusivity	Decision between mutually exclusive actions.
OV	Overlap or double-counting risk	Keep both selectable, but flag "portfolio score may be overestimated or underestimated".
DP	Dependency	If dependent action is selected, show required prerequisite action (or warning).
SY	Synergy	Flag as "potential upside". As a conservative approach, the effects and score are not increased.
RB	Rebound risk	Flag as "needs monitoring". Treat scenario bands as potentially optimistic.

Implications for practical applicability

The limitations discussed above affect how the framework should be used in practice and what decisions it can (and cannot) support. The main implications are summarized below. Overall, the framework is best understood as a screening and prioritization tool that helps users narrow down promising actions under realistic data constraints.

First, the results should be interpreted as relative, scenario-based rankings, not as guaranteed or already realized savings. In practical terms, high-ranking actions are good candidates for further planning, while actions with wide scenario bands should be treated as "data-sensitive" and checked with better local data before major investment decisions.

Second, the compact indicator set, the use of equal weighting, and additive aggregation mean that rankings can change if a company has different priorities (for example, a climate focus versus strict land or water constraints). For important decisions, users should therefore run at least one simple weighting sensitivity check to see whether the top-ranked actions remain stable under their preferences.

Third, the action library limits what can be prioritized, since the framework can only rank actions that are included in the catalog. In addition, the current parameterization is mainly calibrated for European conditions, so transferring the framework to other regions requires adapting key background parameters (e.g., electricity mix, mobility patterns) to avoid biased results.

Fourth, portfolio scores assume additive effects, so overlaps or dependencies between actions can lead to over- or underestimation of combined results. In practice, portfolio results should be treated as approximate until major interactions are checked qualitatively (and, if needed, with a more detailed follow-up assessment).

Fifth, score comparability is primarily ensured within one company or industrial park, because the normalization is based on company-specific maximum saving potentials. Therefore, cross-company comparisons of absolute "points" should be treated with caution unless a harmonized normalization basis is applied.

Finally, the framework focuses on environmental indicators and does not integrate economic and social dimensions quantitatively. This means final implementation decisions

should be complemented by feasibility checks such as costs, payback time, organizational constraints, and stakeholder acceptance. For actions with high investment volume or strategic relevance, the screening results should be followed by a project-specific assessment (e.g., a more detailed LCA model and/or engineering and financial analysis).

A practical checklist for users could include steps such as:

- Use the ranking to select a short list of candidate actions, then validate the top actions with local data where uncertainty bands are wide.
- Run a quick weighting sensitivity check if the company has clear priorities (e.g., climate vs. land/water constraints).
- Adapt region-specific parameters before transferring results to other countries or energy systems.
- Check action overlaps qualitatively before interpreting portfolio scores as additive.
- Complement the environmental screening with cost and feasibility assessment for final decisions, and perform a project-specific follow-up analysis for high-investment actions.

Summary

In summary, the framework developed in this thesis provides a structured and transparent approach to ex-ante environmental evaluation and prioritization of actions in industrial and company contexts, but it operates within clearly defined boundaries. It offers relative, scenario-based rankings rather than predictions, focuses on a compact set of environmental indicators and uses equal weighting and additive aggregation. It also relies on a limited, currently Europe-calibrated action catalog and does not model interactions among actions or integrate economic and social dimensions. Acknowledging these limitations is essential for responsible use of the framework and directly motivates several avenues for future research and development outlined in Chapter 6.

At the same time, the numerical applications in the four case studies showed that even a deliberately simplified framework can differentiate clearly between action portfolios and reveal non-intuitive trade-offs. For example, trade-offs between climate- and LU impacts of renewable-electricity options or between mobility and building-related actions in service-oriented organizations. Observing how rankings changed under alternative scenarios confirmed that explicit representation of each indicator and uncertainty, even in the form of discrete best- and worst-case bands, provides more informative support for ex-ante prioritization than a single deterministic score. These observations suggest that, despite its methodological constraints, the framework can already serve as a useful screening and structuring tool for environmental decision-support, while also pointing to where future refinements would have the greatest effect.

6 Conclusion & Outlook

6.1 Overview of the key findings and implications

The overarching aim of this cumulative thesis was to develop and critically reflect a generic, ex-ante methodological framework that supports environmental evaluation and prioritization of operational actions at company (micro) and industrial-park (meso) levels under practically available data and capacity constraints. The actions considered in this thesis are targeted operational interventions in the fields of e.g., mobility, energy use, shared infrastructure and circularity, and aim to reduce climate- and resource-related impacts. The work combined three methodological pillars introduced in Section 1.3 and developed in Publications I–III: a structured, CE-aware environmental indicator base for industrial and urban symbiosis (Publication I), an action- and scenario-based prospective LCA approach (KREGI approach, Publication II), and a low-effort LCA-MCDM DST (DST, Publication III).

Building on this synthesis, the key findings and implications at thesis level can be summarized as follows:

- The indicator landscape for industrial and urban symbiosis and EIPs is highly heterogeneous, but a relatively small core of energy-, climate- and resource-oriented indicators is used consistently. This underpins the compact five-indicator set applied in this framework.
- Mapping indicators to R-strategies showed that high-circularity strategies such as Rethink, Reduce, and Reuse are reasonably well represented, whereas strategies like Refuse, Refurbish and Remanufacture remain underrepresented in meso-level practice. This gap highlights where future indicator and method development could further support CE implementation at industrial-park scale.
- The KREGI approach demonstrated that scenario-based prospective LCA applied ex-ante to actions can be systematically structured along industrial-park life-cycle phases (planning, building, operation) and across CE levels (nano, micro, meso). The approach also uses clear requirements for action definition and a reusable three-step quantification procedure. This provides a generic way to move from abstract goals and indicators to concrete, comparable actions.
- A library of pre-quantified actions, evaluated under status-quo, best-case and worst-case scenarios, proved sufficient to generate internally consistent environmental rankings when combined with a small set of company-specific inputs in the DST. This shows that meaningful ex-ante screening is possible without full bespoke LCA for each individual company and action.
- The LCA-MCDM scoring design, based on action-oriented normalization, equal weighting of five environmental indicators and weighted-sum aggregation, yielded coherent rankings across four contrasting case studies (consulting, electronics manufacturing, soil treatment, detergent production). The framework also allows

detrimental effects in individual indicators to remain visible through negative normalized values.

- The case applications confirmed that high-leverage actions and the distribution of environmental benefits across indicators are strongly context-dependent: In service-oriented contexts, actions related to workspace use and employee mobility tend to have the greatest impact, whereas in resource-intensive sectors, logistics- and material-intensive actions are usually the main drivers. This underlines that no universal hierarchy of "best" actions exists and that context-specific analysis is essential.
- Scenario bands for best- and worst-case conditions made trade-offs and uncertainties explicit, especially for energy-related actions with conflicting effects on climate/energy versus LU. This supports more nuanced ex-ante prioritization than a single deterministic score and emphasizes the importance of transparent treatment of uncertainty in decision-support.
- Throughout the framework, circularity is treated as a complementary but distinct dimension relative to environmental impacts. CE concepts and R-strategies structure and interpret actions, whereas LCA-derived environmental indicators form the quantitative basis for scoring. This separation avoids compensatory aggregation between circularity metrics and environmental pressures and helps to keep rebound and burden-shifting risks visible.

Taken together, these findings show that the MRQ can be answered affirmatively within the stated boundary conditions: a generic, low-effort ex-ante framework that combines a structured indicator base, scenario-based action quantification and a simple LCA-MCDM scoring scheme can provide decision-relevant, relative environmental rankings of actions and portfolios at micro and meso levels while making key trade-offs and uncertainties explicit. The main methodological novelty of this thesis is therefore not a single tool or indicator set, but the integration of three components into a coherent ex-ante framework. In doing so, the framework bridges a gap between high-level IE and CE concepts and the operational need to select and prioritize concrete actions in companies and industrial parks under data and capacity constraints.

The cumulative work also yielded several methodological insights that were not fully evident at the outset. The scoping review made clear that, despite the strong policy emphasis on circularity, a small set of climate- and resource-oriented indicators still dominates meso-level assessment practice. This justified focusing the framework on a compact environmental core rather than attempting a much broader but less manageable indicator set. In the numerical case applications, it became apparent that actions targeting workspace use and mobility can rival or exceed energy-supply actions in their contribution to composite scores in service-oriented contexts. On the other hand, logistics- and material-oriented actions dominate in production-oriented settings, underlining the importance of retaining a generic, scenario-based design instead of assuming a fixed hierarchy of most effective action types.

At the same time, the analysis confirmed that the framework remains constrained by its limited action catalog, equal-weighting choice and Europe-centered parameterization, and that it does not predict realized environmental outcomes or cover economic and social dimensions. These limitations, together with the empirical and methodological findings summarized above, directly inform the directions for future research and development outlined in Section 6.2. Figure 6.1 summarizes these overarching findings as three key messages, each linked to one of the main methodological pillars of the thesis: the scoping review, the KREGI approach and the DST.

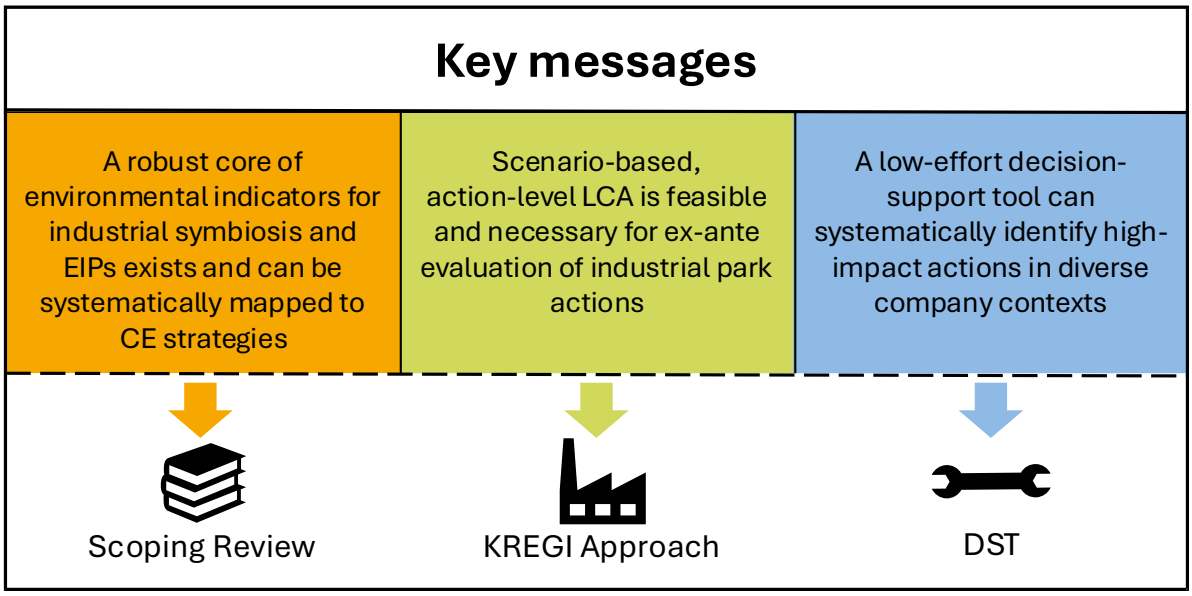


Figure 6.1: Key messages of the cumulative thesis, showing how the scoping review, KREGI approach and DST contribute to the overall framework.

6.2 Directions for future research and development

The framework developed in this thesis demonstrates that ex-ante, low-effort environmental evaluation of actions at company (micro) and industrial-park (meso) levels is feasible and practically applicable under practically available data and capacity constraints. At the same time, the critical appraisal in Section 5.5 highlights several limitations that point to concrete directions for further work. These directions can be grouped into four main areas: (i) indicators and methodological refinements, (ii) extension of the action catalog and sectoral/geographical scope, (iii) integration of sustainability assessment, and (iv) digital implementation, validation and co-creation with practitioners.

(i) Environmental indicators and methodological refinements

- **Broaden environmental indicator coverage**

  The current framework focuses on GWP, CED, RMI, LU and WU, which capture key climate- and resource-related pressures but do not explicitly cover wider impact categories such as eutrophication, toxicity or biodiversity loss. Expanding the indicator base is important to avoid burden shifting and to capture sector-specific hotspots beyond climate and resource use. Future work could extend the indicator base to such categories where methods and data are sufficiently robust, particularly for sectors

where these impacts are central, while carefully managing the additional complexity and data requirements. A useful starting point for such extensions is the indicator mapping in Publication I, which catalogs 624 environmental indicators for industrial and urban symbiosis and EIPs.

- **Refine the treatment of circularity indicators**

  The scoping review of Publication I showed that indicators associated with some R-strategies (for example Refuse, Refurbish or Remanufacture) are underrepresented compared to more established strategies such as Reduce or Recycle. Future research could develop and integrate additional CE indicators and simple maturity concepts for industrial symbiosis and EIPs to operationalize currently underrepresented high-circularity R-strategies and improve the interpretability of action portfolios. To preserve the low-effort character, these additional indicators could be implemented as an optional, non-compensatory reporting layer with clearly documented definitions and data requirements. This would make the circularity dimension more visible and strengthen the interpretive linkage between circularity strategies (R-strategies) and the quantified environmental results without aggregating circularity into the environmental score.

- **Incorporate temporal aspects where relevant**

  The present framework uses static impact indicators, so the explicit timing of emissions and resource flows is not considered. For actions and sectors where temporal patterns are expected to be important, such as long-lived infrastructure or systems involving biogenic carbon, future work could link the action-based approach to dynamic LCA methods. It could then be tested how temporal profiles influence the relative performance of actions and portfolios.

- **Explore alternative weighting and aggregation schemes**

  Equal weighting and weighted-sum aggregation were chosen as transparent defaults under heterogeneous and partly unknown preference structures. The case studies in Publication III showed that these choices can influence rankings when indicators are in conflict, for example between climate- and land- or water-related impacts. Future research should systematically analyze sensitivity to stakeholder-elicited or sector-specific weights. Also alternative, possibly less compensatory aggregation methods, balancing improved preference representation against methodological transparency and data needs could be explored.

- **Implement a qualitative action-interaction assessment**
  Building on the qualitative action-interaction screening introduced in Chapter 5 (Table 5.3), future work should formalize mutual exclusivity and dependency constraints and test conservative overlap adjustments while preserving the low-effort character of the DST.

(ii) Action catalog and sectoral/geographical expansion

- **Expand and diversify the action catalog**

  The current action catalog covers a set of generic actions related to mobility, workspace use, energy supply and sharing concepts, as well as a limited number of sector-specific actions for electronics, soil treatment and detergents. Extending this library to additional sectors with high environmental relevance, such as chemicals, food or construction, and to further life-cycle phases of industrial parks would increase the applicability of the framework and improve coverage of sector-specific levers.

- **Differentiate technological variants within actions**

  Some actions currently bundle heterogeneous technical options, for example "renewable electricity" or "circular product options". Modeling distinct variants, such as rooftop versus ground-mounted photovoltaic systems, different renewable-electricity mixes or alternative mobility and recycling technologies, as separate actions would reduce internal uncertainty and provide more granular decision-support. This is particularly relevant where LU or other trade-offs are critical.

- **Adapt parameterization to other regions and time horizons**

  Many assumptions in the action quantifications (for example on electricity mixes, transport behavior or waste-management systems) reflect current European or German conditions. Applying the framework in other regions or under future decarbonization pathways will require systematic adaptation of background data and scenario assumptions. Ideally the adaptation and assumptions use transparent procedures that allow users to adjust key parameters to local conditions and anticipated developments. They could also rely on the step-wise protocol of Section 5.5.

- **Connect action-level results to macro-level scenarios**

  The quantified effects of actions and portfolios at company and industrial-park level could be aggregated and used as bottom-up inputs for national or sectoral CE and climate-mitigation scenarios. Such scenarios could, for example, be implemented using IAM-linked prospective LCI tools such as PREMISE, which generate scenario-specific versions of ecoinvent based on pathways from models like REMIND or IMAGE. This would help bridge the gap between detailed, action-level assessment and macro-level policy analysis and allow exploration of how widespread adoption of certain action types might affect regional or national environmental roadmaps.

(iii) Integration of sustainability assessment

- **Add structured but simple economic indicators**

  The current framework focuses on environmental performance and only allows optional cost entries at action level. Future extensions could systematically incorporate basic economic metrics such as cost ranges, cost per unit of environmental improvement or approximate payback times as a separate assessment dimension. The

extension should maintain the low-effort character of the tool and avoid double counting. Additionally, LCC modules aligned with the existing LCA system boundaries and functional units could be added to support integrated environmental-economic evaluation of actions within the same decision-support structure.

- **Introduce selected social indicators.**

  Social aspects, for example employment effects, worker safety or mobility equity, are not explicitly considered, even though they can influence the acceptability and prioritization of actions and portfolios. Based on the structure of the existing framework, a small set of pragmatic social indicators could be added to capture such aspects at least in a screening manner. A full life-cycle sustainability assessment could be the second step.

- **Link to absolute environmental performance requirements**

  At present, the framework provides relative rankings and scenario-based improvements, but does not explicitly relate action portfolios to absolute environmental budgets or targets. Future work could explore how the results can be connected to company- or park-level targets that are consistent with science-based climate targets or other budget-oriented approaches. This would strengthen the link between relative prioritization and absolute sustainability requirements.

(iv) Digital implementation, validation and co-creation

- **Develop advanced digital implementations**

  The current DST is implemented in a spreadsheet environment to maximize accessibility. Web-based or database-backed implementations could support automated data import from corporate systems, parameter updates, version control and anonymized benchmarking between companies or industrial parks. It could thereby increase usability, maintainability and potential for wider dissemination.

- **Undertake empirical validation through longitudinal case studies**

  The applications in Chapter 4 are ex-ante and scenario-based, and realized environmental outcomes have not yet been tracked. Following industrial parks and companies that apply the framework over time would allow comparison of ex-ante results with observed changes and help calibrate scenario assumptions. It would also reveal enablers as well as organizational and institutional barriers that are not fully captured in the current quantitative modeling.

- **Use the framework in teaching and multi-stakeholder processes**

  The structure of the framework makes it suitable not only for research but also for teaching and for facilitating dialogue between municipalities, park operators, companies and other actors in industrial regions. Applying the tool in courses, workshops or co-creation settings would provide feedback on usability, inform further development of the action catalog and support integration into existing EIP and CE planning processes.

Summary

Taken together, these directions outline a research and development agenda that builds directly on the methodological foundations, empirical insights and limitations identified in this thesis. Future work can extend the indicator base, expand the action catalog and sectoral scope, integrate economic and social dimensions, and advance digital implementation and empirical validation. Together, these developments can increase the robustness and practical impact of the framework as a bridge between IE concepts, CE strategies, and operational decision-making in companies and industrial parks. Figure 6.2 summarizes these future research and development directions and shows how they build on the current framework developed in this thesis.

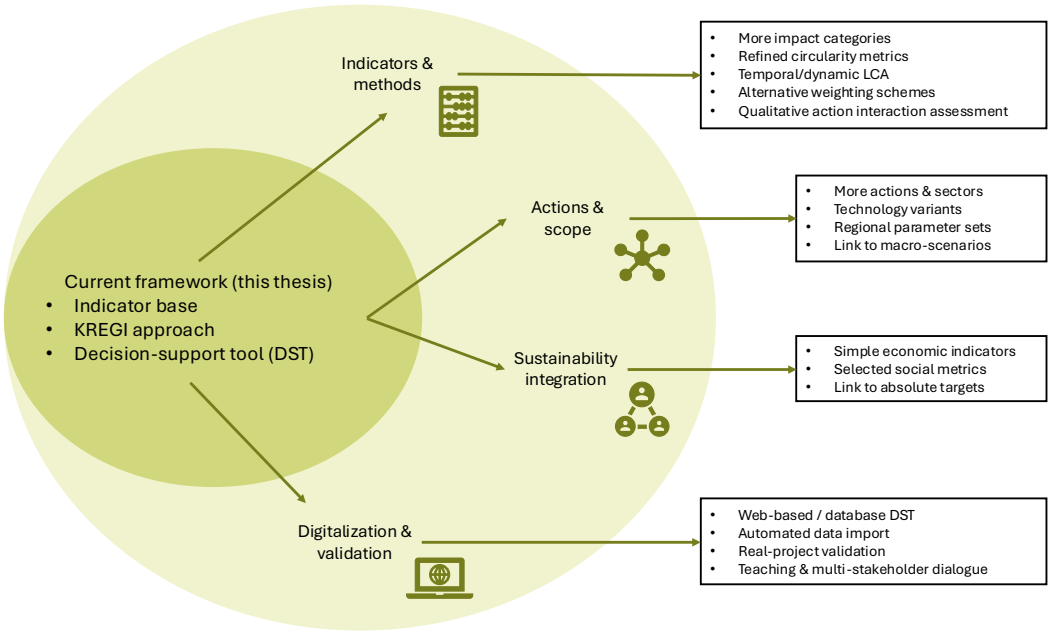


Figure 6.2: Future research and development directions building on the current framework (indicator base, KREGI approach and DST), grouped into four areas: indicators & methods, actions & scope, sustainability integration, and digitalization & validation.

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Appendices

Appendix A

Supplementary information for Publication I

A 1 Indicator overview

In the following Table A 1 the processed data is shown. More detailed information is available in the supplementary materials.

Table A 1: Indicator overview with all considered indicators and information.

Indicator	Unit	Context	Type	Category	R-strategy	Sum of sources
CO_2 (equivalent) / carbon (emissions/intensity) (reduction/saving)	kg CO_2 eq/a + % + kg CO_2 eq + kg CO_2 eq/kg product + kg CO_2 eq/monetary value + kg CO_2 + kg CO_2/kg product + kg CO_2/kg fuel	I.Symb+U.Symb+EIP+CE-Meso	Qual. + Quan.	Env.+Em.	(Reduce)	111
Energy/power consumption/demand/use (reduction/save/avoided/conservation)	J/employed person + J + J/a + kg/a + kg CO_2 + J/GDP + J/IaV + J/monetary value + J/kg product + sej + J/J + % + m^3 diesel/kg*m + J/m^3 + m^3 + W	I.Symb+U.Symb+EIP	Quan.	Energy	(Reduce)	103
Waste generated/produced/emission (intensity/reduction/diversion/saving/mitigation)	m^3/a + kg + kg/GDP + kg/IAV + % + kg/capita + mol/a + /IAV + kg/monetary value + kg/kg CO_2 + number of firms producing + J/a + /GDP + /monetary value + m^3/monetary value	I.Symb+U.Symb+EIP	Qual. + Quan.	MWW	(Reduce)	78
Global warming (potential) / climate change (reduction)	kg CO_2 eq + kg CO_2 eq/a + kg CO_2 eq/kg (waste, input or product) + % + kg CO_2 eq/J + kg CO_2 eq/FU	I.Symb+U.Symb+EIP	Qual. + Quan.	Env.+Em.	(Reduce)	73
Water/wastewater/freshwater/groundwater use/demand/consumption (reduction/saving/conservation)	m^3 + kg + m^3/GDP + m^3/IAV + m^3/kg product + /Capita + n + % + m^3/a	I.Symb+U.Symb+EIP	Quan.	MWW	(Reduce)	67
Greenhouse gas (CH_4/N_2O) (emissions) reduction/mitigation/saving/offset/removal	kg CO_2 eq + kg CO_2 eq/a + kg CO_2 + kg/a + kg + kg CO_2 eq/kg (product/waste/input) + kg CO_2 eq/J + % + sej/CO_2 eq	I.Symb+U.Symb+EIP	Quan.	Env.+Em.	(Reduce)	48
(Raw/virgin) Material consumption/use/output/type/demand (saved/avoided/reduced)	kg + kg/a + kg/kg product + m^3/kg product + /IAV + /monetary value + sej + /capita	I.Symb+U.Symb+EIP+CE-Meso	Qual. + Quan.	MWW	(Reduce)	46
Waste (dangerous/hazardous) to landfill/disposal (rate/diversion/saving/reduction)	kg/a + kg/GDP + % + m^3/capita + kg + m^3	I.Symb+U.Symb+EIP	Qual. + Quan.	MWW	(Reduce)	42
Water/wastewater recycling/regeneration/reclaim/treatment/reuse (rate/efficiency)	% + m^3 + m^3/product + kg/a + monetary value/m^3	I.Symb+U.Symb+EIP	Quan.	MWW	Reduce+Reuse+Recycle	39
Acidification (potential) (reduction)	kg SO_2 eq + mol(e/c) H+ eq + % (reduction) + kg/IaV + points + kg SO_2 eq/FU + mol H+/t + mol H+ eq/a + kg NO_3 eq	I.Symb+U.Symb+EIP	Quan.	Env.+Em.	(Reduce)	38
Land use/occupation/area/conversion/change/transformation (intensity/rate/saved)	m^2 + % + kg C deficit + point/a + m^2/kg product + m^2/a + monetary value/m^2 + IAV/m^2 + m^2/GDP + m^2/capita + GDP/m^2	I.Symb+U.Symb+EIP	Quan.	Env.+Em.	(Reduce)	38
Environmental emissions (various pollutants) (to air) (reduction/impact)	kg + kg/kg + /GDP + kg CO_2/a + kg/m^2 + % + m^3/a	I.Symb+U.Symb+EIP	Qual. + Quan.	Env.+Em.	(Reduce)	37
SO_2/SO_x (emissions) (change/impact/intensity/efficiency) (reduction)	kg/GDP + kg + kg/a + % + sej + kg/IAV + kg/kg product + kg/monetary value	I.Symb+EIP	Quan.	Env.+Em.	(Reduce)	37
Waste use/utilization/consumption/exploited/treated (rate/potential/efficiency)	sej + % + kg/a + sej/monetary value + kg/J	I.Symb+U.Symb+EIP	Quan.	MWW	Reduce	36
Resource (consumption/use/demand/mining) (reduction/conservation/saving/efficiency)	kg + kg/a + J/kg + J/a + % + sej + /capita + monetary value/kg	I.Symb+U.Symb+EIP+CE-Meso	Qual. + Quan.	MWW	(Reduce)	35
Eutrophication (potential) (reduction) (unspecified)	kg PO_4 eq + kg PO_4 eq/kg + kg P eq + kg N eq + kg SO_2 eq + kg O_2 eq/kg + kg N/kg	I.Symb+U.Symb+EIP	Quan.	Env.+Em.	(Reduce)	33
Fuel/biofuel consumption/demand/flow/use (reduction/intensity/efficiency)	m^3/m + J + J/a + J/kg + L/a + kg/a + kg/employed person + kg + kg/monetary value + m^3/a + m^3 + m^3/m + %	I.Symb+U.Symb+EIP	Qual. + Quan.	MWW + Energy	(Reduce)	33
(Transport/delivery) Distance (average/critical)	m + kg*m + m/trip	I.Symb+U.Symb+EIP	Qual. + Quan.	MWW		30
Waste recycling (potential/rate)	kg/a + % + kg	I.Symb+U.Symb+EIP+CE-Meso	Quan.	MWW	Recycle	30

(Human) Toxicity (non) (carcinogenic) (effects)	kg 1.4 DCB + kg 1.4 DCB eq + kg C_2H_3Cl eq + kg 1.4 DB-eq/kg + kg PM 2.5 eq	I.Symb+U.Symb+EIP	Quan.	Env.+Em.		29
(Stratospheric) Ozone depletion (potential)	kg CFC-11 eq + % + kg R11 eq	I.Symb+U.Symb+EIP	Quan.	Env.+Em.		29
(Recycled/recycling) Material/resources use/productivity (rate) / recycling rate	/n + % + kg + monetary value/kg + GDP/kg	I.Symb+U.Symb+EIP+CE-Meso	Qual. + Quan.	MWW	Recycle	27
Particulate matter formation (PMF) 2.5/10 (reduction)	kg + kg/a + kg/GDP + % + kg/kg product + disease incidences	I.Symb+U.Symb+EIP	Quan.	Env.+Em.	(Reduce)	26
Waste reuse (rate/ratio)	kg + %	I.Symb+U.Symb+EIP+CE-Meso	Quan.	MWW	Reuse	26
Electricity (consumption/demand) (density/intensity/saving/conservation)	J + J/a + J/monetary value + J/m^2 + W + J/m^3 + J/kg product	I.Symb+U.Symb+EIP	Quan.	Energy	(Reduce)	23
Nitrogen/NO_x (use/input/flow/output/emission/ratio) (efficiency) (reduction)	kg/GDP + kg + kg/kg product + kg/J heat + kg/a + % + kg/m^3	I.Symb+EIP	Quan.	Env.+Em.	(Reduce)	23
Water/wastewater generation/production/discharge	m^3/a + kg/IAV + +kg/a + /GDP + /monetary value + m^3 + kg + /m^2 + % + n	I.Symb+EIP	Qual. + Quan.	MWW		22
Eutrophication (potential) marine/aquatic/water	kg PO_4 eq + kg N eq + kg N eq/a + % + kg P eq + kg P eq/a	I.Symb+U.Symb+EIP	Quan.	Env.+Em. + MWW		21
(Centralized) Waste/sewage/wastewater treatment facilities/plants/system (rate/concentration)	%	I.Symb+EIP	Qual. + Quan.	Energy	(Rethink)	20
(Local) Renewable energy/emergy use ratio/share/produced/renewability	% + J	I.Symb+U.Symb+EIP	Qual. + Quan.	MWW	Reduce	20
(Solid) Waste (undefined)	kg/a + kg + %	I.Symb+U.Symb+EIP	Quan.	Symb.+Shar. + MWW		20
Chemical oxygen demand (COD) generation/emission/discharge/redundancy (intensity) (reduction)	kg + kg/IAV + kg/GDP + kg/monetary value + sej + kg/m^3 + kg/kg + %	I.Symb+EIP	Quan.	Env.+Em.	(Reduce)	19
Environmental impacts (mitigation)	sej + Points/a + kg CO_2 eq + Points + Ecopoints/J	I.Symb+EIP	Qual. + Quan.	Env.+Em.	(Reduce)	19
Resource depletion (mineral, fossil, renewable, metal) (reduction) (potential)	% + kg Sb eq + kg Cu eq + kg Fe eq + J + kg oil eq	I.Symb+U.Symb	Quan.	Env.+Em. + MWW	(Reduce)	18
Water/wastewater/freshwater (undefined use)	m^3 + m^3/a + kg + kg/a	I.Symb+U.Symb+EIP	Qual. + Quan.	MWW		17
(Input) Material substitution (through waste usage) (rate)	kg/a + kg	I.Symb+U.Symb+EIP	Qual. + Quan.	MWW	Rethink+Reduce	16
Ecotoxicity (aquatic/freshwater/marine)	CTUe + kg DCB eq + kg 1.4 DB eq + %	I.Symb+U.Symb+EIP	Quan.	Env.+Em.		15
Waste recovered/reclaimed/collected/received/mining (rate)	kg + kg/a + kg CO_2 eq/a + %	I.Symb+U.Symb+EIP	Quan.	MWW		15
Water pollution/pollutants/contamination/emissions (COD, NH_3-H, mercury…) (avoidance/efficiency/intensity)	kg + m^3/kg + kg/monetary value + m^3/monetary value	I.Symb+EIP	Qual. + Quan.	Env.+Em. + MWW	(Reduce)	15
Energy (saving) efficiency	J/monetary value + %	I.Symb+U.Symb+EIP	Qual. + Quan.	Energy	Reduce	14
(Total) (solar) Emergy (increase/density)	sej + sej/m^2	I.Symb+U.Symb+EIP	Quan.	Energy		13
Byproduct use/input/valorization/export/availability	n + kg + m^3 + J	I.Symb+CE-Meso	Qual. + Quan.	Energy	Reuse	13
Energy/power production/generation/supply	J/a + % + J/kg + W	I.Symb+U.Symb+EIP	Quan.	Env.+Em.		13
Terrestrial (eco) toxicity	kg DCB eq + kg 1.4 DB eq + % + (species*a/kg)	I.Symb+U.Symb+EIP	Quan.	MWW		13
Abiotic depletion (potential) (elements)	kg Sb eq + J	I.Symb+U.Symb+EIP	Quan.	Energy		12
Eco-efficiency	monetary value/kg CO_2 eq + kg/a	I.Symb+U.Symb+EIP	Quan.	Energy	Reduce	12
Emergy yield (ratio)	sej	I.Symb+U.Symb+EIP	Quan.	Env.+Em. + MWW		12
Energy/power (undefined/thermal)	J + % + J/a	I.Symb+EIP	Qual. + Quan.	Other		12
Byproduct produced	kg/a + m^3/a + n + kg + m^3 + J	I.Symb	Quan.	Energy		11
Carbon footprint (mitigation)	kg CO_2 + kg CO_2 eq + kg CO_2 eq/J + kg CO_2 eq/kg	I.Symb+U.Symb	Quan.	Env.+Em.	(Reduce)	11
Environmental load ratio (ELR)	Not displayed	I.Symb+U.Symb+EIP	Quan.	Env.+Em.		11
Environmental management (systems/mechanism) (perfection/certification)	Not displayed	I.Symb+EIP	Qual.	Env.+Em.		11
Heat demand/consumption	J + J/a + J/m^2 + W/kg + J/m^3 water + W	I.Symb+U.Symb+EIP	Quan.	Env.+Em. + Energy		11
Resources/material recovered (potential/rate)	kg/a + % + kg	I.Symb+U.Symb+EIP	Quan.	MWW	Reduce+Recycle	11
Terrestrial acidification (potential)	kg SO_2 eq + % (reduction)	I.Symb	Quan.	MWW		11
Emergy sustainability index (ESI + ESI') / Index of sustainability for eco-industrial park (PESI)	Not displayed	I.Symb+U.Symb	Quan.	Energy		10

Emergy: (local available) non-renewable resources (inputs/outputs/ratio)	sej + sej/a + %	I.Symb+U.Symb+ EIP	Quan.	Energy		10
Emergy: (local available) renewable resources (inputs)	sej + sej/a	I.Symb+U.Symb+ EIP	Quan.	Energy		10
Energy intensity	kg of fuel eq + J/GDP + % + J/monetary value	I.Symb+U.Symb+ EIP	Quan.	Energy		10
Export/Import emergy (ratio)	Not displayed	I.Symb+U.Symb+ EIP	Quan.	Energy		10
Natural/green land cover (rate)	% + /capita	I.Symb+U.Symb+ EIP	Quan.	Env.+Em.		10
Resources accessibility/robustness/origin/security/availability/scarcity (potential)	kg oil eq	I.Symb+U.Symb+ EIP	Qual. + Quan.	MWW		10
Waste/residuals exchanged (symbiotic)	% + kg/a + kg	I.Symb	Quan.	Symb.+Shar. + MWW	Rethink	10
Byproduct reuse (rate)	kg + % + kg/a	I.Symb+EIP	Quan.	MWW	Reuse	9
Efficiency (current, highest achievable, production, sorting, utilization, technical, area, entrepreneurs managing green logistics)	%	I.Symb+U.Symb+ EIP	Quan.	Energy	Reduce	8
Exergy (efficiency/savings/consumed)	% + J/kg product + W + J/a + J/mol + J/monetary value	I.Symb+U.Symb+ EIP	Quan.	Energy	Reduce	8
Heat waste (available/usage/utilization ratio/potential)	J + W + J/a + %	I.Symb+U.Symb	Quan.	Env.+Em.	Rethink+Reduce	8
Information/knowledge sharing networks/platform (completeness)	%	I.Symb+EIP	Qual. + Quan.	MWW	Rethink	8
Material imported/purchased	kg/a + sej + kg + mol/a	I.Symb+U.Symb+ EIP	Quan.	MWW		8
Output (flow/product/material/resource)	m^3 + kg + kg/a + W + m^3/a + %	I.Symb+EIP+CE-Meso	Quan.	Env.+Em. + MWW		8
Respiratory effects/(in)organics	kg PM 2.5 eq + kg C_2H_4 eq + % + kg 1.4 DCB eq	I.Symb+EIP	Quan.	Env.+Em. + MWW		8
Waste emission (reduction/intensity)	kg/a + kg + /GDP + /IAV + kg/monetary value + m^3/monetary value	I.Symb+EIP	Quan.	Other	(Reduce)	8
Water/watershed/wastewater/water for reuse quality (index)	Not displayed	I.Symb+EIP	Qual. + Quan.	Symb.+Shar.	Reuse	8
(Raw) (material) Reuse (rate/efficiency)	kg/a + % + kg	I.Symb+U.Symb+ EIP+CE-Meso	Qual. + Quan.	Energy	Reuse	7
(Symbiotic) Synergy/cooperation (creation)	kg/a	I.Symb+EIP	Qual. + Quan.	Energy	Rethink	7
Byproducts or waste type	Not displayed	I.Symb	Qual.	Energy		7
Emergy investment/money/GDP ratio	monetary value/sej + sej/monetary value + sej/GDP	I.Symb+EIP	Quan.	Energy		7
Emergy saving (performance/efficiency/relative)	sej + % + sej/kg	I.Symb+U.Symb+ EIP	Quan.	Energy	Reduce	7
Energy resource exchange (potential) (energy, heat, steam)	n + % + J + W + kg/a	I.Symb	Quan.	Env.+Em.	Rethink+Reduce	7
Environmental benefits	sej + kg + kg/a	I.Symb+EIP	Quan.	Env.+Em.		7
Environmental reporting	n/a	I.Symb+EIP	Qual.	Env.+Em.		7
Input (flow/product/demand) (unspecified)	kg + m^3 + kg/a	I.Symb	Quan.	Env.+Em.		7
Ionising radiation (human health)	kg U235 eq + kg Co-60 eq + CTUe + % + kg NOx eq + kBq U235 eq/a	I.Symb	Quan.	Symb.+Shar. + Energy		7
Non-renewable / fossil energy	J + J/kg + sej + J_primary	I.Symb+EIP	Quan.	MWW		7
Primary energy (demand)	J + %	I.Symb	Quan.	MWW		7
Public satisfaction/perception of (local) environment (quality/health) / eco-industrial park	%	I.Symb+EIP	Quan.	MWW		7
Resource exchange (unspecified)	n + kg/a + kg + %	I.Symb+U.Symb+ EIP	Qual. + Quan.	MWW	Rethink	7
Resources (minerals, environmental, natural/renewable)	J + points + % + kg/a	I.Symb+EIP	Quan.	MWW		7
Steam (surplus/consumption/production/transfer/demand)	% + kg/a + J/a + J + W	I.Symb+U.Symb+ EIP	Quan.	Symb.+Shar.	(Rethink)	7
Water (resource) depletion	m^3 / % + m^3 water eq	I.Symb+U.Symb	Quan.	Symb.+Shar. + MWW		7
(Abiotic depletion) Fossil fuel depletion	J surplus + J + J/kg + % reduction	I.Symb+EIP	Quan.	Energy		6
Byproduct exchange/synergies	kg + kg/a + % + n	I.Symb+EIP	Qual. + Quan.	Env.+Em.	Rethink	6
Byproduct recycling (rate)	%	I.Symb+EIP	Quan.	Env.+Em.	Recycle	6
Cleaner/environmental friendly production (rate)	%	I.Symb+EIP	Quan.	Env.+Em.	Rethink+Reduce	6
Dust (emission) (reduction)	sej + kg + kg/kg	I.Symb+EIP	Qual. + Quan.	Env.+Em.	(Reduce)	6
Environmental performance (quality)	%	I.Symb+EIP	Qual. + Quan.	MWW		6

Environmental/landscape protection/conservation (system/supervision)	Not displayed	U.Symb+EIP	Qual.	MWW		6
Eutrophication (potential) terrestrial	mol N eq + mol N eq/a	I.Symb	Quan.	MWW		6
Hazardous waste generation/production (reduction/diversion/saving)	kg/capita + kg/a + kg	I.Symb+U.Symb+EIP	Quan.	Symb.+Shar.	(Reduce)	6
Industrial symbiosis indicator (ISI)	Not displayed	I.Symb	Quan.	Env.+Em. + MWW	Rethink	6
Product (amount/surplus)	% + kg/a + kg	I.Symb+EIP	Quan.	Symb.+Shar. + MWW		6
(Product) Eco-design / design for environment	Yes/No	I.Symb+EIP	Qual.	Energy	Rethink	5
Carbon monoxide (CO) (emissions) (reduction)	kg/kg product + kg + %	I.Symb	Quan.	Env.+Em.	(Reduce)	5
Chemicals (ecological) (consumption)	kg/a + /GDP + kg + kg/m^2	I.Symb+EIP	Quan.	Env.+Em.		5
Cyclicity	%	I.Symb+U.Symb+EIP	Quan.	Env.+Em.	*Reduce, Reuse, Rethink, Recycle, Recover, Repurpose, Repair, Refuse, Refurbish, Remanufacture	5
Destination of byproduct/waste	Not displayed	I.Symb	Qual.	Env.+Em. + Energy		5
Direct material consumption (DMC)	kg/capita + kg	I.Symb+U.Symb	Quan.	MWW		5
Energy mix / electricity emission factor (change)	kg CO_2 eq/J + %	I.Symb+EIP	Quan.	MWW		5
Energy recycling (rate)	Not displayed	I.Symb+EIP	Quan.	MWW	Reduce+Recycle	5
Green building / sustainable architecture design (ratio)	%	EIP	Quan.	MWW	Rethink+Reduce	5
Noise (impact) decrease / control	Not displayed	I.Symb+EIP	Qual. + Quan.	Other	(Reduce)	5
Pollution prevention and control	Not displayed	I.Symb	Qual.	Other	Reduce	5
Waste collection system (is available)	Yes/No	EIP	Qual.	Other		5
Water footprint (blue/gray) (reduction/symbiosis) (impact on reduction)	m^3/m^2 + kg/a + m^3/a + m^3/kg*a + %	I.Symb+U.Symb+EIP+CE-Meso	Quan.	Symb.+Shar. + MWW	(Rethink+Reduce)	5
((Non) renewable) Materials (undefined)	kg + sej	I.Symb+CE-Meso	Qual. + Quan.	Energy		4
(Effective) Electrical efficiency	%	I.Symb+U.Symb+EIP	Qual. + Quan.	Energy	Reduce	4
(Industrial park management entity operates an/promotes) environmental/energy management/recording system	Yes/No	EIP	Qual.	Energy	Reduce	4
(Industrial) Symbiotic exchange	kg + n + mol/a	I.Symb+EIP	Qual. + Quan.	Energy	Rethink	4
(Raw) (material) Utilization (rate/efficiency)	%	I.Symb+EIP	Unknown	Energy		4
Aquatic/ocean acidification	kg SO_2 eq + %	I.Symb+EIP	Quan.	Energy		4
CO_2 storage/capture	kg/a	I.Symb+U.Symb	Quan.	Energy	Reduce	4
Cooperative/sharing infrastructure/technology	Not displayed	I.Symb+EIP	Unknown	Energy	Rethink	4
Distance from/to airport/highway/port/railway station/urban center/river/protected areas/urban areas/residential areas/water network/housing	m	I.Symb+U.Symb+EIP	Quan.	Env.+Em.		4
Distance traveled (by employees)	m + m/m^2 occupied space	I.Symb+EIP	Quan.	Env.+Em.		4
Eco-connectance	Not displayed	I.Symb	Quan.	Env.+Em.		4
Ecosystem quality	Impact ccore (points) + % + PDF*m^2*a + Pt	I.Symb+EIP	Quan.	Env.+Em.		4
Electricity production/generation/supply (increase)	J/a + J/kg + %	I.Symb	Quan.	Env.+Em.		4
Energy exported/imports	J/a + J	I.Symb+U.Symb+EIP	Quan.	Env.+Em.		4
Energy recovery (efficiency)	J/kg + %	I.Symb+U.Symb+EIP	Quan.	Env.+Em.	Rethink+Reduce	4
Energy/exergy loss	J/a + kg/kg product + J/kg + J/monetary value	I.Symb+U.Symb	Quan.	Env.+Em. + Energy		4
Enterprises that have passed ISO14001 certification	n + %	EIP	Quan.	Symb.+Shar. + Energy	Reduce	4
Environmental factor	% + kg/kg	I.Symb+EIP	Quan.	MWW		4
Green land / open space for native flora and fauna	m^2 + %	EIP	Qual. + Quan.	MWW		4
Heat flow/output/export/supplied (to district heat)	W + J + J/a	I.Symb+U.Symb+EIP	Quan.	MWW	(Rethink)	4

Heat recovery/reclamation	J/a + W	I.Symb+U.Symb	Quan.	Other	Reduce	4
Land capacity / available land	Not displayed	EIP	Qual.	Other		4
Material resource exchange (potential) (water/material)	n + % kg/a	I.Symb	Quan.	Other	Rethink	4
Pipeline distance (connecting thermal storage to customer)	m	I.Symb+U.Symb	Quan.	Symb.+Shar.		4
Resource use, fossil	J + J/a	I.Symb	Quan.	Symb.+Shar.		4
Supporting programs (e.g., energy efficiency networks) are in place to improve the energy efficiency of (major energy-consuming) businesses in the industrial park	Yes/No	U.Symb+EIP	Qual.	Env.+Em. + MWW	Rethink+Reduce	4
Transport (inland/export) (freight)	kg*m + kg	I.Symb	Quan.	Symb.+Shar. + MWW		4
(Photochemical/tropospheric) Ozone formation (human health / terrestrial ecosystems / vegetation)	kg NOx + kg NMVOC eq	I.Symb	Quan.	Energy		3
(Waste) Heat discharge/loss (decrease/rate)	%	I.Symb+U.Symb	Quan.	Energy	(Reduce)	3
A program is established to monitor, mitigate, and/or minimize greenhouse gas emissions	Not displayed	EIP	Qual.	Energy	Reduce	3
Air quality	Not displayed	I.Symb+EIP	Unknown	Energy		3
Betweenness/degree centrality/centralization	Not displayed	I.Symb+EIP	Quan.	Energy		3
CO_2 utilization (fraction) / recycling	%	I.Symb+EIP	Quan.	Energy	Rethink+Repurpose+Recycle	3
Connectance (with/without cannibalism): the number of direct waste flows within a symbiotic network divided by the total number of theoretically possible flows	Not displayed	I.Symb+EIP	Quan.	Energy	Rethink	3
Cumulative energy demand (CED)	J/kg + J	I.Symb+U.Symb	Quan.	Energy		3
Eco-industrial chain/synergies (added after enforcing EIP demonstration program)	n	EIP	Quan.	Energy	Rethink	3
Elastic coefficient of energy consumption	%	EIP	Quan.	Env.+Em.		3
Electricity/fuel recovery	% + J	I.Symb+U.Symb	Quan.	Env.+Em.	Reuse	3
Emergy loss percent/changes/dilution	% + sej	I.Symb+U.Symb	Quan.	Env.+Em.		3
Environmental (co) benefit: energy/emergy	kg/a + sej	I.Symb+U.Symb+EIP	Quan.	Env.+Em.		3
Environmental risk prevention and control system (completion rate) (framework in place)	%	EIP	Quan.	Env.+Em.		3
Generalization: The number of waste producer firms interacted per waste receiver firm within a symbiotic network	%	I.Symb+EIP	Quan.	Env.+Em.	Rethink	3
Geographic proximity (evaluation)	Not displayed	I.Symb	Qual.	Env.+Em.		3
Improved environmental loading ratio (IELR / PELR)	Not displayed	I.Symb+EIP	Quan.	MWW + Energy		3
Incineration/combustable amount (waste)	kg + kg/(person*a)	I.Symb+U.Symb+EIP	Quan.	Symb.+Shar. + Energy	Recover	3
Link density: average number of waste flow per firm within a symbiotic network	%	I.Symb+EIP	Quan.	MWW	Rethink	3
Material (re)cycling (used)	Not displayed	I.Symb+U.Symb+EIP+CE-Meso	Qual.	MWW	Recycle	3
Material flow/required	kg/a	I.Symb+EIP	Qual. + Quan.	MWW		3
Mineral (extraction)	%	I.Symb	Quan.	MWW		3
Net energy	J + W + J/a	I.Symb+U.Symb	Quan.	MWW		3
Network of experts with technical and commercial knowledge that enhances the use of byproducts and waste in industry	Not displayed	I.Symb	Unknown	MWW	Rethink	3
Planned amount / capacity of treatment (of waste/wastewater)	kg/a	I.Symb+EIP	Quan.	MWW	Recycle	3
Plant production reduction (savings)	J/a + %	I.Symb+EIP	Quan.	MWW	Reduce	3
Proportion of firms in industrial park which appropriately handle, store, transport and dispose of toxic and hazardous materials	%	EIP	Quan.	MWW		3
Renewable energy ratio over national average	% + kg CO_2/J	EIP	Qual. + Quan.	MWW		3
Renewable/natural resources share/use rate	%	I.Symb+EIP	Quan.	Symb.+Shar.	Reduce	3
Resource use, minerals and metals	kg Sb eq + kg Sb eq/a	I.Symb	Quan.	Symb.+Shar.		3

Smog (precursors/formation)	kg O_3 eq + kg VOC eq + NO_x eq	I.Symb+EIP	Quan.	Symb.+Shar.		3
Spatial distribution/range of (exchange-based) industrial symbiosis	n + m	I.Symb	Quan.	Symb.+Shar.	Rethink	3
Synergistic heating (opportunities)	Not displayed	I.Symb+EIP	Qual.	Env.+Em. + MWW	Rethink	3
The industrial park and businesses have systems in place / plans / documentations to increase water savings and reuse	Yes/No	EIP	Qual.	Symb.+Shar. + MWW	Reduce+Reuse	3
The industrial park has a plan to assess/limit/understand environmental impacts	Not displayed	EIP	Qual.	Symb.+Shar. + MWW	Reduce	3
The industrial park has metering and monitoring systems in place to measure energy consumption	%	EIP	Qual. + Quan.	Symb.+Shar. + MWW		3
Vulnerability: the number of waste receiver firms per waste producer firm within a symbiotic network	%	I.Symb+EIP	Quan.	Symb.+Shar. + MWW	Rethink	3
Waste management	Not displayed	I.Symb+EIP	Unknown	Symb.+Shar. + MWW		3
(Potential) Reuse of products/components	Not displayed	I.Symb+CE-Meso	Qual.	Energy	Reuse	2
(Reduced) material stock(piling)	kg/a + kg	I.Symb+EIP	Quan.	Energy	Reduce	2
(Sustainable use of) Natural resources	kg	I.Symb+EIP	Qual. + Quan.	Energy		2
Ability to enter into new partnerships to share resources with other geographically close industries	High, Medium, Low	I.Symb	Qual.	Energy	Rethink	2
Ability to tools for transforming the current production process into a circular process	High, Medium, Low	I.Symb	Qual.	Env.+Em.	*Reduce, Reuse, Rethink, Recycle, Recover, Repurpose, Repair, Refuse, Refurbish, Remanufacture	2
Access to infrastructure that allows the resources exchange with another co-located industry	Not displayed	I.Symb	Qual.	Env.+Em.	Rethink	2
Access/accessibility to tools for industrial symbiosis / exchange network implementation/development	High, Medium, Low	I.Symb	Qual.	Env.+Em.	Rethink	2
Activity degree of water/energy network	Not displayed	I.Symb	Quan.	Env.+Em.	Rethink	2
Area of harmful algal blooms / nutrient recirculation / red tide area	Not displayed	I.Symb	Qual.	Env.+Em.		2
Available (increment) of (clean) water resource	kg	EIP	Quan.	Env.+Em.		2
Average distance to collection points / waste collection distance	m	I.Symb	Quan.	Env.+Em.		2
Biodiversity (damage)	Not displayed	I.Symb	Quan.	Env.+Em.		2
Byproduct unused/discarded/unrecovered	kg + m^3 + J	I.Symb+EIP	Quan.	Env.+Em. + Energy		2
Capacity of environmental policies and regulations to encourage industrial symbiosis	High, Medium, Low	I.Symb	Qual.	MWW + Energy	Rethink	2
Climate change - atmospheric CO_2 concentration	%	I.Symb	Quan.	MWW + Energy + Symb.+Shar.		2
Climate change - energy imbalance at top-of-atmosphere	%	I.Symb	Quan.	MWW + Energy + Symb.+Shar.		2
CO_2 emission effect: CO_2 emissions produced through energy conversion or technology development within the same / other energy source group	Not displayed	EIP	Quan.	Env.+Em. + MWW		2
CO_2 emission factor for the transportation	kg CO_2 /kg*m	EIP	Quan.	MWW		2
Coefficient of circularity	Not displayed	I.Symb	Quan.	MWW	*Reduce, Reuse, Rethink, Recycle, Recover, Repurpose, Repair, Refuse, Refurbish, Remanufacture	2
Construction of roads / road area	m^2/capita	I.Symb+EIP	Quan.	MWW		2
Direct material input (DMI)	kg/a + kg + %	I.Symb+U.Symb	Quan.	MWW		2
Eco-industrial training	Not displayed	EIP	Unknown	MWW	Rethink	2
Elastic coefficient of main pollutant emission	%	EIP	Quan.	MWW		2

Elasticity coefficient of freshwater consumption	%	EIP	Quan.	MWW		2
Emergy: ecological beneficial ratio (EBR)	%	I.Symb+U.Symb	Quan.	MWW		2
Energy/power (carrying) capacity	W	EIP	Qual.	MWW		2
Environmental (function) compliance (rate)	Yes/No	EIP	Qual.	MWW		2
Environmental emissions / greenhouse gas mitigation through eco-industrial network	kg + sej	EIP	Quan.	MWW	Rethink+Reduce	2
Environmental footprint (reduction)	/kg	I.Symb	Quan.	MWW	(Reduce)	2
Environmental impact (resource + waste)	%	I.Symb+EIP	Quan.	MWW		2
Environmental impact momentum (EIM)	Not displayed	I.Symb	Quan.	Other		2
Environmental policies and regulations favor the exchange of resources with another co-located industry	Not displayed	I.Symb	Unknown	Other	Rethink	2
Estimated amount of collectable waste (via platform)	Not displayed	I.Symb	Quan.	Other	Rethink	2
Exchange travel distance	m	I.Symb+U.Symb	Quan.	Other		2
Monitoring natural/environmental sites	n	EIP	Qual. + Quan.	Other		2
Number of links: total number of direct waste flows between firms within a symbiotic network	n	I.Symb+EIP	Quan.	Other	Rethink	2
Plant savings due to reduction of plant generation of wastes	J/a	I.Symb	Quan.	Other	Reduce	2
Plant savings due to variation in the components	J/a	I.Symb	Quan.	Other	Reduce	2
Predator: waste receiver firms in a symbiotic network	Not displayed	I.Symb+EIP	Quan.	Symb.+Shar.	Rethink	2
Prey to predator ratio: the ratio of the number of waste producer firms to waste receiver firms within a symbiotic network	Not displayed	I.Symb+EIP	Quan.	Symb.+Shar.	Rethink	2
Prey: waste producer firms in a symbiotic network	%	I.Symb+EIP	Quan.	Env.+Em. + MWW	Rethink	2
Public/employee cognition/awareness of eco-industrial park	Not displayed	EIP	Unknown	Symb.+Shar.		2
Recycle/reuse (undefined)	mol/a	I.Symb	Qual.	Env.+Em. + MWW	Reuse+Recycle	2
Recycled/refuse-derived fuel (production/energy substitution)	kg/person/y + J	I.Symb+U.Symb	Quan.	Symb.+Shar. + MWW	Recycle	2
Reduction of irreversibility in components	J/a	I.Symb	Quan.	Symb.+Shar. + MWW	Rethink	2
Resource sharing / passed on	%	I.Symb	Qual. + Quan.	Symb.+Shar. + MWW	Rethink	2
Share of generated wastes processed at industrial symbiosis network	%	I.Symb+EIP	Quan.	Symb.+Shar. + MWW	Rethink	2
Sharing (waste/water/byproducts/energy) with another co-located industry (proportion/frequency/ability)	Frequency	I.Symb	Qual. + Quan.	Symb.+Shar. + MWW	Rethink+Reuse+Reduce	2
Substitution of water/groundwater with surface water	m^3/a + kg	I.Symb	Quan.	Symb.+Shar. + MWW	Reduce	2
Symbiotic utilization (share)	%	I.Symb	Quan.	Symb.+Shar. + MWW	Rethink	2
Total circularity index (TCI)	Not displayed	I.Symb+U.Symb	Quan.	Symb.+Shar. + MWW	*Reduce, Reuse, Rethink, Recycle, Recover, Repurpose, Repair, Refuse, Refurbish, Remanufacture	2
Transportation factor between industries	kg CO_2 /kg*m	I.Symb+EIP	Quan.	Env.+Em. + Symb.+Shar.		2
Waste exports/imports	kg/a	I.Symb	Qual. + Quan.	Env.+Em. + Symb.+Shar.		2
Yield rate	%	I.Symb	Quan.	Env.+Em. + Symb.+Shar.		2
(Un)verified mass exchanged	kg	I.Symb	Quan.	Energy	Rethink	1
100 % of the total water demand from firms in the industrial park does not have significant negative impacts on local water sources or local communities.	Not displayed	EIP	Qual.	Energy		1
A Master Plan (or equivalent planning document) for any new and existing industrial park has been developed and is reviewed periodically (and updated if required), including the following core elements: site selection study based on various risk analyses; essential and efficient infrastructure, utilities, and	Not displayed	EIP	Qual.	Energy	Rethink	1

transportation network; environmental and social issues; internal industrial park land zoning; buffer zone around the park; procedure to safely locate high-risk industries; and cluster synergistic industries.						
A mechanism is in place to appropriately monitor water consumption across the industrial park	Yes/No	EIP	Qual.	Energy		1
A mechanism is in place to promote and encourage reuse and recycling of materials by firms in the industrial park	Yes/No	EIP	Qual.	Energy	Reuse+Recycle	1
A monitoring system is in place that controls and registers origin, type, mode and route of transport, and final destination of waste/secondary raw material leaving the industrial park	Yes/No	EIP	Qual.	Energy		1
A program is established to reduce and avoid the use of dangerous hazardous materials by firms in the industrial park	Yes/No	EIP	Qual.	Energy	Reduce	1
A program/mechanism is in place to identify opportunities for common energy and heat exchange networks to be established	Yes/No	EIP	Qual.	Energy	Rethink	1
Ability to monitor ecological changes in the (eco-industrial) park	Not displayed	EIP	Unknown	Energy		1
Acid precipitation	kg SO_2	I.Symb	Quan.	Energy		1
Activity degree of energy network	Not displayed	I.Symb	Quan.	Energy	Rethink	1
Amount of wasted/unused energy (with temperature N at facility I in period t)	m^3	I.Symb	Quan.	Energy		1
Amounts of illegal dumping	Not displayed	I.Symb+U.Symb	Quan.	Energy		1
Area of seawater inferior to the fourth category of water quality	Not displayed	I.Symb	Qual.	Energy		1
Area scale of permeable pavement in rigid pavement	Not displayed	EIP	Quan.	Energy		1
At least 20 % of solid waste generated by firms is reused by other firms, neighboring communities, or municipalities.	Not displayed	EIP	Qual.	Energy	Rethink+Reuse	1
At least 50 % of total industrial wastewater from firms in the industrial park is reused responsibly within or outside the industrial park	Not displayed	EIP	Qual.	Energy	Rethink+Reuse	1
At least 95 % of industrial wastewater generated by the industrial park and resident firms is treated to appropriate environmental standards.	Not displayed	EIP	Qual.	Energy		1
Available electricity	J/a	I.Symb	Quan.	Energy		1
Available increment of energy resource	kg	EIP	Quan.	Energy		1
Average annual concentration of pollutants in the industrial park network	kg/m^3	EIP	Quan.	Energy		1
Average workload / wear rate of eco-industrial parks infrastructure	Not displayed	EIP	Quan.	Energy		1
Avoidance of incineration of wastes or by-products	Not displayed	EIP	Qual.	Energy	Reduce	1
Bio abundance index	Not displayed	U.Symb	Quan.	Energy		1
Bio-based electricity (remaining)	Not displayed	I.Symb	Quan.	Energy	Recover	1
Biogeochemical flow (phosphorus)	%	I.Symb	Quan.	Energy		1
Biological production	Not displayed	I.Symb	Qual.	Energy		1
Building density	Not displayed	EIP	Quan.	Energy		1
Byproduct recoverable	% + kg/a	I.Symb	Quan.	Energy	Recycle	1
Capability level in connecting the resources	Not displayed	EIP	Quan.	Energy		1
Carbon information statistics and disclosure	Not displayed	EIP	Unknown	Energy		1
Carbon sequestration/carbon capture and storage	Not displayed	I.Symb	Qual.	Energy	Rethink+Reduce	1
Change of material inflow if strategy implemented	kg/a	I.Symb	Quan.	Energy		1
Chemical release due to dust containment avoided	Not displayed	I.Symb	Quan.	Energy		1
Chlorine loss rate	%	I.Symb	Quan.	Energy		1
Circular economy orientated organisational policy	Not displayed	CE-Meso	Qual.	Energy	*Reduce, Reuse, Rethink, Recycle, Recover, Repurpose, Repair,	1

					Refuse, Refurbish, Remanufacture	
Circular economy related consumer/employee training	Not displayed	CE-Meso	Qual.	Energy	*Reduce, Reuse, Rethink, Recycle, Recover, Repurpose, Repair, Refuse, Refurbish, Remanufacture	1
Circular efficiency	Not displayed	CE-Meso	Quan.	Energy	*Reduce, Reuse, Rethink, Recycle, Recover, Repurpose, Repair, Refuse, Refurbish, Remanufacture	1
Circular material use rate	%	I.Symb	Quan.	Energy	*(Rethink+Reduce+Recycle)*	1
Circularity	Not displayed	I.Symb	Unknown	Energy	*Reduce, Reuse, Rethink, Recycle, Recover, Repurpose, Repair, Refuse, Refurbish, Remanufacture	1
Circularity indicator	Not displayed	I.Symb	Quan.	Env.+Em. + Energy	*Reduce, Reuse, Rethink, Recycle, Recover, Repurpose, Repair, Refuse, Refurbish, Remanufacture	1
Circularity quality (β)	Not displayed	CE-Meso	Quan.	Env.+Em.	*Reduce, Reuse, Rethink, Recycle, Recover, Repurpose, Repair, Refuse, Refurbish, Remanufacture	1
Circularity quantity (α)	Not displayed	CE-Meso	Quan.	Env.+Em.	*Reduce, Reuse, Rethink, Recycle, Recover, Repurpose, Repair, Refuse, Refurbish, Remanufacture	1
Classification and collection rate of municipal solid wastes	Not displayed	EIP	Qual. + Quan.	Env.+Em.		1
Cluster cold/hot utilization	W	I.Symb	Quan.	Env.+Em. + Energy	Rethink+Reduce	1
CO_2 gain	kg CO_2 eq/a	U.Symb	Quan.	Env.+Em.		1
CO_2 reduction per internal product exchange	kg/kg	I.Symb+EIP	Quan.	Env.+Em.	Rethink+Reduce	1
Co-benefits in terms of materials items achieved through eco-industrial network	sej	EIP	Quan.	Env.+Em.	Rethink	1
Coefficient of non-wastefulness of eco-industrial park's resident enterprises	Not displayed	EIP	Quan.	Env.+Em.	Rethink	1
Coefficient of remoteness of eco-industrial park's residents from their main marketing areas	Not displayed	EIP	Quan.	Env.+Em.		1
Coefficient of remoteness of mineral resources	Not displayed	EIP	Quan.	Env.+Em.		1
Coefficient of the residents' needs in raw materials and resources covered by using the waste of other industrial park residents	Not displayed	EIP	Quan.	Env.+Em.	Rethink+Reduce	1
Co-generation (heat & electricity)	Not displayed	I.Symb	Qual.	Env.+Em.		1
Companies adopting waste minimisation	Not displayed	I.Symb	Qual.	Env.+Em. + Energy	Reduce	1
Completion degree of environmental management strategies	%	EIP	Quan.	Env.+Em.		1
Concentration potential of demand/source	Not displayed	I.Symb	Quan.	Env.+Em.		1
Conditions of national and local key pollutant emissions	Not displayed	EIP	Qual.	Env.+Em.		1
Contaminant concentration at the estuary	%	EIP	Quan.	Env.+Em.		1

Conversion rate	%	I.Symb	Quan.	Env.+Em.		1
Cooling demand	J/a	I.Symb+U.Symb	Quan.	Env.+Em.		1
Cumulative exergy extraction from the natural environment (CEENE)	J + %	I.Symb	Quan.	Env.+Em.		1
Dangerous and toxic material	Not displayed	EIP	Quan.	Env.+Em.		1
Dangerous substances exchange rate	Not displayed	I.Symb	Quan.	Env.+Em.	Rethink	1
Decoupling indicator of energy consumption (D_energy)	Not displayed	I.Symb+U.Symb	Quan.	Env.+Em.		1
Decoupling indicators of emissions	Not displayed	I.Symb+U.Symb	Quan.	Env.+Em. + Energy		1
Degree of metabolic connectivity	Not displayed	I.Symb	Quan.	Env.+Em. + Energy	Rethink	1
Degree of resource exchange activity / material network	Not displayed	I.Symb	Quan.	Env.+Em. + Energy	Rethink	1
Degree of secondary source involvement	Not displayed	I.Symb	Qual.	Env.+Em. + Energy		1
Degree to which the environmental management department participates in major decision-making of enterprises	Not displayed	EIP	Quan.	Env.+Em.		1
Demand for sector waste	Not displayed	I.Symb	Quan.	Env.+Em.		1
Destination of recycled residuals leaving generating facilities beyond/within X km	kg	I.Symb	Quan.	Env.+Em. + Energy	Recycle	1
Disposal reduction of recyclable material by industrial network	kg	I.Symb	Quan.	Env.+Em.	Reduce+Recycle	1
Diversity of the industrial symbiosis network (ISN)	Not displayed	I.Symb	Unknown	Env.+Em. + Energy	Rethink	1
Diversity of using/producing wastes	Not displayed	I.Symb	Unknown	Env.+Em.		1
Eco-indicator 99	Points	I.Symb	Quan.	Env.+Em.		1
Ecological environment	Not displayed	EIP	Unknown	Env.+Em. + Energy		1
Ecological footprint (change due to eco-industrial development)	m^2 + %	EIP	Quan.	Env.+Em.		1
Ecological level	Not displayed	EIP	Unknown	Env.+Em.		1
Ecosystem interaction	Not displayed	I.Symb	Qual.	Env.+Em.		1
Efficiency of the symbiotic system ((process) energy returned on energy invested - (P)EROI)	J/J	I.Symb	Quan.	Env.+Em.	Rethink	1
Efficiency of the transportation system	Not displayed	EIP	Quan.	Env.+Em.		1
Element utilization efficiency along the symbiotic network	%	I.Symb	Quan.	Env.+Em.	Rethink+Reduce	1
Embodied carbon of the symbiotic network (EC)	kg CO_2	I.Symb	Quan.	Env.+Em.		1
Emergy ecological footprint/carrying capacity (per capita)	m^2	EIP	Quan.	Env.+Em.		1
Emergy of cyclic utilization (R')	sej	EIP	Quan.	Env.+Em.		1
Emergy productivity	monetary value/sej	I.Symb	Quan.	Env.+Em.	Reduce	1
Emergy self-sufficiency ratio	%	I.Symb	Quan.	Env.+Em.		1
Emergy: environmental services provided by natural ecosystem to dilute the air and water pollutions	sej	I.Symb	Quan.	MWW + Energy		1
Encouragement to the development and reuse of abandoned site	Not displayed	EIP	Unknown	Env.+Em.	Reuse	1
Energy assessment & popularization rate	Not displayed	EIP	Quan.	Env.+Em.		1
Energy cascade utilization: available amount	kg	I.Symb	Quan.	Env.+Em.	Rethink+Reduce	1
Energy consumption impact (ECI)	kg CO_2	I.Symb	Quan.	Env.+Em.		1
Energy density	J/m^2	EIP	Quan.	MWW + Energy		1
Energy efficiency/intensity strategies are in place (for industrial park management infrastructure)	Yes/No	EIP	Qual.	Env.+Em.	Reduce	1
Energy flows	W	EIP	Quan.	Env.+Em.		1
Energy substitution	kg	I.Symb	Quan.	MWW + Energy	Reduce	1
Environment and technology	Not displayed	I.Symb	Qual.	Env.+Em.		1
Environmental and societal regulations	Not displayed	I.Symb	Unknown	Env.+Em.		1
Environmental benefits of waste generators: waste reduction	kg	I.Symb+U.Symb	Quan.	Env.+Em.	Reduce	1

Environmental friendliness	Not displayed	EIP	Un-known	Env.+Em.		1
Environmental impact of providing energy with temperature hn for customer j at symbiosis network	Not displayed	I.Symb	Quan.	Env.+Em.	Rethink	1
Environmental objective	kg	I.Symb	Quan.	Env.+Em.		1
Environmental performance index (EPI)	Not displayed	EIP	Quan.	Env.+Em.		1
Environmental performance quality (EnvPQ): Energy	Not displayed	I.Symb	Quan.	Env.+Em.		1
Environmental performance quality (EnvPQ): Water	Not displayed	I.Symb	Quan.	Env.+Em.		1
Environmental projects with the community	Not displayed	I.Symb	Qual.	Env.+Em.		1
Environmental quality	Not displayed	EIP	Un-known	Env.+Em.		1
Environmental resilience	Not displayed	I.Symb	Qual.	Env.+Em.		1
Environmental risk (propagation coefficient of distance) (index)	Not displayed	I.Symb	Quan.	Env.+Em.		1
Environmental sustainability index	Not displayed	I.Symb	Quan.	Env.+Em.		1
Environmental technical change (ETC)	Not displayed	EIP	Un-known	Env.+Em.		1
Environmental/energy infrastructure and services	Not displayed	EIP	Quan.	Env.+Em.		1
Equivalent CO_2 emission potentials of exergy destruction/losses	kg/IAV + kg/kg	I.Symb	Quan.	MWW + Energy		1
Equivalent of at least 10 % of the total CO_2 emissions (scope 1 and 2) at industrial park level is covered by the percentage of firms that have a qualified energy efficiency certification (LEED, Industry EDGE, DGNB or ISO 50001 or their national equivalent).	%	EIP	Quan.	Env.+Em.	Reduce	1
Equivalent primary resource consumption (EPRC)	kg	I.Symb	Quan.	Env.+Em.		1
Exchange quality evaluation	Not displayed	I.Symb	Qual.	MWW + Energy		1
External agent waste management	Not displayed	I.Symb	Un-known	Env.+Em.		1
Facilitated exchanges	kg	I.Symb+U.Symb	Quan.	Env.+Em.	Rethink	1
Facilitator impact on number of completed exchanges/weight	Not displayed	I.Symb+U.Symb	Quan.	Env.+Em.	Rethink	1
Final destinations of waste plastics outside/within city	kg/a	I.Symb+U.Symb	Quan.	Env.+Em.		1
Finn cycling index (FCI)	Not displayed	I.Symb	Quan.	Env.+Em.		1
Fixed carbon in products	kg CO_2/kg	I.Symb	Quan.	Env.+Em.		1
Flora and fauna	Not displayed	EIP	Un-known	Env.+Em.		1
Flue gas treatment reactants	kg CO_2 eq/y + %	I.Symb	Quan.	Env.+Em.		1
Frequency of severe environmental accidents	n	EIP	Quan.	Env.+Em.		1
Fuel diversification (alternative/secondary fuels)	Not displayed	I.Symb	Qual.	Env.+Em.	Rethink	1
Fume emission	/m^2	EIP	Quan.	Env.+Em.		1
Function/structure Entropy	Not displayed	EIP	Quan.	Env.+Em.		1
GHG emission mitigation emergy	sej/CO_2 eq + sej	EIP	Quan.	Env.+Em.	Reduce	1
Gray embodied energy	J/kg	U.Symb	Quan.	Symb.+Shar. + Energy		1
Green packing	Not displayed	EIP	Un-known	Symb.+Shar. + Energy	Rethink+Reduce+Reuse	1
Green transportation design	Not displayed	EIP	Un-known	Symb.+Shar. + Energy	Rethink	1
Green urban areas	m^2/inhabitant	I.Symb	Quan.	Env.+Em.	Rethink+Reduce	1
Hazardous materials collection and centralized disposal facilities	Not displayed	EIP	Qual.	Symb.+Shar. + Energy	Rethink	1
Hazardous waste consumed	kg/capita	I.Symb+U.Symb	Quan.	Env.+Em.		1
Heat transport distance	m	U.Symb	Quan.	Env.+Em.		1
High air quality days compliance rate	%	EIP	Quan.	Symb.+Shar. + Energy		1
Highest amount of input which is possible to save through waste exchanges	Not displayed	I.Symb	Quan.	Symb.+Shar. + Energy	Rethink+Reduce	1
Highest amount of waste which is possible to recover through waste exchanges at time t	Not displayed	I.Symb	Quan.	Symb.+Shar. + Energy	Rethink+Reduce	1

Host region's endowment with natural and secondary resources	Not displayed	EIP	Un-known	Symb.+Shar. + Energy	Reduce	1
Impact that recovering one unit of waste has on the creation of service α	Not displayed	I.Symb	Quan.	Symb.+Shar. + Energy	Rethink+Re-duce	1
Impact that saving one unit of input has on the creation of service α	Not displayed	I.Symb	Quan.	Symb.+Shar. + Energy	Rethink+Re-duce	1
Improved emergy sustainable index (IESI)	%	I.Symb	Quan.	Symb.+Shar. + Energy		1
Incentive mechanism for recycling and reuse (products and packaging) for stake-holders	Not displayed	CE-Meso	Qual.	MWW + En-ergy + Symb.+Shar.	Reuse+Recycle	1
Index of global environmental impact (IGEI)	Not displayed	EIP	Quan.	Env.+Em. + MWW		1
Index of global measurement of sustaina-ble performance (IGMSP)	Not displayed	EIP	Quan.	Env.+Em. + MWW		1
Indicator of development of the hard road network and the railway network in the host region	Not displayed	EIP	Quan.	Env.+Em. + MWW		1
Indirect mobilized Energy for waste col-lection and transport / treatment	J/kg	U.Symb	Quan.	Env.+Em. + MWW		1
Industrial agglomeration	Not displayed	EIP	Un-known	Env.+Em. + MWW		1
Industrial cooperation index	Not displayed	I.Symb	Quan.	MWW	Rethink	1
Industrial development index	Not displayed	I.Symb	Quan.	MWW		1
Industrial park management entity keeps updated records on energy, water, waste products, and materials inefficiencies and needs at tenant firms to provide a ba-sis for industrial synergies development	Yes/No	EIP	Qual.	MWW	Rethink	1
Industrial park management entity pro-vides the physical network for water re-use/cascading of water	Yes/No	EIP	Qual.	MWW	Rethink+Reuse	1
Industrial park management entity sets and works toward ambitious (beyond in-dustry norms) maximum carbon intensity targets (maximum kilograms of carbon di-oxide equivalent (kg CO2-eq)/kilowatt hour (kWh) for the park and its residents. Targets should be established for the short, medium, and long term, in line with local norms and industry sector bench-marks.	Not displayed	EIP	Qual.	MWW	Reduce	1
Industrial park management provides the physical network for waste heat/energy exchange at park level, and assists firms to connect to the network. A commonly accepted rewards system for waste heat/energy provision/use is in place	Yes/No	EIP	Qual.	MWW	Rethink+Re-duce	1
Industrial symbiosis index	Not displayed	I.Symb	Quan.	MWW	Rethink	1
Industries waste ratio (IWR)	%	I.Symb	Quan.	MWW		1
Informal market recycling	kg	I.Symb	Quan.	MWW	Recycle	1
Integration level of knowledge, technolo-gies and resources	Not displayed	I.Symb	Qual.	MWW		1
Integration of water recycling systems	m^3/a	I.Symb+U.Symb	Quan.	MWW	Recycle	1
Integration with power plant	Not displayed	I.Symb	Qual.	MWW	Rethink	1
Intelligent micro-grid technology	Not displayed	EIP	Un-known	MWW	Rethink	1
International transport networks and re-lated services	Not displayed	EIP	Un-known	MWW		1
Joint use of emissions	Not displayed	U.Symb	Un-known	MWW	Rethink+Re-duce	1
Land coverage ratio of industrial regional administrative office and living service fa-cilities	Not displayed	EIP	Quan.	MWW		1
Level of (reduction) contribution in its own eco-industrial park	%	EIP	Quan.	MWW	Reduce	1
Material conservation emergy	sej	EIP	Quan.	MWW		1
Material exchange capacity	kg	I.Symb	Quan.	MWW	Rethink	1
Material exchange utilization	%	EIP	Quan.	MWW	Rethink	1
Material formation benefit	sej	EIP	Quan.	MWW		1
Material indicator	kg	EIP	Quan.	MWW		1
Material input	kg/a	EIP	Quan.	MWW		1
Material reused rate (MRR)	%	EIP	Quan.	MWW	Reuse	1

Maximum indirect discharging concentration of pollutant	kg/m^3	I.Symb	Quan.	MWW		1
Measures for promoting pollution prevention and resource recovery	Not displayed	EIP	Unknown	MWW	Reduce	1
Mileage of expressway	Not displayed	I.Symb	Quan.	MWW		1
Mobility	Not displayed	EIP	Unknown	MWW		1
Native flora and fauna are important to maintain the proportion of natural areas. They are integrated within the industrial park and natural ecosystem where possible	Yes/No	EIP	Qual.	MWW		1
Natural capital	Points	I.Symb	Quan.	MWW		1
Network outputs: power	J	EIP	Quan.	Env.+Em. + MWW	Rethink	1
New building energy-saving standard enforcement	Not displayed	EIP	Unknown	MWW	Reduce	1
New index of sustainability for eco-industrial park with power plant (PESI)	Not displayed	EIP	Quan.	MWW		1
Non-renewable CO_2 at the stack	kg CO_2 eq/a + %	I.Symb	Quan.	MWW		1
Normalized difference vegetation index (NDVI) mean	Not displayed	U.Symb	Quan.	Env.+Em. + MWW		1
Normative implementation of environmental impact assessment	Not displayed	EIP	Unknown	MWW		1
Number of (different) waste flows controlled	Not displayed	I.Symb	Quan.	MWW		1
Number of (symbiotic) matchings by resource category	n	I.Symb	Quan.	MWW	Rethink	1
Number of days per year of household waste collection	n	EIP	Quan.	MWW		1
Number of incidents of non-compliance with noise regulations in industrial park	Not displayed	EIP	Quan.	MWW		1
Number of organizations and households which are composting	n + kg/a	EIP	Quan.	MWW		1
Number of pleaded environmental pollution events	Not displayed	EIP	Quan.	MWW		1
Number of relationships with different industries	n	I.Symb	Quan.	MWW	Rethink	1
Number of reuse patterns	n	I.Symb	Quan.	MWW	Reuse	1
Number of secondary facilities co-locating in the area	n	EIP	Quan.	MWW	Rethink+Reduce	1
Number of times that various sectors were affected by inappropriate water allocation	Not displayed	EIP	Quan.	MWW		1
Number of trips per carrier	Not displayed	I.Symb	Quan.	MWW		1
Number of vehicles	Not displayed	EIP	Quan.	MWW		1
Obeying the principles of circular economy is part of the industrial park's code of conduct, and any legally binding agreement between tenant firms and the industrial park authority	Yes/No	EIP	Qual.	MWW	*Reduce, Reuse, Rethink, Recycle, Recover, Repurpose, Repair, Refuse, Refurbish, Remanufacture	1
Obeying the principles of good practices for the management of hazardous materials and waste as part of legally binding agreements.	Yes/No	EIP	Qual.	MWW		1
Objects collected and diverted for reuse	Not displayed	I.Symb+U.Symb	Quan.	Env.+Em. + MWW	Reuse	1
Objects recovered in reuse centers	Not displayed	I.Symb+U.Symb	Quan.	MWW	Reuse	1
Objects repaired	Not displayed	I.Symb+U.Symb	Quan.	MWW	Repair	1
One-time/ongoing exchanges	kg	I.Symb+U.Symb	Quan.	MWW	Rethink	1
Operating rate	%	I.Symb	Quan.	MWW		1
Optimized energy	J/a	U.Symb	Quan.	MWW	Reduce	1
Overall relative performance of the eco-industrial park	Not displayed	EIP	Quan.	MWW		1
Passive exchanges	kg	I.Symb+U.Symb	Quan.	MWW	Rethink	1
Percent of area permanently protected as open space	%	EIP	Quan.	MWW		1
Percent of firms that purchase together, share equipment or personnel	%	EIP	Quan.	MWW	Rethink	1
Percent of impervious surface	%	EIP	Quan.	MWW		1

Percent-added of industrial park energy productivity	%	EIP	Quan.	MWW	Reduce	1
Percentage of commuters using transit, carpool, biking, walking, or working from home	%	EIP	Quan.	MWW	Rethink+Reduce	1
Percentage of local industrial demand for each input that could be met through industrial symbiosis	%	I.Symb	Quan.	MWW	Rethink	1
Percentage of primary/secondary recycled products and packages	Not displayed	EIP	Quan.	MWW	Recycle	1
Percentage of reusable products in total products	Not displayed	EIP	Quan.	MWW	Reuse	1
Perfect degree of environmental management capability improvement	%	EIP	Quan.	MWW		1
Performance value of environmental perspectives	Not displayed	I.Symb	Quan.	MWW		1
Plot ratio	Not displayed	EIP	Quan.	MWW		1
Pollution sensitivity index/indicator	Not displayed	EIP	Quan.	MWW		1
Potential type of recycling implementable in existing provincial context	Not displayed	I.Symb	Qual.	MWW	Recycle	1
Power to transport water (and wastewater stream(s) for direct reuse)	W	EIP	Quan.	MWW	(Reuse)	1
Pre-heating/drying	Not displayed	I.Symb	Qual.	MWW		1
Primary energy performance	Not displayed	I.Symb	Qual.	MWW		1
Probability of emission reduction activities	Not displayed	I.Symb	Quan.	MWW	Reduce	1
Production cooperation	Not displayed	EIP	Unknown	MWW	Rethink	1
Proportion / total of redundant input or output: Freshwater/wastewater/waste	m^3 + kg	EIP	Quan.	MWW		1
Proportion of alternative energy use changed to clean energy	Not displayed	EIP	Quan.	MWW	Rethink+Reduce	1
Proportion of clean-process company	Not displayed	EIP	Quan.	MWW		1
Proportion of ecological construction investment in GDP	Not displayed	EIP	Quan.	MWW		1
Proportion of employees traveling alone by car when commuting	Not displayed	EIP	Quan.	MWW		1
Proportion of green travel	Not displayed	EIP	Quan.	MWW	Rethink	1
Proportion of manufacturing firms adopting circular economy practices, including engagement in Industrial Symbiosis Networks in the industrial park; or actively exchanging secondary raw materials, or waste, or other circular economy practices	%	EIP	Quan.	MWW	*Reduce, Reuse, Rethink, Recycle, Recover, Repurpose, Repair, Refuse, Refurbish, Remanufacture	1
Proportion of redundancy: energy	%	EIP	Quan.	MWW		1
Proportion of second-class industrial land in industrial land	Not displayed	EIP	Quan.	MWW		1
Proportion of the enterprises within industrial park that have finished greenhouse gas verification	Not displayed	EIP	Quan.	MWW		1
Proportion of the entrepreneurs producing environmentally friendly goods	Not displayed	EIP	Quan.	MWW	Reduce	1
Proportion of the industrial park management and tenant firms that have a metering system in place	%	EIP	Quan.	MWW		1
Proximity to a combined transport hub	Not displayed	EIP	Quan.	MWW	Rethink	1
Qualitative/quantitative classification of each byproduct type	Not displayed	I.Symb	Qual. + Quan.	MWW		1
Quality of the digital platform for interaction	Not displayed	I.Symb	Qual.	MWW	Rethink	1
Quantity match (It verifies that the quantity of byproducts (including materials, energy, water) required and supplied by a symbiotic partner coincide)	kg + n	I.Symb	Quan.	MWW	Rethink	1
Quantity of clean energy used per product	Not displayed	I.Symb	Quan.	MWW	Rethink+Reduce	1
Rate of change: freshwater/wastewater/waste	%	EIP	Quan.	MWW		1
Rate of reaching the discharging standard for key pollution sources	%	EIP	Quan.	MWW		1
Rate of renewable resources exploitation	%	I.Symb	Quan.	MWW		1
Rate of waste recovered through industrial symbiosis	Not displayed	I.Symb	Quan.	MWW	Rethink+Reduce	1
Ratio of production to consumption of energy resources in the host region	Not displayed	EIP	Quan.	MWW		1

Ratio of wastes to the total emergy (EWR)	Not displayed	EIP	Quan.	MWW		1
Rationality of resource development planning	Not displayed	EIP	Un-known	MWW		1
Realisation of material cycles	Not displayed	U.Symb	Un-known	MWW		1
Recyclable goods	kg	EIP	Quan.	MWW	Recycle	1
Recycling and reuse benefit ratio (RRBR)	%	I.Symb	Quan.	MWW	Reuse+Recycle	1
Recycling exchanges	kg	I.Symb+U.Symb	Quan.	MWW	Rethink+Recy-cle	1
Reducing CO_2 emissions is an integral part of the industrial park's code of con-duct, which urges firms to reduce their carbon footprint. The park acknowledges actions in this regard through an awards and incentive system.	Yes/No	EIP	Qual.	MWW	Reduce	1
Reducing CO_2 emissions through re-source saving and waste reduction	kg CO_2/a	I.Symb	Quan.	MWW	Reduce	1
Reduction of dependence on petroleum-based materials	Not displayed	I.Symb	Quan.	MWW	Reduce	1
Regional nitrogen balances	kg	EIP	Quan.	MWW		1
Regional phosphorus balances	kg	EIP	Quan.	MWW		1
Regulations for waste management	Not displayed	I.Symb	Qual.	MWW		1
Relative contributions of industrial/urban symbiosis	%	I.Symb+U.Symb	Quan.	MWW	Rethink	1
Relative industrial symbiosis indicator (ISIr)	%	I.Symb	Quan.	MWW	Rethink	1
Removal mass load	kg/a	I.Symb	Quan.	Other		1
Removal of elements of environmental risk	Not displayed	I.Symb	Un-known	Other	Reduce	1
Repaired e-waste	Not displayed	I.Symb+U.Symb	Quan.	Other	Repair	1
Resource and energy efficiency improve-ment level	Not displayed	I.Symb	Qual.	Other	Reduce	1
Resource endowment	Not displayed	I.Symb	Qual.	Other		1
Resource productivity index	Not displayed	I.Symb	Quan.	Other		1
Reusable packages in total packages	%	EIP	Quan.	Other	Reuse	1
Reusable waste flows from industrial symbiosis activities	kg	I.Symb	Quan.	Other	Rethink+Reuse	1
Reuse exchanges	kg	I.Symb+U.Symb	Quan.	Other	Rethink+Reuse	1
Reused energy	J	I.Symb	Quan.	Other	Reuse	1
Reused waste within facility	kg	I.Symb	Quan.	Other	Reuse	1
Reuse-manufacturing	kg	I.Symb	Quan.	Other	Reuse	1
Road network density	Not displayed	EIP	Quan.	Other		1
Saving emergy for symbiosis	sej	I.Symb	Quan.	Other	Rethink+Re-duce	1
Score of degree (D)	Not displayed	I.Symb	Quan.	Other		1
Score of in-degree (Din)	Not displayed	I.Symb	Quan.	Other		1
Score of out-degree (Dout)	Not displayed	I.Symb	Quan.	Other		1
Sea level change length	Not displayed	I.Symb	Qual.	Other		1
Self assessment: we always boost the flow of the materials / encourage system integration to ensure that their value cre-ation is as high as possible	Not displayed	I.Symb	Qual.	Other		1
Self assessment: we proactively expand our symbiotic network across companies and industries to seek better resource ef-ficiency	Not displayed	I.Symb	Qual.	Other	Rethink+Re-duce	1
Self assessment: we promote sharing fa-cilities in our symbiotic network to opti-mize resource use efficiency	Not displayed	I.Symb	Qual.	Other	Rethink+Re-duce	1
Self assessment: we stimulate visualiza-tion of the flow of resources in our symbi-otic network to optimize management ef-ficiency	Not displayed	I.Symb	Qual.	Other	Rethink+Re-duce	1
Self-consumption	%	U.Symb	Quan.	Other		1
Self-sufficiency	%	U.Symb	Quan.	Other		1

Service from natural gas network	Not displayed	EIP	Un-known	Other		1
Setup/planning of low-carbon industrial park leadership and operating mecha-nism	Not displayed	EIP	Un-known	Other	Rethink+Re-duce	1
Share of impact reductions (Greenhouse gas emissions only) for avoided products and energy demand due to exchanges in the IS network	%	I.Symb	Quan.	Other	Rethink+Re-duce	1
Share of new energy vehicles in the vehi-cles for public use	Not displayed	EIP	Quan.	Other	Rethink	1
Share of renewable fuels	Not displayed	I.Symb	Quan.	Other	Rethink+Re-duce	1
Sharing waste transport	Not displayed	I.Symb	Un-known	Other	Rethink+Re-duce	1
Size, shape, and composition of wildlife habitat areas	Not displayed	EIP	Qual. + Quan.	Other		1
Slow lane density	Not displayed	EIP	Quan.	Other		1
SO_2 emission decoupling	Not displayed	I.Symb+U.Symb	Quan.	Other	Reduce	1
SO_2 environmental capacity	Not displayed	EIP	Quan.	Other		1
SO_2 redundancy	kg + %	EIP	Quan.	Other		1
Soil	Not displayed	I.Symb	Un-known	Other		1
Solid waste disposal infrastructure	Not displayed	EIP	Qual.	Other		1
Specialization on certain types of activity	Not displayed	EIP	Un-known	Other		1
Species richness	Not displayed	EIP	Quan.	Other		1
Speed of response to changing partner requests	Not displayed	I.Symb	Qual.	Other		1
Storage capacity of energy with tempera-ture X at symbiosis network	m^3	I.Symb	Quan.	Other	Rethink	1
Storage conditions of waste	Not displayed	I.Symb	Un-known	Other		1
Stream network and slope (to decrease the chance of pollution affecting ground-water tables, by discarded oils, paints, and other chemical poisons draining into the streams)	Not displayed	EIP	Quan.	Other	Reduce	1
Structural adjustment (improvement in industrial layout: regional industrial transfers and relocation)	Not displayed	CE-Meso	Un-known	Other		1
Structural performance	Not displayed	I.Symb	Quan.	Other		1
Substance reduction cycle	Not displayed	EIP	Quan.	Other	Reduce	1
Success level of the eco-team's opera-tion in the development of eco-industries	Not displayed	EIP	Un-known	Other	*Reduce, Re-use, Rethink, Recycle, Re-cover, Repur-pose, Repair, Refuse, Refur-bish, Remanu-facture	1
Sustainability performance	Not displayed	I.Symb	Quan.	Other		1
Sustainable competitive advantage	Not displayed	EIP	Qual.	Other		1
Sustainable competitiveness index	Not displayed	I.Symb	Quan.	Other		1
Sustainable development indicator (ESI)	Not displayed	EIP	Quan.	Other		1
Sustainable transportation management	Yes/No	EIP	Qual.	Other	Rethink	1
Sustainably oriented water footprint (SOWF)	Not displayed	I.Symb	Quan.	Other		1
Symbiotic efficiency	Not displayed	I.Symb+U.Symb	Quan.	Other	Rethink+Re-duce	1
Symbiotic performance indices (SPI)	Not displayed	U.Symb	Qual.	Symb.+Shar.	Rethink	1
Symbiotic potential: circular	Not displayed	I.Symb	Qual.	Symb.+Shar.	*Reduce, Re-use, Rethink, Recycle, Re-cover, Repur-pose, Repair, Refuse, Refur-bish, Remanu-facture	1
Symbiotic potential: socio-ecological	Not displayed	I.Symb	Qual.	Symb.+Shar. + MWW	Rethink	1
Synergy potential	kg/cluster	I.Symb	Quan.	Symb.+Shar. + MWW	Rethink	1

System cycle index	Not displayed	EIP	Quan.	Symb.+Shar. + MWW	*Reduce, Reuse, Rethink, Recycle, Recover, Repurpose, Repair, Refuse, Refurbish, Remanufacture	1
System loss rate	%	I.Symb	Quan.	Symb.+Shar.		1
Systemic carbon fix rate (CFR)	%	I.Symb	Quan.	Symb.+Shar. + MWW		1
Technical capacity or means to mediate the transfer of waste and byproduct streams between industrial processes	Not displayed	I.Symb	Unknown	Symb.+Shar. + MWW	Rethink	1
Technical-scientific support for the valorization of waste and byproducts	Not displayed	I.Symb	Unknown	Symb.+Shar.	Rethink	1
Terrestrial nutrification	Not displayed	I.Symb	Quan.	Symb.+Shar. + MWW		1
The industrial park has set up measures to mitigate all point source pollution and GHG emissions	Yes/No	EIP	Qual.	Symb.+Shar.	Reduce	1
The industrial park management implements measures to protect biodiversity, and protects or creates natural/recreational areas in and surrounding the park.	Yes/No	EIP	Qual.	Symb.+Shar.	Rethink+Reduce	1
The number of different types of energy required in a symbiotic network	n	I.Symb	Quan.	Symb.+Shar. + MWW	Rethink	1
The number of inputs involved in the symbiotic network	n	I.Symb	Quan.	Symb.+Shar.	Rethink	1
The number of orders completed within the residents' cooperation scheme	n	EIP	Quan.	Symb.+Shar.	Rethink	1
The number of pairwise exchanges in the symbiotic network	n	I.Symb	Quan.	Symb.+Shar. + MWW	Rethink	1
There is potential receiver located within the industrial zone	Not displayed	I.Symb	Qual.	Symb.+Shar. + MWW	Rethink	1
Total area of buildings reused and as % of all former buildings	m^2 + %	EIP	Quan.	Symb.+Shar. + MWW	Reuse	1
Total avoided effect from energy production	kg CO_2 eq/y + %	I.Symb	Quan.	Symb.+Shar.	Reduce	1
Total emission control level of national key pollutants and local characteristic pollutants	Not displayed	EIP	Qual.	Symb.+Shar.		1
Total environmental benefits: energy symbiosis	kg	I.Symb+U.Symb	Quan.	Symb.+Shar. + MWW	Rethink	1
Total environmental benefits: material + water	kg	I.Symb+U.Symb	Quan.	Symb.+Shar. + MWW		1
Total environmental impact of symbiotic synergy (ENVI)	Not displayed	I.Symb	Quan.	Symb.+Shar.	Rethink	1
Total number of completed exchanges	Not displayed	I.Symb+U.Symb	Quan.	Symb.+Shar. + MWW	Rethink	1
Total organic carbon (TOC)	kg/kg product	I.Symb	Quan.	Symb.+Shar.		1
Total site solid waste integration	kg/a	I.Symb+U.Symb	Quan.	Symb.+Shar.		1
Total water demand from firms in industrial park that does not negatively impact local water sources or communities	%	EIP	Quan.	Symb.+Shar.		1
Transfer losses	Not displayed	I.Symb	Quan.	Symb.+Shar. + MWW		1
Transformity	sej/J	I.Symb	Quan.	Symb.+Shar. + MWW		1
Trigeneration load	J	I.Symb+U.Symb	Quan.	Symb.+Shar. + MWW		1
Type of processing involved	Not displayed	I.Symb	Qual.	Symb.+Shar. + MWW		1
Type of valorization (Energy)	Not displayed	U.Symb	Qual.	Symb.+Shar.		1
Type of valorization (Secondary material)	Not displayed	U.Symb	Qual.	Symb.+Shar.		1
Undesired material exchange	kg/a	I.Symb	Quan.	Symb.+Shar.	Rethink	1
Untreated wastewater	Not displayed	I.Symb	Quan.	Symb.+Shar.		1
Unused resources	Not displayed	I.Symb	Quan.	Symb.+Shar.		1
Urban ecosystem	Not displayed	I.Symb	Unknown	Symb.+Shar.	Rethink+Reduce	1
Use of non recyclable materials	Not displayed	I.Symb+U.Symb	Quan.	Symb.+Shar.		1
Use rate of recovered used products (URRUP)	kg + %	I.Symb+U.Symb	Quan.	Symb.+Shar. + MWW	*(Repair+Refurbish+Remanufacture+Repurpose)*	1
Use/lifetime of products	Not displayed	CE-Meso	Qual.	Symb.+Shar.	Rethink	1

Utility demands of companies	kg/a + J/a	EIP	Quan.	Symb.+Shar. + MWW		1
Utility synergies (energy)	J	EIP	Quan.	Symb.+Shar.	Rethink	1
Utilization and exploitation rate of underground space	Not displayed	EIP	Quan.	Symb.+Shar. + MWW	Rethink+Reduce	1
Utilization rate of nontraditional water source	Not displayed	EIP	Quan.	Symb.+Shar. + MWW	Rethink	1
Valorizing activity	Not displayed	U.Symb	Qual.	Symb.+Shar. + MWW		1
Vehicle fill percent, and empty running per cent	Not displayed	EIP	Quan.	Symb.+Shar.		1
Virgin resource consumed in the recycling process	kg/a	I.Symb	Quan.	Symb.+Shar.	Recycle	1
Volume flexibility	Not displayed	I.Symb	Qual.	Symb.+Shar. + MWW		1
Waste chain perfection	Not displayed	EIP	Qual.	Symb.+Shar. + MWW		1
Waste environmental impact	Not displayed	I.Symb	Quan.	Symb.+Shar.		1
Waste factors	Not displayed	I.Symb	Quan.	Symb.+Shar. + MWW		1
Waste flow circulation index (CI)	Not displayed	I.Symb+U.Symb	Quan.	Symb.+Shar. + MWW	*(Rethink+Reduce+Reuse+Recycle)*	1
Waste flow trend by co-processing target	kg/a	I.Symb	Quan.	Symb.+Shar. + MWW	Rethink	1
Waste participating index, WPI	Not displayed	I.Symb	Quan.	Symb.+Shar. + MWW		1
Waste reuse quality (WRQ)	Not displayed	I.Symb	Quan.	Symb.+Shar. + MWW	Reuse	1
Waste storage space sharing	Not displayed	I.Symb	Unknown	Symb.+Shar.	Rethink	1
Waste turnover rate	Not displayed	I.Symb	Quan.	Symb.+Shar.		1
Waste unutilized	Not displayed	EIP	Quan.	Symb.+Shar.		1
Waste water quality comparison of surface and groundwater	Not displayed	EIP	Quan.	Symb.+Shar. + MWW		1
Waste/material to energy (recovery/effect)	kg/a + % + kg CO_2 eq/a	I.Symb	Quan.	Symb.+Shar.	Recover	1
Water carrying capacity	Not displayed	EIP	Quan.	Symb.+Shar.		1
Water consumption as percent of available supply	%	EIP	Quan.	Symb.+Shar.		1
Water consumption: ratio of treated wastewater to total wastewater	%	EIP	Quan.	Symb.+Shar.	Recycle	1
Water coverage	Not displayed	U.Symb	Quan.	Symb.+Shar.		1
Water environmental service benefit	sej	EIP	Quan.	Symb.+Shar. + MWW		1
Water flow provided through symbiosis for water supply method for process	Not displayed	I.Symb	Quan.	Symb.+Shar.	Rethink	1
Water footprint symbiosis	%	I.Symb	Quan.	Symb.+Shar.	Rethink	1
Water lost	Not displayed	I.Symb+U.Symb	Quan.	Symb.+Shar.		1
Water network (freshwater/wastewater)	mol/a	I.Symb	Quan.	Symb.+Shar.	Rethink	1
Water productivity (percent-added of park)	%	EIP	Quan.	Symb.+Shar.	Reduce	1
Water quality compliance rate	%	EIP	Quan.	Env.+Em. + Symb.+Shar.		1
Water resources carrying capacity	Not displayed	EIP	Qual.	Env.+Em. + Symb.+Shar.		1
Water scarcity index (WSI)	m^3/kg	I.Symb	Quan.	Env.+Em. + Symb.+Shar.		1
Water scarcity potential (WCP)	m^3	I.Symb	Quan.	Env.+Em. + Symb.+Shar. + Energy		1
Where required, industrial park management has a plan in place to react to possible negative impacts due to climate change risks (heat waves and droughts, storms and floodwater events). All adaption needs for infrastructure and services are identified and in place for the industrial estate to protect against climate change risks and potential damages.	Not displayed	EIP	Qual.	Env.+Em. + Symb.+Shar. + Energy		1
Wildlife	Not displayed	I.Symb	Unknown	Env.+Em. + Symb.+Shar. + MWW		1

I.Symb=industrial symbiosis; U.Symb=urban symbiosis; EIP=eco-industrial park; CE-Meso: circular economy on the meso level; Qual.=qualitative; Quan.=quantitative; Env.+Em.=environment and emissions; Symb.+Shar.=symbiosis and sharing; MWW=material, waste and water;

R-strategies marked with a "*"=a clear assignment based on the name is not possible, but a relationship to R-strategies is evident;
If parallel aspects are clustered, they are marked by a "/" between the aspects, such as "water/wastewater." If not all sources include an aspect, that aspect is marked by "()" as in "water/wastewater (reduction).".

A 2 PRISMA-ScR Checklist

Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist.

Table A 2: PRISMA-ScR Checklist.

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE # (original article)
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	4-8
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	4-12
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	8-9
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	9-12
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	9-12
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	10-12
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	9-12
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	10-13
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	9-16
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	11
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	13
RESULTS			

Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	11
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	Appendix A + supplementary materials
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	Not done
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	Appendix A + supplementary materials
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	16-26
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	26-30
Limitations	20	Discuss the limitations of the scoping review process.	27-30
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	30-32
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	32

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 16 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

From: Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMAScR): Checklist and Explanation. Ann Intern Med. 2018;169:467–473. doi: 10.7326/M18-0850.

Appendix B

Supplementary information for Publication II

B 1 Background information for applied action

Several aspects are relevant for the application example of *implementing a car sharing station*, which are elaborated below.

Current modal split

The modal split, representing the share of each transport mode (Rodrigue 2020), is crucial as it serves as the operating indicator for the action. For the status quo, two main sources were identified: one study examining work commuters based on a median from 112 medium-sized European cities (Santos et al. 2013) and another focused on Germany with data from 2020 (Statistisches Bundesamt 2022). Various other publications evaluate the modal split for individual cities, both in scientific literature (Mendiola and González 2018; Drliciak et al. 2020) and gray literature (Statistics Canada 2023; Hubrich et al. 2024), but city-specific data was deemed too narrow for consideration. Additionally, some publications analyze the modal split of passenger transport in general (Stadt Wien 2024; Eurostat 2025a), but since they do not focus on work relating aspects or car sharing, they are considered inappropriate. Therefore, given the emphasis on applications in Germany, data from Statistisches Bundesamt (2022) will serve as the basis for the status quo, summarized in Table B 1.

Table B 1: Modal split for work commuting for Germany with data from 2020 (Statistisches Bundesamt 2022) which is used as basis for the status quo.

Modal split for work commuting	Share as mean value [%]
Car	68
Motorcycle	1
Bicycle	11
Walk	7
Bus	4
Subway, tram	5
Train	5

Vehicle type and distance for commuting

Since the modal split of Germany is used as the basis, vehicle type and distance for work commuting will also rely on German data. As of January 1, 2024, the vehicle fuel type share in Germany was 62.4 % petrol, 28.8 % diesel, 2.9 % BEV, 4.0 % mild-hybrid, and 1.9 % plug-in hybrid vehicle (PHEV) (Kraftfahrt-Bundesamt 2024). The data for petrol cars was not explicitly provided but was self-calculated to fill gaps and achieve a total of 100 %. As additional information, the average work-commute distance in Germany for 2023 is 17.2 km (Bundesinstitut für Bau-, Stadt- und Raumforschung 2024).

Change of modal split of work commuting through car sharing

For commuters using carpooling, waiting time and pick-up distance are factors influencing the use rate of car sharing (Yi et al. 2022). Similarly, for car sharing, waiting time and distance to the sharing station are presumed relevant factors. It's also important to consider what is substituted by car sharing and how user behavior changes. A study in the Netherlands (van der Linden et al. 2025) found that car sharing trips primarily substitute

public transport (36 %), followed by private cars (25 %) and vehicles from family or friends (10 %). After participating in car sharing, overall car use declined by 39 %, while there was a 27 % increase in usage among some users (van der Linden et al. 2025). However, these are average values, and the study noted that behavior varies across different user clusters. The study is not limited to work commuting, which accounts for 13 %, but evaluates various trip types, with visiting family and friends (66 %) and picking up/dropping off goods (56 %) being the most common purposes for car sharing (van der Linden et al. 2025). Due to the recency of the studies and their geographical proximity to Germany, this data is considered appropriate. Additionally, aspects such as reductions in driven distance through car sharing (Nijland and van Meerkerk 2017) will not be included since the work commuting distance remains constant.

The data from van der Linden et al. (2025) was modified by eliminating instances of previously used car sharing, as these do not affect the modal split. Additionally, trips outside of work commuting were removed, including those that would not have been made otherwise. The remaining data was scaled to achieve a 100 % share. The resulting data is summarized in Table B 2.

Table B 2: Adopted values for car sharing substitution based on van der Linden et al. (2025) for trip substitution related to work commuting.

Car sharing trip substitution	Class 1 [%]	Class 2 [%]	Class 3 [%]	Class 4 [%]	Class 5 [%]	Class 6 [%]	Full sample [%]
Private car	37	28	43	33	25	48	36
Public Transport	49	59	50	56	71	35	52
(E–)bike	10	7	4	7	3	12	7
Other	4	6	3	4	1	5	4
Total	100	100	100	100	100	100	100

In the best-case scenario, the placement of the car sharing station is assumed to be optimal, resulting in minimal waiting time and pick-up distance, which enhances user acceptance. This leads to the highest substitution of private cars as the basis for the modal split change. Substitution is based on class 6 from van der Linden et al. (2025), indicating that car sharing substitutes 48 % private cars, 35 % public transport, 12 % bikes, and 5 % other modes. Conversely, the worst-case scenario relies on class 5 from van der Linden et al. (2025) reflecting poorer substitution rates: 25 % private cars, 71 % public transport, 3 % bikes, and 1 % other modes. The results for both scenarios are presented in Table B 3.

Table B 3: Summarizing which commuting type will be changed to work commuting when implementing car sharing for each scenario.

Scenario	Best-case [%]	Worst-case [%]
Private car	48	25
Public Transport	35	71
(E–)bike	12	3
Other	5	1
Sum	100	100

Building on the type of changes, the following quantification focuses on how many people use car sharing and alter their modal split. The study by van der Linden et al. (2025)

indicates that 10 % to 15 % of individuals use car sharing for commuting, with a mean value of 13 %. Another study from the Netherlands found that car sharing is utilized by 7 % for travel to work or school (Witte et al. 2024).

In our status quo scenario, no car sharing options are available in the industrial park, resulting in no additional users for work commuting. Based on the previous studies, the percentage of car sharing users is set at 15 % in the best-case scenario and 7 % in the worst-case for those utilizing the car sharing station in the industrial park.

Therefore, the 15 % and 7 % changes are distributed with the data of Table B 1 according to the allocation in Table B 3. Since both data sets are not fully compatible, public transportation types are summarized, and the change for other modes is assigned to walking. Motorcycles, with a share of 1 %, will be excluded due to their low significance to achieve a total of 100 %. The following data is summarized in Table B 4.

Table B 4: Resulting modal split based on the literature for each scenario (summarized).

Modal Split for work commuting	Status Quo (Statistisches Bundesamt 2022) [%]	Best-case scenario [%]	Worst-case scenario [%]
Individual car	68	61	66
Car sharing	0	15	7
Public transport	14	9	9
(E–)bike	11	9	11
Walking	7	6	7

The data will be disaggregated to align with the modal split data for Germany. The public transportation system is assumed to consist of one-third trams, buses, and trains, reflecting the current situation in Germany (Statistisches Bundesamt 2022). However, the bus share is reduced to 4 % as defined in Statistisches Bundesamt (2022) to maintain a total of 100 %. Additionally, clustered (E-) bicycles are divided evenly into 50 % electric and 50 % non-electric. In the best-case scenario, car sharing is assumed to be 100 % BEV, while in the worst-case scenario, it consists of 50 % BEV and 50 % petrol and diesel vehicles. In linking hybrid and PHEV vehicles with the ecoinvent database (see Appendix B), it was found that no data exists for these aspects; therefore, PHEVs were added to BEVs and hybrid cars were allocated between petrol and diesel based on their respective shares in Germany (Kraftfahrt-Bundesamt 2024). The data is summarized in Table B 5.

Table B 5: Resulting modal split of work commuting specified for an industrial park in Germany for each scenario (detailed).

Modal Split for work commuting	Status Quo (Statistisches Bundesamt 2022) [%]	Best-case scenario [%]	Worst-case scenario [%]
Car, Private, Petrol	44.0	39.3	42.9
Car, Private, Diesel	21.0	18.8	20.5
Car, Private, BEV	3.0	2.7	2.9
Car, Sharing, Petrol	0.0	0.0	2.4
Car, Sharing, Diesel	0.0	0.0	1.1
Car, Sharing, BEV	0.0	15.0	3.5
Tram	5.0	3.1	3.2
Bus	4.0	2.5	2.6
Train	5.0	3.1	3.2
Bicycle (electric)	5.5	4.6	5.4
Bicycle (non-electric)	5.5	4.6	5.4
Walking	7.0	6.3	6.9

The annual traveled passenger distance is assumed to be 6,880 pkm, based on a one-way commuting distance of 17.2 km (Bundesinstitut für Bau-, Stadt- und Raumforschung 2024) over 200 working days for a full-time workforce.

Substitution of private cars through car sharing

Also, the substitution of private cars due to car sharing is an important factor to consider. Two studies from the Netherlands evaluated the effects of car sharing on different user groups (Witte et al. 2024; van der Linden et al. 2025). On average, 28 % of users disposed of one private car (ranging from 13 % to 40 %), while 1 % disposed of two or more cars after using car sharing (van der Linden et al. 2025). Other studies indicate that one car used for car sharing can replace about nine private cars in Germany (Kolleck 2021) and nine to thirteen in North America (Martin et al. 2010). However, under the assumed conditions, the overall use of cars increases with the establishment of car sharing (Table B 5), leading to a greater demand for vehicles. Consequently, existing cars have a higher occupancy rate and reach end-of-life more quickly, leading to faster vehicle exchanges. This accelerated exchange allows technological advancements in production and operation efficiency to enter the market sooner.

Car sharing vehicles are typically exchanged after approximately 1-3 years (Mont 2004; Mitropoulos and Prevedouros 2014) before reaching the second-hand market, whereas the average lifespan of vehicles in Germany is about 10.3 years (Kraftfahrt-Bundesamt 2024). The annual driving distance and lifespan of car sharing vehicles compared to privately owned cars remain unclear due to conflicting studies (Amatuni et al. 2020; Morfeldt and Johansson 2022). Consequently, it is assumed that the increased need for cars and accelerated technological improvements will offset each other, although improved operational efficiency will still be considered.

Efficiency gain through car sharing

Technological improvements have led to newer car sharing vehicles requiring less fuel during use (Arbeláez Vélez and Plepys 2021). For example, the specific fuel consumption of combustion vehicles in the EU decreased by 32 % from 2006 to 2015 (Hu and Chen 2016) and by 6.4 % in China from 2014 to 2018 (Yu et al. 2021a). In Germany, between 2014 and 2022, gasoline cars saw a decrease in specific fuel consumption of 4.7 %, while diesel vehicles increased by 1.3 %, resulting in an overall decline of 2.1 % (Statistisches Bundesamt 2024). For the 342 different BEV vehicle types sold in Europe from autumn 2023 to summer 2024, the mean electricity demand is certified at 19.4 kWh per 100 km, with real-world consumption averaging 20.7 kWh per 100 km (Weiss et al. 2024). The range of these values is +/- 4 kWh per 100 km (Weiss et al. 2024). As a result, for combustion vehicles, the efficiency gain from using car sharing instead of private vehicles is quantified at 5 % in the best-case scenario and 1 % in the worst-case scenario. For BEV, the efficiency gain is quantified at 19 % in the best-case and 5 % in the worst-case.

Additionally, shared cars are typically smaller than privately owned vehicles. For example, 80 % of the fleet from a German car sharing company consists of small cars (cambio Mobilitätsservice GmbH & Co. KG 2019), while the average for small cars in Germany is only

18 % (Statista GmbH 2024b). The impact of car size on BEVs is estimated to reduce the required amount of electricity and battery capacity, based on assumed car weights of 1,200 kg, 1,400 kg, and 2,000 kg (Del Pero et al. 2020), as ecoinvent data for each BEV size is not available compared to combustion vehicles. The aspects, car size, fuel type, and efficiency gain enable the inclusion of nano level aspects into the action. The distribution for each scenario is shown in Table B 6.

Table B 6: Modeling assumptions for car use, both with and without car sharing, for fuel types petrol, diesel, and BEV, along with the corresponding efficiency gains for each scenario.

Usage	Car size in fleet		Efficiency gains
	Size	Share [%]	
Car, Private, Petrol	Small	27	-
	Medium	57	
	Large	16	
Car, Private, Diesel	Small	27	-
	Medium	57	
	Large	16	
Car, Private, BEV	Small	27	-
	Medium	57	
	Large	16	
Car, Shared (Best), Petrol	Small	80	Amount of Petrol and all elementary flows reduced by 5 %
	Medium	15	
	Large	5	
Car, Shared (Best), Diesel	Small	80	Amount of Diesel and all elementary flows reduced by 5 %
	Medium	15	
	Large	5	
Car, Shared (Best), BEV	Small	80	Amount of electricity use reduced by 19 %
	Medium	15	
	Large	5	
Car, Shared (Worst), Petrol	Small	50	Amount of Petrol and all elementary flows reduced by 1 %
	Medium	40	
	Large	10	
Car, Shared (Worst), Diesel	Small	50	Amount of Diesel and all elementary flows reduced by 1 %
	Medium	40	
	Large	10	
Car, Shared (Worst), BEV	Small	50	Amount of electricity use reduced by 5 %
	Medium	40	
	Large	10	

Business Trips

Approximately 150 million business trips are made in Germany each year (Statista GmbH 2024c), based on current trip and pre-pandemic data. The average driving distance for business trips in Germany is 80 km (infas Institut für angewandte Sozialwissenschaft GmbH 2018). Germany has 46 million employees (Statistisches Bundesamt 2025b), with part-time workers making up 30 % of this total (Statistisches Bundesamt 2023). Given that part-time workers average 21 hours per week compared to 40 for full-time workers (Statistisches Bundesamt 2023), it is assumed that two part-time workers equate to one full-time worker. This adjustment brings the number of full-time equivalent employees in Germany to 39.1 million. Combining this with the number and length of business trips results in an estimated 307 person kilometers for business trips per year per full-time employee.

For business trips, it is assumed that a private car or a company car used exclusively by one company is substituted by a car sharing trip with a pool car available to multiple

companies. Cars account for 86.2% of business trips (DLR and DIW 2024), reducing the considered distance to 265 pkm per year. Since the case for lighter and more efficient vehicles is less compelling for business cars, the fleet car size follows the same distribution as the worst-case scenario for work commuting. The resulting modal split for business trips is shown in Table B 7. A shift from other transport modes, such as increased public transport use due to car sharing, is not considered.

Table B 7: Modal Split for the application business trip for each scenario.

Mode	Status Quo [%]	Best-case scenario [%]	Worst-case scenario [%]
Car, Private, Petrol	65	0	0
Car, Private, Diesel	31	0	0
Car, Private, BEV	4	0	0
Car, Sharing, Petrol	0	0	34
Car, Sharing, Diesel	0	0	16
Car, Sharing, BEV	0	100	50

Private car sharing

The modal split for private car sharing differs from that of work commuting and is based on the case study for the Netherlands by Amatuni et al. (2020). The share of electric cars in car sharing stations in Germany is 20 % for the year 2023 (Statista GmbH 2024a) which will be adopted.

A distinction is made between the best-case and worst-case scenario regarding the passenger distance traveled with a shared car. The case study indicates an average total distance of 11,000 kilometers per user per year (Amatuni et al. 2020). Adoption rates are based on assumptions made in work commuting based on van der Linden et al. (2025) and Witte et al. (2024) with a best-case of 15 % and a worst-case of 7 %. It is assumed that employees who use car sharing for work commuting also utilize it for personal trips. Consequently, the traveled passenger distance inducing a change in modal split is estimated at 770 person kilometers per year per employee (worst-case) and 1,650 person kilometers per year per employee (best-case). The resulting modal split is shown in Table B 8.

Table B 8: Modal Split for private car sharing. Modal split is based on Amatuni et al. (2020) and adapted for a German use case.

Mode	Status Quo [%]	Best-case scenario [%]	Worst-case scenario [%]
Car, Private, Petrol[1]	54.5	32.3	32.3
Car, Private, Diesel[1]	26.0	15.4	15.4
Car, Private, BEV[1]	3.4	2.0	2.0
Car, Sharing, Petrol[2]	0.0	8.9	8.9
Car, Sharing, Diesel[2]	0.0	4.2	4.2
Car, Sharing, BEV[2]	0.0	3.3	3.3
Tram	1.0	2.0	2.0
Bus	1.1	2.7	2.7
Train	13.0	27.2	27.2
Bicycle (electric)	0.5	1.0	1.0
Bicycle (non-electric)	0.5	1.0	1.0

[1] adapted to German shares (Kraftfahrt-Bundesamt 2024) based on a total car share of 84 % without car sharing and 50 % with car sharing for the Netherlands (Amatuni et al. 2020)

[2] adapted to German share for BEV in car sharing with 20 % and following adapted values for petrol and diesel

Best-case: 1,650 person kilometers per year and employee; worst-case: 770 person kilometers per year and employee

Charging station

For the car sharing station, the share of electric pooled cars is assumed to be 100 % in the best-case and 50 % in the worst-case. It is initially assumed that every electric car requires a charging point, with each charging station consisting of two points. Thus, in the best-case scenario, 7.5 charging stations are needed per 100 full-time employees, based on a 15 % share of BEV shared cars. In the worst-case scenario, 1.75 charging stations are required per 100 full-time employees, based on a 3.5 % share of BEV shared cars.

However, it is also assumed that not all vehicles will need to charge simultaneously; thus, the dimensioning is reduced from the maximum requirement. Unused charging points can be made available for public use in the best-case to increase occupancy rates. The load factor for charging stations is set at 0.5 for the best-case and 0.75 for the worst-case as a multiplier for demand. A study from Germany estimates the lifespan of public charging stations to be eight years (Hecht et al. 2022), resulting in a need for approximately 0.005 charging stations per employee per year in the best-case and 0.002 in the worst-case.

Parking space

A change in parking space requirements is assumed to be irrelevant. Although the share of work commuters using a car increases, the overall number of cars decreases due to shared vehicles. It is believed that these effects offset each other and are not decisive factors and carry high uncertainty.

B 2 Further elaboration of the conducted quantification

After quantifying the benefits and efforts, these will be linked to the environmental impacts through an LCA. The LCA is based on ISO 14040 and ISO 14044. The ecoinvent database, version 3.10, together with IPCC (2021) for GWP, CED from Frischknecht et al. (2015), and RMI adopted from Mostert and Bringezu (2019) as impact assessment methods, will serve as the foundation for linking these aspects to environmental impacts. The

linked ecoinvent processes are shown in Table B 9. The functional unit is *full-time employee without home office in Germany per year (pkm/a)*.

Table B 9: ecoinvent processes used in this study for vehicles based on ecoinvent in the version 3.10.

Vehicle	Fuel type	Size	Ecoinvent process [UUID]
Car	petrol	small	6615b393-289f-3f00-b9fb-f14b050194b7 [1]
		medium	7485d89a-ac59-3711-bb9f-c0b53bcf8a3d [1]
		large	40a090c6-f874-353d-8c17-fdc8f257dc65 [1]
	diesel	small	6d7181a4-ef29-3da5-b6b8-72acb7a4b84d [1]
		medium	3578bb71-1e78-367f-aba7-e5592344f98b [1]
		large	bb4f220a-d112-35b8-907c-7a1cebef1992 [1]
	electricity	small	9289ade8-cbf6-3697-97d0-02b3ca343bb9 [1, 2, 3]
		medium	9289ade8-cbf6-3697-97d0-02b3ca343bb9 [1, 2, 3]
		large	9289ade8-cbf6-3697-97d0-02b3ca343bb9 [1, 2, 3]
Bus	-	-	209a7998-a8d5-39c8-844e-15cddc41e5d0
Tram	-	-	536fcfde-3af4-4bed-a867-0fd9d3a449f1 [2]
Train	-	-	9cc52c36-e346-35dd-886a-0643cd37d590
Bicycle (electric)	-	-	1baf10dd-cdb6-458e-b2eb-3fbbaf85ed13 [2]
Bicycle (non-electric)	-	-	6bb80734-2043-332d-ab1a-9593ec9426a3

[1] vehicle kilometers for car transportation were converted to person-kilometers by dividing by the average occupancy of 1.4 persons per car

[2] adapted to German electricity mix

[3] The effect of car size is estimated as a reduction in the needed amount of electricity and battery, based on (Del Pero et al. 2020) and assumed car weights of 1,200, 1,400 and 2,000 kg

Some processes shown in Table B 9 were adapted for German conditions. The electricity mix for electric cars, trams, and electric bicycles was updated to reflect the German electricity mix. Additionally, vehicle kilometers for car transportation were converted to person-kilometers by dividing by the average occupancy of 1.4 persons per car (Umweltbundesamt 2023). Along with the established boundaries and assumptions, the impact factors for each mode of transport considered per person kilometer (pkm) are presented in Table B 10.

Table B 10: Impact factors for each mode of transport considered.

Mode	GWP [g CO_2-eq/pkm]	CED [MJ-eq/pkm]	RMI [kg/pkm]
Car, Private, Petrol, Small	212	2.97	0.23
Car, Private, Petrol, Medium	267	3.73	0.29
Car, Private, Petrol, Large	321	4.50	0.36
Car, Private, Diesel, Small	188	2.75	0.22
Car, Private, Diesel, Medium	243	3.56	0.29
Car, Private, Diesel, Large	303	4.44	0.36
Car, Private, BEV, Small	123	2.25	0.28
Car, Private, BEV, Medium	137	2.50	0.32
Car, Private, BEV, Large	180	3.23	0.42
Car, Shared (Best), Petrol, Small	204	2.86	0.22
Car, Shared (Best), Petrol, Medium	257	3.60	0.29
Car, Shared (Best), Petrol, Large	310	4.35	0.36
Car, Shared (Best), Diesel, Small	181	2.66	0.22
Car, Shared (Best), Diesel, Medium	235	3.44	0.29
Car, Shared (Best), Diesel, Large	293	4.29	0.36
Car, Shared (Best), BEV, Small	112	2.02	0.27
Car, Shared (Best), BEV, Medium	125	2.24	0.30
Car, Shared (Best), BEV, Large	165	2.91	0.40
Car, Sharing (Worst), Petrol, Small	211	2.95	0.23
Car, Sharing (Worst), Petrol, Medium	265	3.71	0.29
Car, Sharing (Worst), Petrol, Large	319	4.47	0.36
Car, Sharing (Worst), Diesel, Small	186	2.73	0.22
Car, Sharing (Worst), Diesel, Medium	241	3.53	0.29
Car, Sharing (Worst), Diesel, Large	301	4.41	0.36
Car, Sharing (Worst), BEV, Small	120	2.19	0.28
Car, Sharing (Worst), BEV, Medium	134	2.43	0.31
Car, Sharing (Worst), BEV, Large	176	3.15	0.41
Tram	51	1.00	0.09
Bus	114	1.67	0.11
Train	62	1.11	0.12
Bicycle (electric)	23	0.37	0.05
Bicycle (non-electric)	12	0.16	0.02
Walking	0.00	0.00	0.00

pkm = person kilometers

The assumptions for the charging station are summarized in Table B 11. The end-of-life of the charging station could not be included, as it was not part of the ecoinvent dataset. However, its impact is considered negligible, as demonstrated by previous studies (Zhang et al. 2019).

Table B 11: Quantification for each aspect of the considered charging station used in the LCA.

Charging Station aspect			
Mass of charging station (Mennekes Elektrotechnik GmbH & Co. KG)	70 kg		
Life-time (Hecht et al. 2022)	8 years		
Ecoinvent process [UUID]	ea6de7b7-79e7-3593-a24b-202d95208b88		
Life cycle impacts (without end-of-life)	GWP: 2,045 kg CO_2-eq	RMI: 8,457 kg	CED: 28,068 MJ-eq

The overall results for each aspect of the scenarios considered are summarized in Table B 12. The resulting impact savings are shown in Section 3.3.

Table B 12: Impacts for various car sharing aspects and applications, as well as the total for the functional unit defined as a full-time employee without home office in Germany per year.

Considered aspect	Status quo scenario			Best-case scenario			Worst-case scenario		
	GWP [kg CO_2-eq/a]	CED [MJ-eq/a]	RMI [kg/a]	GWP [kg CO_2-eq/a]	CED [MJ-eq/a]	RMI [kg/a]	GWP [kg CO_2-eq/a]	CED [MJ-eq/a]	RMI [kg/a]
Work commuting	1,245	17,981	1,474	1,214	17,905	1,580	1,279	18,521	1,541
Business Trip	62	882	71	33	582	79	49	759	76
Private Car Sharing [1]	361[1a] 168[1b]	5,204[1a] 2,429[1b]	427[1a] 199[1b]	291	4,285	364	139	2,043	173
Charging Stations	0	0	0	10	140	42	4	56	17
Sum[1]	1,668[1a] 1,475[1b]	24,067[1a] 21,292[1b]	1,972[1a] 1,744[1b]	1,548	22,912	2,065	1,471	21,379	1,807

[1] only 15 %[1a] (best-case) and 7 %[1b] (worst-case) of the annual distance driven are considered, as this represents the affected distance.

The resulting environmental impact reduction of each scenario in comparison to the status quo scenario and based on our assumptions are presented in Table B 13. This is also the basis for Figure 3.5 in Section 3.3.2.

Table B 13: Results for impact reduction in the best-case and worst-case scenarios compared to the status quo, including a comparison of GWP, CED, and RMI environmental impacts across all aspects.

Considered aspect	Best-case scenario			Worst-case scenario		
	GWP [kg CO_2-eq/a]	CED [MJ-eq/a]	RMI [kg/a]	GWP [kg CO_2-eq/a]	CED [MJ-eq/a]	RMI [kg/a]
Work commuting	31	76	-106	-34	-540	-67
Business Trip	29	300	-8	13	123	-5
Private Car Sharing	70	919	63	29	386	26
Charging Stations	-10	-140	-42	-4	-56	-17
Total	120	1,155	-93	4	-87	-63

Appendix C

Supplementary information for Publication III

C 1 Methodological details and literature overview for MCDM components

This section provides extended background and source alignment for the indicator selection, normalization, weighting, and aggregation choices described in Section 4.2.

Steps to formulate an MCDM tool and how these are addressed in the paper

As outlined in the main text, the DST is based on MCDM tools. The steps to formulate such a tool are summarized in Table C 1 together with where and how this is addressed in this work.

Table C 1: Steps to formulate an MCDM tool and where as well as how these are addressed.

Steps to formulate an MCDM tool	Where this is addressed	How this is addressed
Goal and scope definition (Goulart Coelho et al. 2017; Torkayesh et al. 2022)	Section 4.1; Section 4.2.1	Ex-ante prioritization of operational actions to reduce environmental impacts; primary users are companies (extendable to park operators/municipalities). Spatial scope: micro (company) and meso (park/symbiosis); nano excluded. Temporal scope: pre-planning/early design. Sustainability perspective: environmental-first with separate circularity view; optional economic inputs. Geographic focus: Germany/Europe. Site selection supported
Criteria definition (Torkayesh et al. 2022)	Section 4.2.3	Primary criterion: environmental performance as a composite of five indicators (GWP, CED, RMI, water use, land use). Complementary criterion: circularity (user-selected CE indicators and R-strategy mapping), reported separately (no aggregation with environmental score). Optional criterion: costs (user-entered) for cost–benefit views.
Theoretical framework definition (Goulart Coelho et al. 2017)	Section 4.2.1	Framework per Gan et al. (Gan et al. 2017): purpose, spatial/temporal scales, and sustainability perspective guide method choices (indicator set, normalization, weighting, aggregation). Action categories span micro and meso; environmental-first to avoid CE compensation; ex-ante focus to inform decisions.
Data collection (Torkayesh et al. 2022)	Section 4.2.2; adopted elements from the KREGI approach; Appendix C 2 / C 3	Three-step approach: (i) literature review/benchmarks, (ii) stakeholder input where appropriate, (iii) LCA-based quantification. All actions are documented in the Appendix C 3
Impact assessment (Torkayesh et al. 2022)	Section 4.2.3; Appendix C 2 / C 3	LCIA methods aligned with indicator choices: GWP (IPCC (IPCC 2021)), CED (Frischknecht et al. (Frischknecht et al. 2015)), RMI (Mostert & Bringezu (Mostert and Bringezu 2019)), water and land use (EU Environmental Footprint (European Commission 2021)). Background LCI from ecoinvent 3.10. Effects computed as scenario reductions relative to baseline and scaled to company context.
Data normalization (Goulart Coelho et al. 2017)	Section 4.2.4; Appendix C 1	Max normalization anchored in the mean of best- and worst-case scenario reductions; company-specific reference is the total mean potential across applicable actions. Negative values allowed when mean effects are detrimental. Normalization performed after all applicable actions are quantified.
Weighting (Torkayesh et al. 2022) and ranking MCDM models (Goulart Coelho et al. 2017; Torkayesh et al. 2022)	Section 4.2.5; Section 4.2.6; Appendix C 1	Default equal weights across environmental indicators; CE indicators remain separate. Aggregation via weighted sum method (WSM) yields a single 0–100 environmental score and action-level rankings; absolute (unnormalized) savings also reported.
Sensitivity analysis (Goulart Coelho et al. 2017) or uncertainty analysis (Torkayesh et al. 2022)	Section 4.2.7	Best- and worst-case scenarios per action form sensitivity bands around the mean-based score; normalization base is retained. Scenario scores may fall below 0 or exceed 100 relative to the mean-based scaling.

Indicator selection

Selecting appropriate indicators is a critical step in decision-support tools and has been extensively discussed in the literature. Multiple indicators are typically necessary to capture environmental performance (Helander et al. 2019), but the set must balance holistic coverage with ease of use (Dale and Beyeler 2001; Zhu et al. 2010; Cagno et al. 2023). Several publications focus on the use and selection of indicators for environmental assessment (Cloquell-Ballester et al. 2006; Niemeijer and Groot 2008; Gareiou et al. 2023) highlighting the complexity of this task.

Reviews and guidance converge on four primary requirements, relevance, unambiguity, measurability, and coherence, supplemented by data quality aspects such as accuracy, comparability, actuality, and controllability. Table C 2 summarizes the frequency of these requirements across selected sources. This synthesis shows measurability, unambiguity, and relevance as the most frequently cited requirements, with coherence mentioned less often but emphasized in statistical guidance (OECD 2008).

Table C 2: Frequency of the requirements for the indicators as stated in the literature.

Source	Relevance	Unambiguity	Coherence	Measurability				
				Availability /measurement options	Accuracy of the data	Controllability of the data	Comparability of the data	Actuality of the data
(Kamali et al. 2018)	X			X	X			
(Patlitzianas et al. 2008)	X	X	X	X			X	
(Zall Kusek and Rist 2004)	X	X	X	X		X		
(Struck 2023)		X	X	X				
(OECD 2008)	X	X	X	X	X	X		X
(King et al. 2024; United Nations 2024)	X	X		X		X		
(International Federation of Red Cross and Red Crescent Societies 2002)			X		X	X		X
(International Organization for Standardization 2019)	X	X	X		X	X	X	
(Valenzuela-Venegas et al. 2016)	X	X		X				
(Zhu et al. 2010)	X	X		X		X		
(Azapagic and Perdan 2000)	X	X		X			X	
(Schomaker 1997)	X	X		X				X
(Richards and Gladwin 1999)	X	X		X				
(Feil et al. 2017)		X		X			X	X
(Baratsas et al. 2022)	X	X		X			X	
Frequency of the specified requirements	12	13	6	15				
Frequency of the specified sub-requirements				13	4	6	5	4

In our tool, these requirements apply to all indicators. The definition for each requirement and the verification approach is as follows:

- Relevance: Indicators must be relevant to assessing company performance on the intended dimension (environmental or circularity). Verification involves checking their use in comparable assessment models and/or a scientifically validated relationship with environmental outcomes or CE constructs.
- Unambiguity: Indicators must be clearly and consistently defined to avoid misunderstandings. Verification is supported by indicator and action fact sheets detailing definitions, units, data sources, and measurement rules.
- Measurability: Data must be available or measurable in a cost-effective and straightforward manner; data collection should be objective, transparent, and verifiable. Verification favors recognized reporting standards (e.g., GRI) or certification systems, with justified alternatives accepted.
- Coherence: Use common concepts, classifications, and definitions across indicators and actions; avoid overlap and double counting. Verification checks interdependencies and system boundaries.

CE indicators are user-selected to ensure relevance across sectors and contexts. They provide a complementary lens and are not aggregated with environmental indicators to avoid compensation (Harris et al. 2021; Elia et al. 2024). Actions are mapped to R-strategies to support CE interpretation. Where process-specific impacts are prevailing, additional categories (e.g., eutrophication, acidification, photochemical ozone formation) can be included to broaden coverage (Park and Behera 2014).

Normalization

Normalization makes heterogeneous indicators comparable, and the chosen method must align with the theoretical framework and data characteristics (Ebert and Welsch 2004; Nardo et al. 2005; OECD 2008). Common approaches include normalization proportional to a maximum or target (max normalization), scaling between observed minimum and maximum (min–max), and categorical (threshold-based) scaling for quantitative and qualitative data (Freudenberg 2003; Jacobs et al. 2004; Sutherland et al. 2022). Max normalization scales values by a chosen maximum, typically yielding normalized scores between 0 and 1. Min–max normalization maps values to the 0–1 range using the observed minimum and maximum, preserving relative positions but remaining sensitive to extremes. Categorical scaling assigns discrete scores based on thresholds (e.g., 25th, 50th, 75th percentiles) and is practical for communication but entails information loss and subjective threshold setting. Table C 3 provides a comparative overview of advantages and disadvantages for these methods.

Table C 3: Normalization methods and its advantages and disadvantages.

Type	Advantages	Disadvantages
Normalization proportional to maximum value (max normalization)	Suitable for integrating a target or benchmark into evaluation [3]	Independence between the indicators is of central importance [1,3] Complete compensation of poor indicators possible [1] Outliers have a major impact [1] Unstable when new data is added [3]
Normalization using minimum and maximum value (min-max normalization)	More robust than the method using a standard deviation when multiple outliers are present [2] Weighting has more influence [2]	Outliers have a major impact [1]
Value attribution using threshold values (categorical scaling)	Can be applied to quantitative and qualitative data [4] Practical and comparative [4]	Determination of threshold values can be subjective [1] Some information is lost because of the categorization [1]

[1] (Freudenberg 2003)
[2] (Jacobs et al. 2004)
[3] (OECD 2008)
[4] (Sutherland et al. 2022)

The literature also differentiates normalization by indicator type. For percentage indicators, values intended to be minimized are often transformed as (1 − percentage), while percentage indicators intended to be maximized can be used directly; non-percentage indicators have to be normalized (Baratsas et al. 2022). In practice, some frameworks use categorical rating schemes (e.g., discrete classes or certification systems) to aid stakeholder communication (Kamali et al. 2018; DGNB 2020; Struck 2023). Other studies compare quantitative indicators to literature-derived reference values, expressing outcomes as percentages, and use expert judgement for qualitative indicators (Zhu et al. 2010). These practices highlight that normalization choices influence interpretability, robustness, and effort, and should be selected to match the decision context.

In this DST, max normalization is adopted at the indicator level, anchored in the mean of best- and worst-case scenario effects and scaled by company inputs, without sector differentiation. For each company, action, and indicator, we quantify reductions relative to the baseline for both scenarios and use their arithmetic mean as the primary reference for normalization and scoring. The normalization base for each indicator is the total potential across all applicable actions (including user-added actions). Dividing the mean reduction of an action by this company-specific reference maximum yields the normalized effect used in aggregation. This action-based, company-tailored normalization aligns comparability with the actual decision context and prevents artificial inflation caused by splitting actions into smaller units.

While max normalization typically yields values bounded above by 1, negative normalized values are deliberately allowed when mean effects are detrimental (e.g., an action worsens land use in the mean case). Allowing negative values preserves information about harmful effects and makes trade-offs explicit, avoiding over-optimistic aggregation. Normalization is executed after quantifying all applicable actions. When new actions are added or case-specific actions are refined, the reference maximum is recalculated to reflect the expanded potential, and normalized values may shift accordingly. This update

behavior mirrors the need to revise extremes in min–max normalization when new data change the observed range (OECD 2008).

Max normalization is preferred here over min–max and categorical scaling for three reasons. It provides a direct reference to the realizable potential rather than to the observed range, which may compress variation if the minimum is high or sensitive to local extremes. It avoids the subjectivity and information loss inherent in categorical thresholds, which are not needed because all actions are quantified and the tool communicates via a single environmental score rather than discrete classes. And it remains transparent and easy to interpret in combination with equal weighting and weighted-sum aggregation, which supports clear communication and sensitivity analysis.

Weighting

Weighting is a critical step in developing assessment models because it reflects the relative importance of indicators and directly influences composite results (Su et al. 2013; Bach et al. 2016; Gan et al. 2017; Kühnapfel 2021; Baratsas et al. 2022). In MCDM, weights are typically normalized to sum to one (Hwang and Yoon 1981). The literature groups weighting approaches into three families: data-driven/statistical methods, participatory (expert/stakeholder) methods, and equal weighting. Some frameworks also introduce compensation parameters to tune the degree of compensability among criteria (Díaz-Balteiro and Romero 2004). The advantages and disadvantages of each weighting method are compared in Table C 4.

Data-driven/statistical methods determine weights via analysis of indicator data, offering objectivity and transparency when robust datasets exist (Odu 2019). Examples include the benefit-of-the-doubt (BOD) approach, which derives weights from performance to form a composite index (Cherchye and Kousmanen 2004; Gan et al. 2017), and principal component analysis (PCA), which reduces dimensionality and mitigates double counting by exploiting correlation structures (Bryant and Yarnold 1995; Sands and Podmore 2000). These methods can be powerful but require sufficient, comparable data and may yield results that are sensitive to data changes or difficult to interpret in contexts without clear causal linkages (OECD 2008; Gan et al. 2017).

Participatory methods elicit preferences from experts or stakeholders, balancing technical rigor with contextual relevance (OECD 2008; Struck 2023). The analytical hierarchy process (AHP) derives weights from pairwise comparisons and is widely used in sustainability assessments (Saaty 1987; Gan et al. 2017), with applications such as life cycle sustainability performance for modular buildings (Kamali et al. 2018). Budget allocation (BA) assigns points to criteria and is simple and transparent (Nardo et al. 2005; OECD 2008), as in Eco-Indicator 99 (Goedkoop and Spriensma 2001; Gan et al. 2017). Conjoint analysis (CA) infers weights statistically from choices among indicator combinations (Nardo et al. 2005), with applications in circular business cannibalization (Koide et al. 2023). Other techniques (swing, Delphi, SMART) can be implemented via expert surveys (Odu 2019). While informative, these methods can be effort-intensive and less suitable when many indicators or low-effort use is required (OECD 2008; Odu 2019).

Equal weighting uniformly assigns the same weight to each indicator and is widely used when empirical preference information is unavailable, heterogeneous, or costly to elicit (Singh et al. 2009; Feil et al. 2017; Gan et al. 2017). It can also be used alongside other weighting methodologies. For instance, Baratsas et al. (Baratsas et al. 2022) apply it to categories and most indicators, with some justifiably deviating, while Zhu et al. (Zhu et al. 2010) weights some indicators using AHP and assigns equal weight to the others.

Table C 4: Weighting methods and its advantages and disadvantages.

Type	Advantages	Disadvantages
Benefit of the doubt approach (BOD)	Improvement potential can be identified from the assessment [1] Integrates weighting, aggregation and index formation [2] Can help in finding trade-offs [1] Low risk of unfair or harmful weighting [10]	Weighting is not uniform [1, 4] Risk of euphemizing the facts [1] Low transparency multiple potential and possibly incomparable results [2]
Principal components analysis (PCA)	Also suitable for many indicators [3] Risk of double weighting due to correlated indicators is reduced [1, 3]	Indicators that do not correlate with others are neglected [1] Sensitive to data changes [1, 3] Unpredictable results may occur when not based on real-world links [6] Needs a sufficient number of indicators [2, 3]
Analytical hierarchy process (AHP)	Can be used for quantitative and qualitative data [1, 3, 6] Can be combined with other methods [2, 11] High transparency [3] Numerous levels of criteria [6] Widely used [2] Provides verification operation [2]	High effort with a large number of indicators [3, 5] Indicators can be completely excluded from the model [4] Subjective [4, 5, 6]
Budget allocation (BA)	Easy to understand [3, 6] Easy to implement [6] Transparency and explicitness [2]	Number of indicators should not exceed 10 [3, 6, 9] Subjective [5, 9] Weights may be specified for only one use case [2]
Conjoint analysis (CA)	Can be used for both quantitative and qualitative data [2] Weightings reflect the significance of trade-offs [1]	Requires a large number of participants and performance data [1, 2] Complex survey process [1, 2] Potential inconsistence [2]
Equal weighting	Can be applied when there is no information on statistical or empirical relevance [2] Easy to apply and easy to understand [7] Can be combined with other methods [4] Particularly suitable for a large number of indicators [4]	Criticized regarding validity and transparency [2] Risk of double weighting [8] No insights in indicator importance [6]

[1] (Nardo et al. 2005)
[2] (Gan et al. 2017)
[3] (OECD 2008)
[4] (Kühnapfel 2021)
[5] (Odu 2019)
[6] (Hermans et al. 2008)
[7] (Paradowski et al. 2021)
[8] (Freudenberg 2003)
[9] (Saisana and Tarantola 2016)
[10] (Cherchye et al. 2007)
[11] (Vaidya and Kumar 2006)

As outlined in Section 4.2.6, the tool adopts equal weighting across environmental indicators by default, with optional local adjustment where context warrants it. This choice is motivated by three considerations aligned with literature:

- Data constraints and usability: In ex-ante planning and site selection, robust, company-specific datasets for data-driven weighting are often unavailable, and the number of actions and indicators makes participatory weighting effort-intensive (OECD 2008; Gan et al. 2017; Odu 2019). Equal weighting is appropriate under incomplete data and long-term perspectives (Singh et al. 2009; Gan et al. 2017).
- Transparency and adaptability: Equal weighting is simple, easily communicated, and weights can be easily adjusted to reflect local priorities (e.g., increasing the weight of water in water-scarce regions), with all changes documented for traceability (Nardo et al. 2005; OECD 2008).
- Robustness via sensitivity: Combined with sensitivity analysis, equal-weight results can be checked for stability, increasing confidence in rankings and scores (Goulart Coelho et al. 2017; Wulf et al. 2019).

In this tool, environmental indicators receive equal weights by default. CE indicators are reported separately and not aggregated or cross-weighted with environmental indicators, consistent with evidence that circularity gains do not necessarily imply environmental impact reductions and to avoid double counting (Harris et al. 2021; Elia et al. 2024). A compensation parameter (Díaz-Balteiro and Romero 2004) is not implemented in the present version but can be explored in future work to tune degrees of compensation if user preferences justify it.

Aggregation and scoring

Aggregation combines normalized, weighted indicators into a comparable performance output and must align with the model's objectives and data structure (OECD 2008; Gan et al. 2017; Taherdoost and Madanchian 2023). The literature distinguishes three types of aggregation methods (Nardo et al. 2005): additive (linear) aggregation, geometric aggregation, and non-compensatory multi-criteria methods. Additive aggregation includes the weighted sum method (WSM), ranking addition, and benchmark methods; it is transparent, easy to implement, and compatible with diverse weighting schemes, but allows full compensation across indicators and therefore relies on careful normalization and interpretation (Nardo et al. 2005; OECD 2008; Gan et al. 2017). Geometric aggregation, such as the weighted product method (WPM), multiplies ratio-scaled indicator values and allows only partial compensation; it can emphasize balance across indicators but is not robust to zero or negative normalized values and imposes strong independence assumptions (Nardo et al. 2005; OECD 2008; Gan et al. 2017). Non-compensatory multi-criteria methods avoid compensation, typically producing rankings or thresholded classifications rather than single scores; they are suitable when criteria are non-substitutable but can entail information loss and higher computational effort with many alternatives (Nardo et al. 2005; Gan et al. 2017). Relative ranking approaches, comparing results as favorable or unfavorable without an absolute score, can be useful but reduce information intensity

and often require multiple quantified alternatives (Warhurst 2002; Munda 2012; Gan et al. 2017). An overview of the advantages and disadvantages of each aggregation method is presented in Table C 5.

Table C 5: Aggregation methods with each property, advantages and disadvantages in comparison.

Type	Method	Properties	Advantages	Disadvantages
Additive aggregation	Weighted sum method (WSM) or also called weighted arithmetic mean Ranking addition method Benchmark method ...	Suitable when all indicators have the same unit of measurement [1] Allows for compensation [1] Evaluation is based on the weight [1]	Compatible with many weighting methods [2] Transparent and easy to implement [3] Sensitivity analysis is easy to conduct [3]	Independence between the indicators is crucial [1, 3] Complete compensation for poor performing indicators is possible [1]
Geometric aggregation	Weighted product method (WPM) ...	Allows for partial compensation only [1] Suitable when the indicators are presented in different ratio scales [1] Evaluation is advantageous for well-performing objects [1]	Compatible with the weighting methods of equal weighting, PCA, and AHP [2] Transparent and easy to execute [3]	Not compatible with negative normalized values [1] Not compatible with the weighting method BOD [2] Independence between the indicators is crucial [1, 3] Partly compensation for poor performing indicators is possible [1, 2] Not all sensitivity and uncertainty quantifications are applicable [3, 4, 5]
Preventing compensation	Non-compensatory multi-criteria methods	Leads to a ranking rather than an assessment score [1, 3] Suitable when all areas are relevant [1]	No compensation [3] for poor performing indicators [1] Quantitative and qualitative value can be used [3]	Information about the intensity of differences between units is lost, because the method yields only ordinal rankings (no cardinal scores) [3] Computational burden increases rapidly with the number of units and indicators (e.g., due to pairwise comparisons/permutations) [3]

[1] (Nardo et al. 2005)
[2] (OECD 2008)
[3] (Gan et al. 2017)
[4] (Calvo et al. 2002)
[5] (Beliakov et al. 2007)

As outlined in Section 4.2.6, the DST adopts additive aggregation via the WSM to produce a single, interpretable environmental score. This choice is motivated by three considerations aligned with the literature:

- Transparency and compatibility: WSM is straightforward, widely used, and compatible with the tool's normalization and weighting design; it supports clear communication and sensitivity analysis (Nardo et al. 2005; OECD 2008; Gan et al. 2017).
- Data properties: Some normalized action effects can be zero or negative (e.g., mean disbenefits in a given indicator). WPM is not robust to such values, whereas WSM accommodates them without collapsing the aggregation (Nardo et al. 2005; Gan et al. 2017).

- Objective and output format: The tool aims to provide a single communicable score rather than a thresholded ranking; non-compensatory multi-criteria methods and pure ranking approaches are therefore not used as the primary output (Warhurst 2002; Gan et al. 2017).

The aggregated environmental score is typically reported on a 0–100 point scale by multiplying the normalized, weighted sum by 100. A score of 100 indicates that the mean potential has been fully realized across the environmental indicators under the chosen weights; in practice, portfolios often score below 100 due to trade-offs as negative effects in some indicators or non-applicability of some actions. Presenting points rather than percentages avoids implying a normative "100 % optimum" and reduces the risk that users overlook beneficial actions not included in the model. To aid expert interpretation and external reporting, absolute, unnormalized environmental deltas are also reported at both the action and indicators levels (Cairns et al. 1993; Gan et al. 2017). Aggregation remains sensitive to method choices; robustness can be checked via sensitivity analysis, consistent with best practice in applied multi-criteria decision-making (OECD 2008; Goulart Coelho et al. 2017).

C 2 General information for quantification of actions

This section summarizes shared assumptions, data sources, and scaling rules used to quantify actions. It provides baseline values (e.g., modal split), functional units, and parameter choices so they need not be repeated in each action fact sheet.

C 2.1 Employment mobility

Mobility was identified as a vital sector within the Global Circularity Protocol for Business, which is why it is also an essential component of the DST (WBCSD 2024). Most employee mobility aspects were elaborated in detail in Verkic et al. (2025b); a concise summary is provided here to support consistent application. The functional unit for mobility-related impacts is full-time employee per year (FTE/a). This unit enables scaling across companies with different employee counts and work-time shares. Part-time workers make up 30 % of the total work force in Germany (Statistisches Bundesamt 2023). Since they average 21 hours per week compared to 40 hours for FTE (Statistisches Bundesamt 2023), it is assumed that two part-time workers are equivalent to one FTE.

Baseline modal split for work commuting in Germany

The modal split represents the share of each transport mode (Rodrigue 2020). The status quo for work commuting is based on 2020 data for Germany (Statistisches Bundesamt 2022), refined by fuel-type shares for cars (Kraftfahrt-Bundesamt 2024). The mean commuting distance is 17.2 km per trip (Bundesinstitut für Bau-, Stadt- und Raumforschung 2024). Table C 6 shows the baseline modal split used in this tool.

Table C 6: Baseline modal split for work commuting in Germany.

Modal Split for work commuting	Status Quo (Statistisches Bundesamt 2022) with (Kraftfahrt-Bundesamt 2024) [%]
Car, Petrol	44.0
Car, Diesel	21.0
Car, BEV	3.0
Tram	5.0
Bus	4.0
Train	5.0
Bike (electric)	5.5
Bike (non-electric)	5.5
Walking	7.0

Car size distribution and BEV size assumptions

The car size distribution (small/medium/large) is assumed to be identical across fuel types and based on Statista GmbH (2024b), small 27 %, medium 57 %, large 16 %. For BEVs, size affects electricity demand and battery capacity. Due to limited size-specific BEV processes in ecoinvent compared to combustion vehicles, BEV energy requirements are adjusted by assumed curb weights of 1,200 kg, 1,400 kg, and 2,000 kg (Del Pero et al. 2020).

Charging infrastructure

Charging station impacts are included where relevant (e.g., actions introducing work-place charging). Mass per unit (70 kg) is based on manufacturer data (Mennekes Elektrotechnik GmbH & Co. KG), which serves as basis for quantifying the mass specified ecoinvent data set. The used and resulting data is summarized in Table C 7.

Table C 7: Quantification for each aspect of the considered charging station used in LCA.

Charging Station aspect			
Mass of charging station (Mennekes Elektrotechnik GmbH & Co. KG)	70 kg		
Life-time (Hecht et al. 2022)	8 years		
Based on ecoinvent process	Market for charger, electric passenger car, GLO		
Life cycle impacts (without end-of-life)	GWP: 1,977 kg CO_2-eq.	RMI: 12,353 kg	CED: 27,348 MJ-eq

Business trips

Assumptions for business travel generally follow Verkic et al. (2025b)Verkic et al. and are updated for consistency. Approximately 150 million business trips are made annually in Germany (Statista GmbH 2024c), based on current and pre-pandemic data. The average driving distance per business trip is 80 km (infas Institut für angewandte Sozialwissenschaft GmbH 2018). Germany has 46 million employees (Statistisches Bundesamt 2025b), of whom 30 % work part-time (Statistisches Bundesamt 2023). Converting part-time to full-time equivalents yields 39.1 million FTEs. This results in approximately 307 passenger-kilometers (pkm) and 4 business trips per FTE per year. The 2021 mean share of car pkm for business trips (preliminary values, adjusted for COVID-19 effects) is 86.2 % (DLR and DIW 2024). Therefore, car-related business travel is set at 265 pkm per FTE per year. A vehicle occupancy of 1.4 is used to convert vehicle-kilometers to pkm

(Umweltbundesamt 2023). Only changes in car travel are considered for BEV transitions in business trips.

C 2.2 Renewable energy mix

Renewable electricity processes in ecoinvent (PV based on 2012 installations; onshore wind >3 MW from early 2000s) are updated using current GWP values for Germany to better represent currently installed technologies (Lauf et al. 2025). Although not from the current year, these updates provide a more representative basis for impacts across production to end-of-life. The mean GWP of current PV panels is 57 g CO_2-eq/kWh. The ecoinvent value for electricity from a 570 kWp ground-mounted multi-Si PV system is 104 g CO_2-eq/kWh, implying a scaling factor of 0.5475.

For wind electricity, only onshore generation is considered, as it provided the majority of Germany's wind output in the first half of 2025 (Fachagentur Wind und Solar e. V. 2025; Deutsche WindGuard GmbH 2025). The average capacity of newly installed onshore turbines in this period was about 5.4 MW (Fachagentur Wind und Solar e. V. 2025). Therefore, the ecoinvent process for German onshore wind plants above 3 MW is used as the background model. To reflect current performance, the process is scaled by the ratio of the current mean life-cycle GWP for onshore wind (18 g CO_2-eq/kWh) to the ecoinvent value for the selected process (34 g CO_2-eq/kWh), yielding a scaling factor of 0.5317.

The current renewable energy mix in Germany is modeled with PV and wind accounting for 75 % of renewable sources (Umweltbundesamt 2025). New capacities from hydropower and biomass (the remaining 25 %) are limited in growth potential (Umweltbundesamt 2025). Thus, the mix focuses on PV and wind only, with shares of 34 % PV and 66 % wind (Umweltbundesamt 2025), resulting in an overall GWP of approximately 31 g CO_2-eq/kWh.

C 2.3 Background processes in ecoinvent

In the following Table C 8 the used and modified background processes for the LCA through ecoinvent are elaborated.

Table C 8: Summary of the ecoinvent processes used within the LCA and their modifications.

Process name	Based on ecoinvent process	Extent and reasoning behind modification
Car Diesel BT SQ	10 %: transport, passenger car, large size, diesel, EURO 5, RER 40 %: transport, passenger car, medium size, diesel, EURO 5, RER 50 %: transport, passenger car, small size, diesel, EURO 5, RER	No.
Car Diesel DE	16 %: transport, passenger car, large size, diesel, EURO 5, RER 57 %: transport, passenger car, medium size, diesel, EURO 5, RER 27 %: transport, passenger car, small size, diesel, EURO 5, RER	No.
Car Diesel shared BT WC	10 %: transport, passenger car, large size, diesel, EURO 5, RER 40 %: transport, passenger car, medium size, diesel, EURO 5, RER	Yes: for the worst-case of a shared combustion vehicle, the efficiency was also improved by reducing the fuel demand and emissions by 1 %.

Process name	Based on ecoinvent process	Extent and reasoning behind modification
	50 %: transport, passenger car, small size, diesel, EURO 5, RER	
Car Diesel shared WC	10 %: transport, passenger car, large size, diesel, EURO 5, RER 40 %: transport, passenger car, medium size, diesel, EURO 5, RER 50 %: transport, passenger car, small size, diesel, EURO 5, RER	Yes: for the worst-case of a shared combustion vehicle, the efficiency was also improved by reducing the fuel demand and emissions by 1 %.
Car Electric BT shared WC	10 %: transport, passenger car, large size, electric, GLO 40 %: transport, passenger car, medium size, electric, GLO 50 %: transport, passenger car, small size, electric, GLO	Yes: as there is no differentiation in ecoinvent of the car sizes, these have been self-calculated based on Del Pero et al. (Del Pero et al. 2020). Also, the electricity mix was changed to the German mix. For the worst-case of a shared electric vehicle, the efficiency was also improved by reducing the electricity demand by 5 %.
Car Electric BT SQ	10 %: transport, passenger car, large size, electric, GLO 40 %: transport, passenger car, medium size, electric, GLO 50 %: transport, passenger car, small size, electric, GLO	Yes: as there is no differentiation in ecoinvent of the car sizes, these have been self-calculated based on Del Pero et al. (Del Pero et al. 2020). Also, the electricity mix was changed to the German mix.
Car Electric DE	16 %: transport, passenger car, large size, electric, GLO 57 %: transport, passenger car, medium size, electric, GLO 27 %: transport, passenger car, small size, electric, GLO	Yes: as there is no differentiation in ecoinvent of the car sizes, these have been self-calculated based on Del Pero et al. (Del Pero et al. 2020). Also, the electricity mix was changed to the German mix.
Car Electric shared BT BC	10 %: transport, passenger car, large size, electric, GLO 40 %: transport, passenger car, medium size, electric, GLO 50 %: transport, passenger car, small size, electric, GLO	Yes: as there is no differentiation in ecoinvent of the car sizes, these have been self-calculated based on Del Pero et al. (Del Pero et al. 2020). Also, the electricity mix was changed to the German mix. For the best-case of a shared electric vehicle, the efficiency was also improved by reducing the electricity demand by 19 %.
Car Petrol BT SQ	10 %: transport, passenger car, large size, petrol, EURO 5, RER 40 %: transport, passenger car, medium size, petrol, EURO 5, RER 50 %: transport, passenger car, small size, petrol, EURO 5, RER	No.
Car Petrol DE	16 %: transport, passenger car, large size, petrol, EURO 5, RER 57 %: transport, passenger car, medium size, petrol, EURO 5, RER 27 %: transport, passenger car, small size, petrol, EURO 5, RER	No.
Car Petrol shared BT WC	10 %: transport, passenger car, large size, petrol, EURO 5, RER 40 %: transport, passenger car, medium size, petrol, EURO 5, RER 50 %: transport, passenger car, small size, petrol, EURO 5, RER	Yes: for the worst-case of a shared combustion vehicle, the efficiency was also improved by reducing the fuel demand and emissions by 1 %.
Car Petrol shared WC	10 %: transport, passenger car, large size, petrol, EURO 5, RER 40 %: transport, passenger car, medium size, petrol, EURO 5, RER 50 %: transport, passenger car, small size, petrol, EURO 5, RER	Yes: for the worst-case of a shared combustion vehicle, the efficiency was also improved by reducing the fuel demand and emissions by 1 %.
Car shared electric BC	5 %: transport, passenger car, large size, electric, GLO 15 %: transport, passenger car, medium size, electric, GLO	Yes: as there is no differentiation in ecoinvent of the car sizes, these have been self-calculated based on Del Pero et al. (Del Pero et al. 2020). Also, the electricity mix was changed to the German mix.

Process name	Based on ecoinvent process	Extent and reasoning behind modification
	80 %: transport, passenger car, small size, electric, GLO	For the best-case of a shared electric vehicle, the efficiency was also improved by reducing the electricity demand by 19 %.
Car shared electric WC	10 %: transport, passenger car, large size, electric, GLO 40 %: transport, passenger car, medium size, electric, GLO 50 %: transport, passenger car, small size, electric, GLO	Yes: as there is no differentiation in ecoinvent of the car sizes, these have been self-calculated based on Del Pero et al. (Del Pero et al. 2020). Also, the electricity mix was changed to the German mix. For the worst-case of a shared electric vehicle, the efficiency was also improved by reducing the electricity demand by 5 %.
Charging station	Market for charger, electric passenger car, GLO	Yes: scaled with the weighted of 70 kg of a charging station with two charging points (Mennekes Elektrotechnik GmbH & Co. KG).
Electricity demand, DE	Market for electricity, medium voltage, DE	No.
Electricity mix DE (Germany)	Market for electricity, medium voltage, DE	No.
Electricity RE DE	Electricity RE Wind + Electricity RE PV	For the renewable energy (RE) process, a mix of 34 % PV and 66 % wind from Germany is utilized.
Electricity RE PV	Electricity production, photovoltaic, 570kWp open ground installation, multi-Si, DE	Yes: scaled to newer GWP values; see section Renewable energy mix.
Electricity RE Wind	Electricity production, wind, >3MW turbine, onshore, DE	Yes: scaled to newer GWP values; see section Renewable energy mix.
E-scooter (kick roller) BC	Market for transport, passenger, electric scooter, GLO	Yes: the environmental impact of the big e-Scooter with a GWP of 0.056 kg CO_2 eq per pkm is scaled to 0.064 kg CO_2 eq per pkm (Severengiz et al., 2020) Also, the electricity mix was changed to the German mix.
E-scooter (kick roller) WC	Market for transport, passenger, electric scooter, GLO	the environmental impact of the big e-Scooter with a GWP of 0.056 kg CO_2 eq per pkm is scaled to 0.237 kg CO_2 eq per pkm (Severengiz et al., 2020) Also, the electricity mix was changed to the German mix.
Extrusion	Extrusion, plastic film | extrusion, plastic film | Cutoff, U - RER	No.
Gravel, crushed, CH	Market for gravel, crushed, CH	No.
HDPE	Polyethylene production, high density, granulate | polyethylene, high density, granulate | Cutoff, U - RER	No.
Heat demand, heat pump, DE	Heat production, air-water heat pump 10kW, Europe without Switzerland	Yes: modified to German electricity mix.
Injection moulding	Injection moulding | injection moulding | Cutoff, U - RER	No.
Landfill, CH	Market for process-specific burdens, inert material landfill, CH	No.
LDPE	Polyethylene production, low density, granulate | polyethylene, low density, granulate | Cutoff, U - RER	No.
LDPE	Polyethylene production, low density, granulate | polyethylene, low density, granulate | Cutoff, U - RER	No.
Office space (modified)	Building construction, hall, CH	Yes: the height of the hall was modified from 7 m to 3.5 m for an office building, resulting in process impacts being divided by a factor of 2. Also the value is adapted for an annual German case based on (Braune et al. 2021).
PA 6.6 production, RER	Nylon 6-6 production, RER	No.

Process name	Based on ecoinvent process	Extent and reasoning behind modification
Parking space	Market for gravel, crushed, CH + mastic asphalt production, CH	Yes: A parking space measures 2.65 m in width and 5.2 m in length, according to updated recommendations in Germany for 2023 (Forschungsgesellschaft für Straßen- und Verkehrswesen 2023). This results in an area of approximately 14 m^2 per parking space. The materials for constructing a parking space are estimated due to the unavailability of an ecoinvent process. A life cycle assessment (LCA) for parking lot pavements estimates that a conventional asphalt pavement requires a thickness of 10 cm of hot mix asphalt and 15 cm of crushed stone (Glick et al. 2013), which is adapted. The density of the hot mix asphalt is given with 2565 kg/m^3 and of the gravel with 1949 kg/m^3 (Glick et al. 2013). Long-life pavement in Germany has a design service life of 30-40 years, which is adapted to a mean value of 35 years (Wang et al. 2022).
PP	Polypropylene production, granulate | polypropylene, granulate | Cutoff, U - RER	No.
Recycled LDPE	Treatment of waste polyethylene, low density, pellets, recycling	Adopted from ecoinvent 3.11.
Recycled PET	Polyethylene terephthalate production, granulate, bottle grade, recycled | polyethylene terephthalate, granulate, bottle grade, recycled | Cutoff, U - CH	No.
Soil treatment, DE electricity	Primary data + Electricity mix DE (Germany)	Primary data from the company indicates that the electricity demand is 13.5 kWh/t. For the DE process, the German electricity mix is utilized.
Soil treatment, RE electricity	Primary data + Electricity RE DE	Primary data from the company indicates that the electricity demand is 13.5 kWh/t. For the renewable energy (RE) process, the process electricity RE DE is utilized.
Stretch blow moulding	Stretch blow moulding | stretch blow moulding | Cutoff, U - RER	No
Transport 3-/-4 Axis DE electric 0 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes, a 3-/4-axle truck with a maximum load of 15 tons is assumed. Electricity consumption is based on data from a manufacturing company and their calculation tool. Battery production will not be considered, as the manufacturer has not provided information about the battery's capacity and technology used. For 0 % loading, the electricity consumption is 0.80 kWh/km. For the DE process, the German electricity mix is utilized.
Transport 3-/-4 Axis DE electric 75 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes, a 3-/4-axle truck with a maximum load of 15 tons is assumed. Electricity consumption is based on data from a manufacturing company and their calculation tool. Battery production will not be considered, as the manufacturer has not provided information about the battery's capacity and technology used. For 75 % loading, the electricity consumption is 1.16 kWh/km. For the DE process, the German electricity mix is utilized.
Transport 3-/-4 Axis Diesel 0 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes: a 3-/4-axle truck with a maximum load of 15 tons is assumed. Diesel consumption is based on primary data from the current transport company and is adjusted along with emissions. For 0 % loading the diesel consumption is 23 l/100 km.
Transport 3-/-4 Axis Diesel 75 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes: a 3-/4-axle truck with a maximum load of 15 tons is assumed. Diesel consumption is based on primary data from the current transport company and is adjusted along with emissions.

Process name	Based on ecoinvent process	Extent and reasoning behind modification
		For 75 % loading the diesel consumption is 30 l/100 km.
Transport 3-/-4 Axis RE electric 0 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes, a 3-/4-axle truck with a maximum load of 15 tons is assumed. Electricity consumption is based on data from a manufacturing company and their calculation tool. Battery production will not be considered, as the manufacturer has not provided information about the battery's capacity and technology used. For 0 % loading, the electricity consumption is 0.80 kWh/km. For the renewable energy (RE) process, the process electricity RE DE is utilized.
Transport 3-/-4 Axis RE electric 75 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes, a 3-/4-axle truck with a maximum load of 15 tons is assumed. Electricity consumption is based on data from a manufacturing company and their calculation tool. Battery production will not be considered, as the manufacturer has not provided information about the battery's capacity and technology used. For 75 % loading, the electricity consumption is 1.16 kWh/km. For the renewable energy (RE) process, the process electricity RE DE is utilized.
Transport bike	Transport, passenger, bike, CH	No.
Transport Bus	Transport, regular bus, CH	No.
Transport electric bike DE modified	Transport, passenger, electric bike, CH	Yes: the electricity mix was changed to the German mix.
Transport Train DE	Transport, passenger train, DE	No.
Transport Tram DE modified	Transport, tram, CH	Yes: the electricity mix was changed to the German mix.
Transport TT DE electric 0 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes: a tractor-trailer with a maximum load of 28 tons is assumed. Electricity consumption is based on data from a manufacturing company and their calculation tool. Battery production will not be considered, as the manufacturer has not provided information about the battery's capacity and technology used. For 0 % loading, the electricity consumption is 0.82 kWh/km. For the DE process, the German electricity mix is utilized.
Transport TT DE electric 100 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes: a tractor-trailer with a maximum load of 28 tons is assumed. Electricity consumption is based on data from a manufacturing company and their calculation tool. Battery production will not be considered, as the manufacturer has not provided information about the battery's capacity and technology used. For 100 % loading, the electricity consumption is 1.62 kWh/km. For the DE process, the German electricity mix is utilized.
Transport TT DE electric 75 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes: a tractor-trailer with a maximum load of 28 tons is assumed. Electricity consumption is based on data from a manufacturing company and their calculation tool. Battery production will not be considered, as the manufacturer has not provided information about the battery's capacity and technology used. For 75 % loading, the electricity consumption is 1.51 kWh/km. For the DE process, the German electricity mix is utilized.
Transport TT Diesel 0 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes: a tractor-trailer with a maximum load of 28 tons is assumed. Diesel consumption is based on primary data from the current transport company and is adjusted along with emissions. For 0 % loading the diesel consumption is 26 l/100 km.

Process name	Based on ecoinvent process	Extent and reasoning behind modification
Transport TT Diesel 100 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes: a tractor-trailer with a maximum load of 28 tons is assumed. Diesel consumption is based on primary data from the current transport company and is adjusted along with emissions. For 0 % loading the diesel consumption is 38 l/100 km.
Transport TT Diesel 85 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes: a tractor-trailer with a maximum load of 28 tons is assumed. Diesel consumption is based on primary data from the current transport company and is adjusted along with emissions. For 85 % loading the diesel consumption is 36 l/100 km.
Transport TT RE electric 0 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes: a tractor-trailer with a maximum load of 28 tons is assumed. Electricity consumption is based on data from a manufacturing company and their calculation tool. Battery production will not be considered, as the manufacturer has not provided information about the battery's capacity and technology used. For 0 % loading, the electricity consumption is 0.82 kWh/km. For the renewable energy (RE) process, the process electricity RE DE is utilized.
Transport TT RE electric 100 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes: a tractor-trailer with a maximum load of 28 tons is assumed. Electricity consumption is based on data from a manufacturing company and their calculation tool. Battery production will not be considered, as the manufacturer has not provided information about the battery's capacity and technology used. For 100 % loading, the electricity consumption is 1.62 kWh/km. For the renewable energy (RE) process, the process electricity RE DE is utilized.
Transport TT RE electric 75 % load	Transport, freight, lorry 16-32 metric ton, EURO6, RER	Yes: a tractor-trailer with a maximum load of 28 tons is assumed. Electricity consumption is based on data from a manufacturing company and their calculation tool. Battery production will not be considered, as the manufacturer has not provided information about the battery's capacity and technology used. For 75 % loading, the electricity consumption is 1.51 kWh/km. For the renewable energy (RE) process, the process electricity RE DE is utilized.
Treatment of mixed plastic waste	Treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | Cutoff, U - GLO	No.
Walking	/	Walking is assumed to inherit no emissions.

C 3 Elaboration of each action

This section provides the action-specific background and quantification. Each action is documented with its literature basis, assumptions, and the three scenario states used in the methodology: status quo (baseline), best-case, and worst-case. In line with Section 2, the arithmetic mean of the best- and worst-case effects is used for normalization and scoring; the individual best/worst results are retained for sensitivity analysis. For each action, the LCI and LCIA results are summarized to give a concise overview of environmental effects across the five indicators (GWP, CED, RMI, land use, and water use). This information forms the basis of the corresponding action fact sheets.

To avoid duplication, general parameters and shared assumptions (e.g., baseline modal split, business trip activity, renewable electricity updates, background ecoinvent processes and UUIDs) are provided in Appendix C 2 and are not repeated here. Where an

action deviates from Appendix C 2 defaults, the deviation and its rationale are explicitly stated in the action entry.

For readability, actions are organized by the categories defined in Section 4.2.3: company mobility concepts (micro), miscellaneous company measures (micro), sharing concepts and industrial symbiosis (meso), and case-specific actions (micro and meso). Within each category, the action entries follow a consistent structure:

- Overview and applicability: brief description and applicability conditions.
- Assumptions and data: action-specific parameters, operative indicators (e.g., modal split), and any deviations from Appendix C 2.
- Scenarios: status quo, best-case, worst-case definitions.
- LCI: composition of the LCI.
- Fact sheet: summary of the action, indicator-level effects for each scenario, the average benefit of the best- and worst-case scenarios relative to the status quo, and notes on coherence and R-strategies.

C 3.1 Company mobility concepts (micro level)

This category covers actions that influence employee mobility and business travel within companies. Each action is quantified using shared parameters from Appendix C 2 (e.g., baseline modal split, commuting and business-trip activity, impact factors per mode, and background processes). Related work on shared mobility and ridesourcing has highlighted that such actions can substantially affect GHG emissions and that dynamic interactions between fleet composition, occupancy, and user choice can be important (Fernando et al. 2023). Coherence notes and possible interactions between the actions follow good practice in integrated travel demand management (Cairns et al. 2010; Günther et al. 2020).

C 3.2 Offer discounted public transport ticket

Overview and applicability

Employer-supported public transport subscriptions can shift commuting from private cars to public transport and reduce greenhouse gas emissions (Redman et al. 2013; Tchervenkov et al. 2021; Hahn et al. 2024). The employer may cover costs partially or fully (Tchervenkov et al. 2021). Applicability depends on local public transport accessibility and company policy.

Assumptions and data

The action is parameterized using evidence from Germany's €9 ticket (June to August 2022), which was widely used for commuting and daily trips (VDV et al. 2022) and aimed to encourage a shift from cars to public transport (Loder et al. 2024). Studies report measured substitution from car to public transport in Munich of 4-8 % (Loder et al. 2024) and 4-5 % across Germany (Liebensteiner et al. 2024); similar policy evaluations show car to public transport shifts when prices drop (Andor et al. 2025). This is consistent with

established fare elasticities and cross-elasticities for public transport demand (Paulley et al. 2006; Litman 2025). Public transport uptake also depends on accessibility (e.g., service frequency, spatial coverage (Geurs and van Wee 2004; Louen 2013). Price reductions can also induce additional trips (Liebensteiner et al. 2024), yet net greenhouse gas effects may still be beneficial; for example, a Brazilian free-fare policy reduced GHG emissions by 4.1 % (Da Mata et al. 2024). Yet, induced extra trips are not quantified here; the focus is the car to public transport substitution effect under discounted fares. The status-quo modal split for work commuting in Germany (Statistisches Bundesamt 2022), refined by car fuel-type shares (Kraftfahrt-Bundesamt 2024), is used as baseline.

Scenarios

- Status quo: employees commute according to the baseline modal split described in Appendix C 2, and no discounted job ticket is offered
- Best-case: the company offers a job ticket with value comparable to the €9 ticket. Public transport connections are good and usage is high, so we assume that 8 % of car trips shift to public transport (Loder et al. 2024), which reduces the total car share by 5.4 percentage points and increases bus/tram/train shares by the corresponding amount.
- Worst-case: the discounted ticket is offered but uptake is limited by weaker public transport connections and strong car preference. We therefore assume a 4 % shift from car to public transport (Loder et al. 2024; Liebensteiner et al. 2024).

Table C 9 summarizes the modal split by scenario.

Table C 9: Scenario modal split for work commuting: offer discounted public transport ticket.

Modal split for work-commuting	Status quo [%]	Best-case scenario [%]	Worst-case scenario [%]
Car, Private, Petrol	44.0	40.5	42.4
Car, Private, Diesel	21.0	19.3	20.2
Car, Private, BEV	3.0	2.8	2.9
Tram	5.0	6.9	6.0
Bus	4.0	5.6	4.8
Train	5.0	6.9	6.0
Bike (electric)	5.5	5.5	5.5
Bike (non-electric)	5.5	5.5	5.5
Walking	7.0	7.0	7.0

LCI summary

Table C 10reports activity per full-time employee per year (FTE/a). Distance is the annual commuting activity used for scaling (Appendix C 2).

Table C 10: Per-FTE annual activity and LCI inputs by scenario: discounted public transport ticket.

Process	Status quo	Best-case	Worst-case	Unit
Car Diesel DE	0.210	0.193	0.202	km
Car Electric DE	0.030	0.028	0.028	km
Car Petrol DE	0.440	0.405	0.424	km
Transport Train DE	0.050	0.069	0.060	pkm
Transport bike	0.055	0.055	0.055	pkm
Transport electric bike DE modified	0.055	0.055	0.055	pkm
Transport Bus	0.040	0.056	0.048	pkm
Transport Tram DE modified	0.050	0.069	0.060	pkm
Walking	0.070	0.070	0.070	pkm
Distance	6,880	6,880	6,880	km/a

Fact sheet

Figure C 1 summarizes the action within a fact sheet.

Offer discounted public transport ticket				
Category	Company mobility concepts			
Intervention/ goal of the action	Employer-supported public transport subscriptions can shift commuting from private cars to public transport and reduce greenhouse gas emissions. The employer may cover costs partially or fully.			
Operative indicator	Modal Split			
Functional unit (FU) / scaling	Full-time employee (FTE)			
Description of each scenario				
Status quo	Employees commute according to the baseline modal split described in Appendix B, and no discounted job ticket is offered.			
Best-case	The company offers a job ticket with value comparable to the €9 ticket. Public transport connections are good and usage is high, so we assume that 8 % of car trips shift to public, which reduces the total car share by 5.4 percentage points and increases bus/tram/train shares by the corresponding amount.			
Worst-case	The discounted ticket is offered but uptake is limited by weaker public transport connections and strong car preference. We therefore assume a 4 % shift from car to public transport.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	1,245	1,180	1,216	47
CED [MJ-eq]	17,980	17,120	17,590	625
RMI [kg]	1,474	1,407	1,442	50
Land use [-]	6,241	5,955	6,110	209
Water use [m^3-eq]	140	135	138	3.5
Miscellaneous				
Coherence notes	This action interacts with other mobility actions (e.g., ride sharing, bike leasing).			
Associated R-strategy	Rethink			

Figure C 1: Fact sheet of the action: offer discounted public transport ticket.

C 3.3 Use of e-bikes for short business trips

Overview and applicability

Providing e-bikes for short work-related trips can reduce emissions and demonstrate low-impact mobility options (Heinen et al. 2013; Roemer and Henseler 2022; Jenkins et al. 2022). Applicability depends on trip length distribution, cycling conditions, and organizational support (e.g., facilities, booking).

Assumptions and data

E-bike trips typically range between 3 and 11.5 km (Bourne et al. 2020), average around 11.4 km (Kämpfer et al. 2016), and are appropriate for German business trips of 5-15 km (Cristescu et al. 2021). Substitution potential from cars to e-bikes can be high (up to 86 % (Bourne et al. 2020)) and moderate from public transport (3-45 % (Bourne et al. 2020)). In

Germany, 41 % of car trips are theoretically replaceable by e-bikes across purposes (Kämpfer et al. 2016), and 47.1 % of respondents report frequent e-bike use for work tasks (Voeth et al. 2019). Life-cycle studies confirm that e-bikes have far lower per-km impacts than cars, and can deliver meaningful mitigation when substituting short car trips (Chester and Horvath 2009; Fishman and Cherry 2016; Brand et al. 2021). Uptake is facilitated by easy booking, security of storage, and showers/lockers (Prill 2015; Cristescu et al. 2021); seasonality and safety also influence use (Reynolds et al. 2009; Böcker and Thorsson 2014). We assume no change in regular bike or pedestrian shares, given small incremental benefits (Rérat et al. 2025). E-bike production is included in ecoinvent; incremental facilities are not quantified due to data limits.

Scenarios

- Status quo: no additional e-bikes are used for business trips, and the commuting modal split (Statistisches Bundesamt 2022) is used as a proxy for short-trip mode shares due to limited data on business-trip modes (DLR and DIW 2024).
- Best-case scenario: an easy booking system and optimal facilities are in place, and 10 % of business-trip activity (307 pkm/FTE/a) shifts to e-bikes, with 75 % of the reduction allocated from car travel and 25 % from public transport.
- Worst-case scenario: acceptance and facilities are limited, and 5 % of business-trip activity shifts to e-bikes, with the reduction split 50 %/50 % from car travel and public transport.

Table C 11 summarizes the modal split by scenario.

Table C 11: Scenario model split for business trips: use of e-bikes for short business trips.

Modal split for business trips	Status quo [%]	Best-case scenario [%]	Worst-case scenario [%]
Car, Private, Petrol	44.0	39.1	42.4
Car, Private, Diesel	21.0	18.7	20.2
Car, Private, BEV	3.0	2.7	2.9
Tram	5.0	4.1	4.1
Bus	4.0	3.3	3.3
Train	5.0	4.1	4.1
Bike (electric)	5.5	15.5	10.5
Bike (non-electric)	5.5	5.5	5.5
Walking	7.0	7.0	7.0

LCI summary

Table C 12 reports activity per full-time employee per year (FTE/a). Distance is the annual business trip activity used for scaling (Appendix C 2).

Table C 12: Per-FTE annual activity and LCI inputs by scenario: use of e-bikes for short business trips.

Process	Status quo	Best-case	Worst-case	Unit
Car Diesel DE	0.210	0.187	0.202	km
Car Electric DE	0.030	0.027	0.029	km
Car Petrol DE	0.440	0.391	0.424	km
Transport Train DE	0.050	0.041	0.041	pkm
Transport bike	0.055	0.055	0.055	pkm
Transport electric bike DE modified	0.055	0.155	0.105	pkm
Transport Bus	0.040	0.033	0.033	pkm
Transport Tram DE modified	0.050	0.041	0.041	pkm
Walking	0.070	0.070	0.070	pkm
Distance	307	307	307	km/a

Fact sheet

Figure C 2 summarizes the action in an action fact sheet.

Use of e-bikes for short business trips				
Category	Company mobility concepts			
Intervention/ goal of the action	Providing e-bikes for short work-related trips can reduce emissions and demonstrate low-impact mobility options.			
Operative indicator	Modal Split			
Functional unit (FU) / scaling	Full-time employee (FTE)			
Description of each scenario				
Status quo	No additional e-bikes are used for business trips, and the commuting modal split is used as a proxy for short-trip mode shares due to limited data on business-trip modes.			
Best-case	An easy booking system and optimal facilities are in place, and 10 % of business-trip activity (307 pkm/FTE/a) shifts to e-bikes, with 75 % of the reduction allocated from car travel and 25 % from public transport.			
Worst-case	Acceptance and facilities are limited, and 5 % of business-trip activity shifts to e-bikes, with the reduction split 50 %/50 % from car travel and public transport.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	56	50	53	3.8
CED [MJ-eq]	802	722	771	55
RMI [kg]	66	60	63	4.1
Land use [-]	278	251	268	19
Water use [m^3-eq]	6.3	5.8	6.1	0.3
Miscellaneous				
Coherence notes	This action interacts with other mobility actions of business trips (e.g., Use of BEV as company vehicles for business trips).			
Associated R-strategy	Rethink			

Figure C 2: Fact sheet of the action: use of the e-bikes for short business trips.

C 3.4 Offer bike leasing for employees

Overview and applicability

Employer bike-leasing (including e-bikes) can increase cycling for commuting and reduce car use (Synek and Koenigstorfer 2018; Deloitte 2025; ECF 2025). Applicability depends on uptake, cycling safety, and workplace support.

Assumptions and data

Cycling is practical for 5-13 km/day (Lopez et al. 2017; Castro et al. 2019; Banerjee et al. 2022), and in German conditions bikes can outperform cars/public transport up to 5.5 km and pedelecs up to 7.5 km (Umweltbundesamt 2014). The UK Cycle to Work scheme reports 24 % daily and 56 % two–three times weekly use post-enrolment (Caulfield and Leahy 2011); German leasing users choose e-bikes in ~80 % of cases (Deloitte 2025). Facilities can meaningfully increase cycling: outdoor parking (+8.6 %), secured indoor

(+13.8 %), indoor + showers (+22.4 %) (Wardman et al. 2007). Broader reviews support workplace measures (Geus et al. 2008; Pucher et al. 2010; Dubuy et al. 2013; Patterson et al. 2020), although some studies find limited effects (Handy and Xing 2011; Bopp et al. 2012; Nehme et al. 2017). Bike production is included in ecoinvent; incremental facilities are not quantified due to data limits.

Scenarios

- Status quo: current German participation (4.3 % of all employees; 10.7 % among those offered leasing) is embedded in the baseline modal split, and we assume a projected active user share of 5.0 % by 2026 (Deloitte 2025).
- Best-case scenario: the program is offered and strongly promoted, cycling safety is improved (e.g., protected lanes and traffic calming (Li et al. 2019; Ferenchak and Marshall 2025)), and workplaces provide secure parking, showers, lockers, and repair services (Wardman et al. 2007; Geus et al. 2008; Pucher et al. 2010; Dubuy et al. 2013; Patterson et al. 2020). Under these conditions, we assume an active user share of 10 %, with substitution primarily from car travel due to insufficient data on differential substitution rates.
- Worst-case scenario: promotion and support are limited, participation barriers are higher, and we assume an active user share of 7.5 %, with substitution split 50 %/50 % from cars and public transport.

Table C 13 summarizes the modal split by scenario.

Table C 13: Scenario modal split for work commuting: offer bike leasing for employees.

Modal split for work-commuting	Status quo [%]	Best-case scenario [%]	Worst-case scenario [%]
Car, Petrol	44.0	41.2	43.4
Car, Diesel	21.0	19.7	20.7
Car, BEV	3.0	2.8	3.0
Tram	5.0	5.0	4.7
Bus	4.0	4.0	3.7
Train	5.0	5.0	4.7
Bike (electric)	5.5	8.9	6.9
Bike (non-electric)	5.5	6.4	5.9
Walking	7.0	7.0	7.0

LCI summary

Table C 14 reports activity per full-time employee per year (FTE/a). Distance is the annual commuting activity used for scaling (Appendix C 2).

Table C 14: Per-FTE annual activity and LCI inputs by scenario: offer bike leasing for employees.

Process	Status quo	Best-case	Worst-case	Unit
Car Diesel DE	0.210	0.197	0.207	km
Car Electric DE	0.030	0.028	0.030	km
Car Petrol DE	0.440	0.412	0.434	km
Transport Train DE	0.050	0.050	0.047	pkm
Transport bike	0.055	0.064	0.059	pkm
Transport electric bike DE modified	0.055	0.089	0.069	pkm
Transport Bus	0.040	0.040	0.037	pkm
Transport Tram DE modified	0.050	0.050	0.047	pkm
Walking	0.070	0.070	0.070	pkm
Distance	6,880	6,880	6,880	km/a

Fact sheet

Figure C 3 summarizes the action in an action fact sheet.

Offer bike leasing for employees				
Category	Company mobility concepts			
Intervention/ goal of the action	Employer bike leasing (including e-bikes) can increase cycling for commuting and reduce car use.			
Operative indicator	Modal Split			
Functional unit (FU) / scaling	Full-time employee (FTE)			
Description of each scenario				
Status quo	Current German participation (4.3 % of all employees; 10.7 % among those offered leasing) is embedded in the baseline modal split, and we assume a projected active user share of 5.0 % by 2026.			
Best-case	The program is offered and strongly promoted, cycling safety is improved (e.g., protected lanes and traffic calming), and workplaces provide secure parking, showers, lockers, and repair services. Under these conditions, we assume an active user share of 10 %, with substitution primarily from car travel due to insufficient data on differential substitution rates.			
Worst-case	Promotion and support are limited, participation barriers are higher, and we assume an active user share of 7.5 %, with substitution split 50 %/50 % from cars and public transport.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	1,245	1,178	1,227	43
CED [MJ-eq]	17,980	17,028	17,720	606
RMI [kg]	1,474	1,401	1,455	46
Land Use [-]	6,241	5,920	6,152	205
Water Use [m^3-eq]	140	134	139	3.5
Miscellaneous				
Coherence notes	This action interacts with other mobility actions (e.g., ride sharing, discounted public transport tickets).			
Associated R-strategy	Rethink			

Figure C 3: Fact sheet of the action: offer bike leasing for employees.

C 3.5 Promotion of ride sharing

Overview and applicability

Ride sharing increases vehicle occupancy on repetitive commuting routes, reducing emissions and time losses (e.g., parking search) (Yin et al. 2018; AlQuhtani 2022). Applicability depends on synchronized/flexible work hours, route matching, and acceptable detours (Mühlethaler et al. 2011; Abedin et al. 2020; Mitropoulos et al. 2021). Awareness campaigns and social norms also matter (Cheah et al. 2022). It is primarily assumed that this action is implemented within a single company, categorizing it as a micro-level action.

Assumptions and data

Baseline car occupancy is 1.4 (Umweltbundesamt 2023). A 5-minute detour tolerance at a mean city speed of 27.8 km/h implies ~2.3 km average detour (Mühlethaler et al. 2011; Statista GmbH 2025a). About 5 % of commutes are as carpool passengers in Germany (infas Institut für angewandte Sozialwissenschaft GmbH 2018). A Swiss multi-company study estimated theoretical car distance savings from ride sharing between 20 % and 47 %, depending on participation and synchronization (Mühlethaler et al. 2011). Reviews of dynamic ridesharing programs identify platform design, schedule coordination, and participation barriers as key determinants of realized benefits (Chan and Shaheen 2012; Furuhata et al. 2013; Mitropoulos et al. 2021; Bhappu et al. 2022).

Scenarios

- Status quo: employees commute according to the baseline activity parameters, approximately 5 % travel as carpool passengers, and typical detours average ~2.3 km with an occupancy of 1.4 persons per car and an average commute of 17.2 km.
- Best-case scenario: the company or industrial park provides an easy-to-use matching platform, runs regular awareness campaigns, and work times are well synchronized; under these conditions, we assume a 47 % reduction in car commuting distance based on the theoretical potential reported by Mühlethaler et al. (Mühlethaler et al. 2011).
- Worst-case scenario: acceptance is lower, work schedules vary, and route matching is weaker, and we therefore assume a 20 % reduction in car commuting distance (Mühlethaler et al. 2011).

LCI summary

Table C 15 reports activity per full-time employee per year (FTE/a). Distance is the annual commuting activity used for scaling (Appendix C 2).

Table C 15: Per-FTE annual activity and LCI inputs by scenario: promotion and ride sharing.

Process	Status quo	Best-case	Worst-case	Unit
Car Diesel DE	0.210	0.111	0.168	km
Car Electric DE	0.030	0.016	0.024	km
Car Petrol DE	0.440	0.233	0.352	km
Transport Train DE	0.050	0.050	0.050	pkm
Transport bike	0.055	0.055	0.055	pkm
Transport electric bike DE modified	0.055	0.055	0.055	pkm
Transport Bus	0.040	0.040	0.040	pkm
Transport Tram DE modified	0.050	0.050	0.050	pkm
Walking	0.070	0.070	0.070	pkm
Distance	6,880	6,880	6,880	km/a

Fact sheet

Figure C 4 summarizes the action in an action fact sheet.

Promotion of ride sharing				
Category	Company mobility concepts			
Intervention/ goal of the action	Ride sharing increases vehicle occupancy on repetitive commuting routes, reducing emissions and time losses.			
Operative indicator	Modal Split			
Functional unit (FU) / scaling	Full-time employee (FTE)			
Description of each scenario				
Status quo	Employees commute according to the baseline activity parameters, approximately 5 % travel as carpool passengers, and typical detours average ~2.3 km with an occupancy of 1.4 persons per car and an average commute of 17.2 km.			
Best-case	The company or industrial park provides an easy to use matching platform, runs regular awareness campaigns, and work times are well synchronized; under these conditions, we assume a 47 % reduction in car commuting distance based on the theoretical potential reported by Mühlethaler et al. (2011).			
Worst-case	Acceptance is lower, work schedules vary, and route matching is weaker, and we therefore assume a 20 % reduction in car commuting distance (Mühlethaler et al. 2011).			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	1,245	699	1,013	389
CED [MJ-eq]	17,980	10,182	14,662	5,558
RMI [kg]	1,474	842	1,205	451
Land Use [-]	6,241	3,555	5,098	1,915
Water Use [m^3-eq]	140	82	115	41
Miscellaneous				
Coherence notes	This action interacts with other mobility actions (e.g., discounted public transport tickets, bike leasing).			
Associated R-strategy	Rethink			

Figure C 4: Fact sheet of the action: promotion of ride sharing.

C 3.6 Use of BEV as company vehicles for business trips

Overview and applicability

Electrifying the company fleet can reduce emissions from business travel and support climate goals (Yang et al. 2021; Bongard and Rosin 2023). Applicability depends on trip patterns (distance and frequency), fleet composition and vehicle sizes, charging availability at workplaces and destinations, and operational policies (vehicle assignment, booking, and charging).

Assumptions and data

Approximately 0.12 fleet cars per employee are assumed (Statista GmbH 2018). One charging point is planned per BEV. Business-trip activity is 265 pkm/FTE/a (86.2 % of

business-trip pkm by car (DLR and DIW 2024)), with a occupancy of 1.4 (Umweltbundesamt 2023). One workplace charging point is planned per BEV used for business trips, aligning with operational availability needs. BEV climate performance depends on the electricity mix (Plötz et al. 2017; Burchart and Przytuła 2024; Aryan et al. 2025). Yet, electricity sourcing is addressed by a separate action (use of renewable energies). Scenario variation focuses on vehicle sizes and efficiency, grounded in segment-level consumption differences (Ellingsen et al. 2016; Del Pero et al. 2020; IEA 2024).

Shared fleets tend to be small: for example, a German car-sharing operator's fleet comprises ~80 % small cars (cambio Mobilitätsservice GmbH & Co. KG 2019), whereas the German market average for small cars is ~18 % (Statista GmbH 2024b). Because ecoinvent does not provide distinct BEV processes by size (unlike combustion vehicles), we adjust BEV electricity use by vehicle size assumptions (e.g., curb weights of 1,200 kg, 1,400 kg, and 2,000 kg) consistent with size-dependent consumption (Del Pero et al. 2020). Data support scenario efficiency gains of 19 % (best-case) and 5 % (worst-case) relative to a baseline BEV use pattern, reflecting smaller vehicle share, optimized driving, and real-world consumption within the observed range (Weiss et al. 2024).

Scenarios

- Status quo: business trips are undertaken with the German vehicle fuel mix (Kraftfahrt-Bundesamt 2024), the existing size distribution (27 % small, 57 % medium, 16 % large), and approximately 0.0018 charging points per employee are required.
- Best-case scenario: all business trips are undertaken with BEVs, the fleet is optimized to small cars (80 % small, 15 % medium, 5 % large), and we assume a 19 % reduction in electricity use relative to the status quo. To support the BEV fleet during business trips, approximately 0.0517 charging points per employee are required.
- Worst-case scenario: all business trips are undertaken with BEVs, the fleet comprises 50 % small, 40 % medium, and 10 % large vehicles, electricity use is reduced by 5 % relative to the status quo, and approximately 0.0517 charging points per employee are required; the current grid mix is assumed for charging.

Table C 16: Scenario vehicle mix and efficiency assumptions: use of BEV as company vehicles for business trips.

Scenario	Vehicle fuel type	Car size in fleet		Efficiency gains
		Size	Share [%]	
Status Quo	German vehicle mix	Small	27	-
		Medium	57	
		Large	16	
Best-case	100 % BEV	Small	80	Electricity use -19 %
		Medium	15	
		Large	5	
Worst-case	100 % BEV	Small	50	Electricity use -5 %
		Medium	40	
		Large	10	

LCI summary

Table C 17 reports activity per full-time employee per year (FTE/a). Distance is the annual business trip activity used for scaling (Appendix C 2).

Table C 17: Per-FTE annual activity and LCI inputs by scenario: use of BEV as company vehicles for business trips.

Process	Status quo	Best-case	Worst-case	Unit
Car Diesel BT SQ	0.310	0.000	0.000	km
Car Electric BT SQ	0.040	0.000	0.000	km
Car Electric BT BC	0.000	1.000	0.000	km
Car Electric BT WC	0.000	0.000	1.000	km
Car Petrol BT SQ	0.650	0.000	0.000	km
Distance	265	265	265	km/a
Charging Stations	0.0018	0.0517	0.0517	n/a

Fact sheet

Figure C 5 summarizes the action in an action fact sheet.

Use of BEV as company vehicles for business trips				
Category	Company mobility concepts			
Intervention/ goal of the action	Electrifying the company fleet can reduce emissions from business travel and support climate goals.			
Operative indicator	Modal Split			
Functional unit (FU) / scaling	Full-time employee (FTE)			
Description of each scenario				
Status quo	Business trips are undertaken with the German vehicle fuel mix, the existing size distribution (27 % small, 57 % medium, 16 % large), and approximately 0.0018 charging points per employee are required.			
Best-case	All business trips are undertaken with BEVs, the fleet is optimized to small cars (80 % small, 15 % medium, 5 % large), and we assume a 19 % reduction in electricity use relative to the status quo. To support the BEV fleet during business trips, approximately 0.0517 charging points per employee are required.			
Worst-case	All business trips are undertaken with BEVs, the fleet comprises 50 % small, 40 % medium, and 10 % large vehicles, electricity use is reduced by 5 % relative to the status quo, and approximately 0.0517 charging points per employee are required; the current grid mix is assumed for charging.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	62	44	48	16
CED [MJ-eq]	889	737	813	114
RMI [kg]	73	130	136	-60
Land Use [-]	304	303	320	-7.5
Water Use [m^3-eq]	6.7	13	14	-6.6
Miscellaneous				
Coherence notes	This action interacts with other mobility actions (e.g. use of e-bikes for short business trips) and the action “use of renewable energies” for operating the BEV.			
Associated R-strategy	Rethink			

Figure C 5: Fact sheet of the action: use of BEV as company vehicles for business trips.

C 3.7 The company provides an increased number of charging stations for electric vehicles with charging discount

Overview and applicability

Expanding workplace charging and offering discounted charging can increase BEV adoption and use, addressing availability and cost barriers (Burra et al. 2024; Tröger and Preuß 2025). Applicability depends on codes and standards (EPBD; GEIG), parking capacity, and company strategy.

Assumptions and data

A charging point serves one vehicle at a time (Netherlands Enterprise Agency 2019). Most charging stations have two points; we assume two points per station (Statista GmbH 2025b). Electrical infrastructure (e.g., cabling) is not modeled due to data gaps. GEIG requires at least one charging point for more than six parking spaces in new non-residential buildings (Bundestag 2021). With 68 % of employees commuting by car (Statistisches Bundesamt 2022), we assume ~0.68 parking spaces per employee; firms with ≥9 employees have ≥6 spaces under GEIG (Bundestag 2021). Workplace charging is associated with higher electric vehicle adoption and driven electric distance (Burra et al. 2024), and other studies show that charging availability causally increases adoption (Guo et al. 2024). Financial incentives (including electricity price discounts) and access to charging are key drivers of EV uptake and usage patterns (Hardman et al. 2018; Steren et al. 2025; Luo and Wang 2025).

Scenarios

- Status quo: the BEV share is assumed at 7 % of the passenger car mix to reflect new-building compliance. No charging discounts are offered, there are approximately 0.68 parking spaces per employee, and we assume one charging point per six parking spaces, which yields approximately 0.056 charging points per employee.
- Best-case scenario: the company offers a 75 % discount on charging electricity costs, the BEV share reaches 35 % of the passenger car mix, there are approximately 0.68 parking spaces per employee, and we assume one charging point per three parking spaces, which yields approximately 0.113 charging points per employee.
- Worst-case scenario: the company offers a 35 % charging discount, the BEV share reaches 25 % of the passenger car mix, there are approximately 0.68 parking spaces per employee, and one charging point per three parking spaces is assumed, which also yields approximately 0.113 charging points per employee.

LCI summary

Table C 18 reports activity per full-time employee per year (FTE/a). Distance is the annual commuting activity used for scaling (Appendix C 2).

Table C 18: Per-FTE annual activity and LCI inputs by scenario: the company provides an increase number of charging stations for electric vehicles with charging discount.

Process	Status quo	Best-case	Worst-case	Unit
Car Diesel DE	0.203	0.142	0.165	km
Car Electric DE	0.050	0.240	0.170	km
Car Petrol DE	0.427	0.298	0.345	km
Distance	6,880	6,880	6,880	km/a
Charging Stations	0.057	0.113	0.113	n/a

Fact sheet

Figure C 6 summarizes the action in an action fact sheet.

The company provides an increased number of charging stations for electric vehicles with charging discount				
Category	Company mobility concepts			
Intervention/ goal of the action	Expanding workplace charging and offering discounted charging can increase BEV adoption and use, addressing availability and cost barriers.			
Operative indicator	Modal Split			
Functional unit (FU) / scaling	Full-time employee (FTE)			
Description of each scenario				
Status quo	The BEV share is assumed at 7 % of the passenger car mix to reflect new building compliance. No charging discounts are offered, there are approximately 0.68 parking spaces per employee, and we assume one charging point per six parking spaces, which yields approximately 0.056 charging points per employee.			
Best-case	The company offers a 75 % discount on charging electricity costs, the BEV share reaches 35 % of the passenger car mix, there are approximately 0.68 parking spaces per employee, and we assume one charging point per three parking spaces, which yields approximately 0.113 charging points per employee.			
Worst-case	The company offers a 35 % charging discount, the BEV share reaches 25 % of the passenger car mix, there are approximately 0.68 parking spaces per employee, and one charging point per three parking spaces is assumed, which also yields approximately 0.113 charging points per employee.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	1,160	1,027	1,081	106
CED [MJ-eq]	16,650	15,482	15,985	916
RMI [kg]	1,410	1,521	1,503	-102
Land Use [-]	5,748	5,554	5,648	147
Water Use [m^3-eq]	131	153	147	-19
Miscellaneous				
Coherence notes	This action interacts with other mobility actions (e.g. use of BEV as company vehicles for business trips) and the action “use of renewable energies” for operating the charging stations.			
Associated R-strategy	/			

Figure C 6: Fact sheet of the action: the company provides an increased number of charging stations for electric vehicles with charging discount.

C 3.8 Miscellaneous (micro level)

This category covers company-internal measures beyond employee mobility, focusing here on freight/operational transport and on-site electricity supply. Each action is

quantified using shared parameters from Appendix C 2 (e.g., background ecoinvent processes and UUIDs, renewable electricity updates, functional units).

C 3.9 Use of electric trucks in operational transport

Overview and applicability

This action replaces vehicles in operational transport with battery-electric trucks on specified routes. Battery-electric transport vehicles are more energy-efficient at the vehicle level and can reduce greenhouse gas emissions, subject to the electricity mix and load factors (Greschner Farkavcova et al. 2018; Elangovan et al. 2021). Applicability depends on route lengths, payload requirements, availability of depot or opportunity charging, and vehicle offerings in the relevant classes (e.g., 3/4-axle rigid, tractor–trailer).

Assumptions and data

Annual transport activity is defined by case study 3 (soil treatment - ST) and its transport operations. The transport distances are calculated as the mean between best-case and worst-case scenarios, resulting in 50 % of transports going to Aldenhoven and 50 % to Horm. Electricity demand for battery electric transport vehicles is sourced from a manufacturer-provided calculator based on vehicle type and load: for 3/4 axle vehicles, 0.80 kWh/km (unloaded) and 1.16 kWh/km (loaded at 11 t); for tractor-trailers, 0.82 kWh/km (unloaded), 1.51 kWh/km (loaded at 24 t), and 1.63 kWh/km (loaded at 28 t). A charging efficiency of 95 % is applied, as indicated by the manufacturer. Electricity mixes follow Appendix C 2: the “renewable electricity” case uses the adapted German onshore wind/PV processes and scaling factors, while the “German electricity mix” case uses the grid process.

Scenarios

- Status quo: operational transport is performed with diesel transport vehicles as outlined in the “treatment of soil instead of landfill” action. No electrification is assumed.
- Best-case scenario: the same transport work is performed by electric transport vehicles charged with the renewable electricity mix modeled in Appendix C 2 (onshore wind/PV adaptation).
- Worst-case scenario: electric transport vehicles are charged with the current German grid mix rather than the renewable mix.

LCI summary

The functional unit is one transport kilometer. For transparency, Table C 19 reports the share of annual transport distance allocated to each directional leg and technology by scenario. Shares sum to 1.0 within each scenario.

Table C 19: Per-km LCI inputs and activity shares by scenario: use of electric trucks in operational transport.

Process	Status quo	Best-case	Worst-case	Unit
Transport Aachen -> ST, 3/4A, 75 % load, Diesel	0.466	0.000	0.000	Share
Transport ST -> Aachen 3/4A, 75 % load, Diesel	0.466	0.000	0.000	Share
Transport Aachen -> ST, 3/4A, 75 % load, Electric RE	0.000	0.466	0.000	Share
Transport ST -> Aachen 3/4A, 75 % load, Electric RE	0.000	0.466	0.000	Share
Transport Aachen -> ST, 3/4A, 75 % load, Electric DE	0.000	0.000	0.466	Share
Transport ST -> Aachen 3/4A, 75 % load, Electric DE	0.000	0.000	0.466	Share
Transport ST -> Aldenhoven, TT 100 % load, Diesel	0.011	0.000	0.000	Share
Transport Aldenhoven -> ST, TT 0 % load, Diesel	0.011	0.000	0.000	Share
Transport ST -> Aldenhoven, TT 100 % load, Electric RE	0.000	0.011	0.000	Share
Transport Aldenhoven -> ST, TT 0 % load, Electric RE	0.000	0.011	0.000	Share
Transport ST -> Aldenhoven, TT 100 % load, Electric DE	0.000	0.000	0.011	Share
Transport Aldenhoven -> ST, TT 0 % load, Electric DE	0.000	0.000	0.011	Share
Transport ST -> Horm TT, 100 % load, Diesel	0.023	0.000	0.000	Share
Transport Horm -> ST TT, 0 % load, Diesel	0.023	0.000	0.000	Share
Transport ST -> Horm TT, 100 % load, Electric RE	0.000	0.023	0.000	Share
Transport Horm -> ST TT, 0 % load, Electric RE	0.000	0.023	0.000	Share
Transport ST -> Horm TT, 100 % load, Electric DE	0.000	0.000	0.023	Share
Transport Horm -> ST TT, 0 % load, Electric DE	0.000	0.000	0.023	Share
Transport distance	343,500	343,500	343,500	km/a

Fact sheet

Figure C 7 summarizes the action in an action fact sheet.

Use of electric trucks in operational transport				
Category	Miscellaneous			
Intervention/ goal of the action	This action replaces vehicles in operational transport with battery electric trucks on specified routes. Battery electric transport vehicles are more energy efficient at the vehicle level and can reduce greenhouse gas emissions, subject to the electricity mix and load factors.			
Operative indicator	Type of transportation			
Functional unit (FU) / scaling	Transport distance (km)			
Description of each scenario				
Status quo	Operational transport is performed with diesel transport vehicles as outlined in the "soil treatment instead of landfill" action. No electrification is assumed.			
Best-case	The same transport work is performed by electric transport vehicles charged with the renewable electricity mix modeled in Appendix B (onshore wind/PV adaptation).			
Worst-case	Electric transport vehicles are charged with the current German grid mix rather than the renewable mix.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	1.1	0.07	0.51	0.80
CED [MJ-eq]	16	5.6	10	7.7
RMI [kg]	0.57	0.30	0.65	0.10
Land Use [-]	2.3	4.8	2.7	-1.4
Water Use [m^3-eq]	0.03	0.05	0.11	-0.05
Miscellaneous				
Coherence notes	When combining this action with "soil treatment instead of landfill," ensure that distance reductions are applied before technology substitution to avoid double counting. Ensure electricity mix assumptions align with the "use of renewable energies" action. The specified values are calculated by dividing the absolute effects by the total distance of 343,500 km per year. Consequently, these values may not be universally applicable due to their dependence on this specific case study.			
Associated R-strategy	Rethink			

Figure C 7: Fact sheet of the action: use of electric trucks in operational transport.

C 3.9.1 Use of renewable energies

Overview and applicability

This action replaces the German grid electricity with renewable electricity. Renewable supply generally improves several environmental indicators (e.g., GWP, water use) but can increase land use depending on technology and siting (Mekonnen et al. 2015; Junne et al. 2020; Baumgärtner et al. 2021; Bolinger and Bolinger 2022). Applicability depends on the company's procurement pathways (PPAs, green tariffs) and on-site/off-site installation options.

Assumptions and data

Background electricity processes follow Appendix C 2: onshore wind and PV processes from ecoinvent are updated to reflect current German performance (scaling factors derived from national data). The status-quo grid mix uses the ecoinvent process.

Scenarios

- Status quo: the site is powered by the German electricity mix.
- Best-case scenario: the site is supplied with onshore wind electricity using the adapted ecoinvent process for Germany (Appendix C 2), representing a lower-impact renewable option under GWP and often water use.
- Worst-case scenario: the site is supplied with PV electricity using the adapted PV process for Germany. This may have higher land use intensity while still reducing GWP relative to the grid.

LCI summary

The functional unit is 1 kWh of electricity demand. Table C 20 reports the electricity source mix per scenario.

Table C 20: Per-kWh LCI inputs by scenario: use of renewable energies.

Process	Status quo	Best-case	Worst-case	Unit
Electricity DE	1	0	0	Share
Electricity RE Wind	0	1	0	Share
Electricity RE PV	0	0	1	Share

Fact sheet

Figure C 8 summarizes the action in an action fact sheet.

Use of renewable energies				
Category	Miscellaneous			
Intervention/ goal of the action	This action replaces the German grid electricity with renewable electricity. Renewable supply generally improves several environmental indicators (e.g., GWP, water use) but can increase land use depending on technology and siting.			
Operative indicator	Energy demand			
Functional unit (FU) / scaling	Energy demand of the site (kWh)			
Description of each scenario				
Status quo	The site is powered by the German electricity mix.			
Best-case	The site is supplied with onshore wind electricity using the adapted ecoinvent process for Germany (Appendix B), representing a lower impact renewable option under GWP and often water use.			
Worst-case	The site is supplied with PV electricity using the adapted PV process for Germany. This may have higher land use intensity while still reducing GWP relative to the grid.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	0.42	0.02	0.06	0.38
CED [MJ-eq]	8.6	4.1	4.7	4.2
RMI [kg]	0.41	0.10	0.09	0.31
Land Use [-]	1.1	0.19	8.2	3.1
Water Use [m^3-eq]	0.09	0.01	0.08	0.04
Miscellaneous				
Coherence notes	This action interacts with any electrification measures (e.g., BEVs for business trips; electric transport vehicles). Ensure the same electricity mix is used across actions for consistent LCIA. When analyzing trade-offs, note that PV typically entails higher land use impacts than wind for the same kWh in the German context.			
Associated R-strategy	Rethink			

Figure C 8: Fact sheet of the action: use of renewable energies.

C 3.10 Sharing concepts and industrial symbiosis (meso level)

This category covers actions implemented at the industrial park level that enable shared use of assets and services across companies (e.g., car sharing, bike/e-scooter sharing, shared parking, shared daycare, shared canteen) and cross-company space optimization (desk sharing across firms). Each action is quantified using shared parameters from Appendix C 2 (e.g., baseline modal split, mode-specific impact factors, background ecoinvent processes).

C 3.10.1 Implementing a car sharing possibility by an established provider for employees and companies of the industrial park

Overview and applicability

Providing car-sharing stations operated by an established provider within the industrial park enables employees and firms to access shared vehicles, including BEVs. Car sharing can shift modal shares for commuting and business trips, reduce private car use, raise vehicle occupancy, and favor newer, smaller vehicles, improving energy efficiency (Amatuni et al. 2020; Arbeláez Vélez and Plepys 2021; Witte et al. 2024; van der Linden et al. 2025). Applicability depends on provider availability, station siting, vehicle mix, pricing, and workplace integration.

Assumptions and data

Car sharing tends to introduce newer, more efficient vehicles into local fleets and increases the share of small cars relative to private ownership (Arbeláez Vélez and Plepys 2021). In Germany, approximately 20 % of car-sharing cars were electric in 2023 (Statista GmbH 2024a). To reflect efficiency and size effects, the vehicle mix and per-km energy/fuel assumptions follow Verkic et al. (Verkic et al. 2025b), with best-/worst-case efficiency gains and size distributions adopted accordingly. For commuting and private car-sharing mode shares, Netherland-based studies (Amatuni et al. 2020; Witte et al. 2024; van der Linden et al. 2025) are adapted to German context by scaling to the German baseline modal split (Statistisches Bundesamt 2022) and fuel-type shares (Kraftfahrt-Bundesamt 2024). For business trips, the annual activity is set at 265 pkm/FTE/a (DLR and DIW 2024), and scenarios differentiate car-sharing vehicle fuel mix (BEV vs. petrol/diesel) and size profile.

Scenarios

The scenarios are summarized as follows:

- Status quo: no car-sharing station is available within the industrial park. Employees commute according to the German baseline modal split (Statistisches Bundesamt 2022) with the current fuel-type shares (Kraftfahrt-Bundesamt 2024), and there is no on-site private car sharing. Business trips are undertaken with privately owned cars following the German vehicle mix; for the 265 pkm/FTE/a used to quantify business trips (DLR and DIW 2024), the modal split is 65 % petrol, 31 % diesel, and 4 % BEV, with no shared vehicles. Vehicle size distributions reflect the German average (27 % small, 57 % medium, 16 % large), and no efficiency gains from shared fleets are applied.
- Best-case scenario: an established provider installs and operates car-sharing stations in the industrial park, and adoption is high. The change is modeled across three domains:
    - Work commuting: The car-sharing station induces a shift from private cars to shared BEVs. The commuting modal split is adapted from Netherlands-based studies (Witte et al. 2024; van der Linden et al. 2025) to the German baseline and yields 15 % shared BEVs, with corresponding reductions in

private petrol and diesel car shares; shared petrol/diesel cars are not used in this best-case commuting scenario. Public transport shares (bus/tram/train) adjust downward per the adapted studies (see Table C 22).
    - Private car sharing: Following Amatuni et al. (Amatuni et al. 2020) and adaptations to the German context, employees add 1,650 pkm per year and FTE of private car-sharing trips. The private car-sharing modal split reflects a 20 % BEV share in car-sharing fleet composition (Statista GmbH 2024a), with the remainder split between petrol and diesel, and with increased shares of rail and bus trips in the overall private travel pattern (see Table C 23).
    - Business trips: All business trips (265 pkm/FTE/a) are made with shared BEVs only. This distinguishes the car-sharing business-trip best-case from the separate BEV-as-company-car action and isolates the effect of using shared BEVs across firms (see Table C 24).

  Across all domains in the best-case, efficiency improvements due to car sharing are applied as adopted from Verkic et al. (Verkic et al. 2025b): for shared fleets the size distribution shifts to 80 % small, 15 % medium, and 5 % large vehicles, and per-kilometer electricity use for BEVs is reduced by 19 % relative to the reference BEV use pattern; for combustion vehicles (where present in non-commuting domains), per-kilometer fuel and associated elementary flows are reduced by 5 % (see Table C 21). To support increased BEV use, charging station needs are calculated from the commuting BEV share (15 %) and a load factor of 0.5, resulting in ~0.005 charging stations per employee per year.
- Worst-case scenario: the car-sharing station is implemented but adoption is limited. The change is modeled across the same three domains:
    - Work commuting: The commuting modal split reflects a modest shift to car sharing across all fuel types, with shared BEV at ~3.5 %, shared petrol ~2.4 %, and shared diesel ~1.1 % (adapted from van der Linden et al. (van der Linden et al. 2025) and Witte et al. (Witte et al. 2024)); private petrol and diesel shares decline slightly relative to the baseline. Public transport shares adjust minimally (see Table C 22).
    - Private car sharing: Employees add 770 pkm/FTE/a of private car-sharing trips (Amatuni et al. 2020), with the car-sharing BEV share set at 20 % and the remainder split between petrol and diesel, and with modest increases in rail and bus shares (see Table C 23).
    - Business trips: Shared vehicles for business trips are mixed by fuel type: 50 % BEV, 34 % petrol, and 16 % diesel (see Table C 24).

  Across all domains in the worst-case, shared fleet efficiency improvements are smaller: the size distribution is 50 % small, 40 % medium, 10 % large; BEV electricity use per kilometer is reduced by 5 % relative to the reference BEV use pattern; and (where present) combustion vehicle fuel and elementary flows are reduced by 1 % (see Table C 21). Charging station needs are derived from the commuting BEV share (3.5 %) and a load factor of 0.75, resulting in ~0.002 charging stations per employee per year.

Scenario vehicle use and efficiency (adopted from Verkic et al. (2025b)) is shown in Table C 21.

Table C 21: Scenario parameters: vehicle size mix and efficiency gains with car sharing.

Usage	Car size in fleet		Efficiency gains
	Size	Share [%]	
Car, Private, Petrol	Small	27	-
	Medium	57	
	Large	16	
Car, Private, Diesel	Small	27	-
	Medium	57	
	Large	16	
Car, Private, BEV	Small	27	-
	Medium	57	
	Large	16	
Car, Shared (Best), Petrol	Small	80	Amount of Petrol and all elementary flows reduced by 5 %
	Medium	15	
	Large	5	
Car, Shared (Best), Diesel	Small	80	Amount of Diesel and all elementary flows reduced by 5 %
	Medium	15	
	Large	5	
Car, Shared (Best), BEV	Small	80	Amount of electricity use reduced by 19 %
	Medium	15	
	Large	5	
Car, Shared (Worst), Petrol	Small	50	Amount of Petrol and all elementary flows reduced by 1 %
	Medium	40	
	Large	10	
Car, Shared (Worst), Diesel	Small	50	Amount of Diesel and all elementary flows reduced by 1 %
	Medium	40	
	Large	10	
Car, Shared (Worst), BEV	Small	50	Amount of electricity use reduced by 5 %
	Medium	40	
	Large	10	

The work commuting scenario modal split, adapted to a German industrial park context and based on the studies by Witte et al. (2024) and van der Linden et al. (2025), is shown in Table C 22.

Table C 22: Scenario parameters: modal split for work commuting.

Modal split for work commuting	Status quo [%]	Best-case scenario [%]	Worst-case scenario [%]
Car, Private, Petrol	44.0	39.3	42.9
Car, Private, Diesel	21.0	18.8	20.5
Car, Private, BEV	3.0	2.7	2.9
Car, Sharing, Petrol	0.0	0.0	2.4
Car, Sharing, Diesel	0.0	0.0	1.1
Car, Sharing, BEV	0.0	15.0	3.5
Tram	5.0	3.1	3.2
Bus	4.0	2.5	2.6
Train	5.0	3.1	3.2
Bike (electric)	5.5	4.6	5.4
Bike (non-electric)	5.5	4.6	5.4
Walking	7.0	6.3	6.9

The private trip modal split is shown in Table C 23 and based on Amatuni et al. (2020). Best-case assumes 1,650 pkm/FTE/a of private car-sharing usage; worst-case assumes

770 pkm/FTE/a, according to Amatuni et al. (2020). German fuel shares (Kraftfahrt-Bundesamt 2024) and BEV share in car sharing (20 %) (Statista GmbH 2024a) are applied.

Table C 23: Scenario parameters: modal split for private car sharing. Modal split is based on Amatuni et al. (Amatuni et al. 2020) and adapted for a German use case.

Modal split for private trips	Status Quo [%]	Best-case scenario [%]	Worst-case scenario [%]
Car, Private, Petrol[1]	54.5	32.3	32.3
Car, Private, Diesel[1]	26.0	15.4	15.4
Car, Private, BEV[1]	3.4	2.0	2.0
Car, Sharing, Petrol[2]	0.0	8.9	8.9
Car, Sharing, Diesel[2]	0.0	4.2	4.2
Car, Sharing, BEV[2]	0.0	3.3	3.3
Tram	1.0	2.0	2.0
Bus	1.1	2.7	2.7
Train	13.0	27.2	27.2
Bike (electric)	0.5	1.0	1.0
Bike (non-electric)	0.5	1.0	1.0

[1] adapted to German shares (Kraftfahrt-Bundesamt 2024) based on a total car share of 84 % without car sharing and 50 % with car sharing for the Netherlands (Amatuni et al. 2020)
[2] adapted to German share for BEV in car sharing with 20 % and following adapted values for petrol and diesel
Best-case: 1,650 pkm/FTE/a; worst-case: 770 pkm/FTE/a

For business trips, the current vehicle types in Germany and an annual car travel distance of 265 pkm/FTE/a (DLR and DIW 2024) serve as the basis and is summarized in Table C 24. Unlike the action BEVs used as company cars, the shared vehicles for business trips will all be of the same increased size, focusing primarily on differences in fuel types and efficiency.

Table C 24: Scenario parameters: modal split for business trips.

Modal split for business trips	Status Quo [%]	Best-case scenario [%]	Worst-case scenario [%]
Car, Private, Petrol	65.0	0	0
Car, Private, Diesel	31.0	0	0
Car, Private, BEV	4.0	0	0
Car, Sharing, Petrol	0	0	34.0
Car, Sharing, Diesel	0	0	16.0
Car, Sharing, BEV	0	100.0	50.0

LCI summary

The per-FTE annual activity and LCI inputs are summarized for work commuting (Table C 25) private use (Table C 26), business trips (Table C 27), and charging stations (Table C 28).

Table C 25: Per-FTE annual activity and LCI inputs by scenario: implementing a car sharing possibility (work commuting).

Process	SQ	BC	WC	Unit
Car Diesel BT SQ	0.310	0.000	0.000	km
Car Diesel shared BT WC	0.000	0.000	0.160	km
Car Electric BT SQ	0.040	0.000	0.000	km
Car Electric shared BT BC	0.000	1.000	0.000	km
Car Electric shared BT WC	0.000	0.000	0.500	km
Car Petrol BT SQ	0.650	0.000	0.000	km
Car Petrol shared BT WC	0.000	0.000	0.340	km
Distance	265	265	265	km/a

Table C 26: Per-FTE annual activity and LCI inputs by scenario: implementing a car sharing possibility (private use).

Process	SQ BC	SQ WC	BC	WC	Unit
Car Diesel DE	0.260	0.260	0.154	0.154	km
Car Electric DE	0.034	0.034	0.020	0.020	km
Car Petrol DE	0.545	0.545	0.323	0.323	km
Car Diesel shared BC	0.000	0.000	0.042	0.000	km
Car Electric shared BC	0.000	0.000	0.033	0.000	km
Car Petrol shared BC	0.000	0.000	0.089	0.000	km
Car Diesel shared WC	0.000	0.000	0.000	0.042	km
Car Electric shared WC	0.000	0.000	0.000	0.033	km
Car Petrol shared WC	0.000	0.000	0.000	0.089	km
Transport Train DE	0.130	0.130	0.272	0.272	pkm
Transport bike	0.005	0.005	0.010	0.010	pkm
Transport electric bike DE modified	0.005	0.005	0.010	0.010	pkm
Transport Bus	0.011	0.011	0.027	0.027	pkm
Transport Tram DE modified	0.010	0.010	0.020	0.020	pkm
Distance	1,650	770	1,650	770	km/a

Table C 27: Per-FTE annual activity and LCI inputs by scenario: implementing a car sharing possibility (business trips).

Process	Status quo	Best-case	Worst-case	Unit
Car Diesel DE	0.210	0.188	0.205	km
Car Electric DE	0.030	0.027	0.029	km
Car Petrol DE	0.440	0.393	0.429	km
Car Diesel shared BC	0.000	0.000	0.000	km
Car Electric shared BC	0.000	0.150	0.000	km
Car Petrol shared BC	0.000	0.000	0.000	km
Car Diesel shared WC	0.000	0.000	0.011	km
Car Electric shared WC	0.000	0.000	0.035	km
Car Petrol shared WC	0.000	0.000	0.024	km
Transport Train DE	0.050	0.031	0.032	pkm
Transport bike	0.055	0.046	0.054	pkm
Transport electric bike DE modified	0.055	0.046	0.054	pkm
Transport Bus	0.040	0.025	0.026	pkm
Transport Tram DE modified	0.050	0.031	0.032	pkm
Walking	0.070	0.070	0.070	pkm
Distance	6,880	6,880	6,880	km/a

Table C 28: Per-FTE annual activity and LCI inputs by scenario: implementing a car sharing possibility (charging stations).

Process	Status quo	Best-case	Worst-case	Unit
Charging Stations	0.000	0.040	0.016	n/a

Fact sheet

Figure C 9 summarizes the action in an action fact sheet.

Implementing a car sharing possibility by an established provider for employees and companies of the industrial park				
Category	Sharing concepts and industrial symbiosis			
Intervention/ goal of the action	Providing car sharing stations operated by an established provider within the industrial park enables employees and firms to access shared vehicles, including BEVs. Car sharing can shift modal shares for commuting and business trips, reduce private car use, raise vehicle occupancy, and favor newer, smaller vehicles, improving energy efficiency.			
Operative indicator	Passenger-kilometers (pkm)			
Functional unit (FU) / scaling	Full-time employee (FTE)			
Description of each scenario				
Status quo	No car sharing stations are available on site; commuting and business trips follow the German baseline modal and vehicle shares.			
Best-case	Car sharing is well adopted: commuting shifts modestly from private cars to shared BEVs; private car sharing trips increase across multiple modes; and business trips use shared BEVs exclusively.			
Worst-case	Adoption is limited: commuting shifts minimally; private car sharing trips grow but include a mix of BEVs and combustion vehicles; and business trips use a mixed car sharing fleet (50 % BEV, 50 % petrol/diesel).			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	This action has a different structure compared to the other actions. More detailed reasoning for the three scenarios is provided in the full text.			94
CED [MJ-eq]				951
RMI [kg]				-4.7
Land Use [-]				142
Water Use [m^3-eq]				-7.1
Miscellaneous				
Coherence notes	This action interacts with other mobility actions (e.g. offer discounted public transport ticket or use BEV as company vehicles for business trips) and the action “use of renewable energies” for operating the BEV.			
Associated R-strategy	Rethink			

Figure C 9: Fact sheet of the action: implementing a car sharing possibility by an established provider for employees and companies of the industrial park.

C 3.10.2 Supporting bike sharing stations

Overview and applicability

Providing bike-sharing stations in the industrial park aims to shift short commuting trips from cars and walking to bikes and public transport, reducing environmental impacts (Chen et al. 2022b; Saltykova et al. 2022; Chen et al. 2024; Ding et al. 2025). A consortium of companies commissions a provider to install and operate stations.

Assumptions and data

Bike sharing primarily substitutes short trips between 1.63 and 2.75 km (Luo et al. 2019). We focus on commuting trips under 5 km (27 % of total trips in Germany (Statistisches Bundesamt 2022)), with an assumed average distance of 2 km, and adjust the modal split categories accordingly. E-bike production is covered by ecoinvent; station construction impacts are not separately quantified due to data limitations. Literature indicates net environmental benefits from bike sharing and positive commuting effects (Zheng et al. 2019; Diao et al. 2023; Chen et al. 2024). Quantified modal split changes are also provided by literature (Teixeira et al. 2021; Martin and Xu 2022).

Scenarios

- Status quo: no bike-sharing station exists at the park, and the commuting modal split for <5 km trips reflects German averages.
- Best-case scenario: bikes replace 23 % of car trips (upper bound of Teixeira et al. (Teixeira et al. 2021) and 20 % of walking (lower bound), and bus share increases by 2.1 percentage points due to reduced car use (upper bound of Martin & Xu (Martin and Xu 2022). 100 % of shared bikes are assumed to be e-bikes.
- Worst-case scenario: bikes replace only 2 % of car trips (lower bound) but 54 % of walking (upper bound of Teixeira et al. (Teixeira et al. 2021), and bus share increases by 1 percentage point (lower bound of Martin & Xu (Martin and Xu 2022). The fleet is assumed to be split 50 % e-bikes and 50 % conventional bikes.

Table C 29 summarizes the modal split by scenario.

Table C 29: Scenario modal split for work commuting: supporting bike sharing stations.

Modal split for work-commuting	Status quo [%]	Best-case scenario [%]	Worst-case scenario [%]
Car, Petrol	26.5	19.1	25.4
Car, Diesel	12.7	9.1	12.1
Car, BEV	1.8	1.3	1.7
Tram	2.9	2.9	2.9
Bus	2.3	4.4	3.3
Train	2.9	2.9	2.9
Bike (electric)	13.0	27.4	20.2
Bike (non-electric)	13.0	13.0	20.2
Walking	25.0	20.0	11.5

LCI summary

Table C 30 reports activity per full-time employee per year (FTE/a). Distance is the annual commuting activity below 5 km used for scaling (Appendix C 2).

Table C 30: Per-FTE annual activity and LCI inputs by scenario: supporting bike sharing stations.

Process	Status quo	Best-case	Worst-case	Unit
Car Diesel DE	0.127	0.091	0.121	km
Car Electric DE	0.018	0.013	0.017	km
Car Petrol DE	0.265	0.191	0.254	km
Transport Train DE	0.029	0.029	0.029	pkm
Transport bike	0.130	0.130	0.202	pkm
Transport electric bike DE modified	0.130	0.274	0.202	pkm
Transport Bus	0.023	0.044	0.033	pkm
Transport Tram DE modified	0.029	0.029	0.029	pkm
Walking	0.250	0.200	0.115	pkm
Distance	216	216	216	km/a

Fact sheet

Figure C 10 summarizes the action in an action fact sheet.

Supporting bike sharing stations				
Category	Sharing concepts and industrial symbiosis			
Intervention/ goal of the action	Providing bike sharing stations in the industrial park aims to shift short commuting trips from cars and walking to bikes and public transport, reducing environmental impacts.			
Operative indicator	Passenger-kilometers (pkm)			
Functional unit (FU) / scaling	Full-time employee (FTE)			
Description of each scenario				
Status quo	No bike sharing station exists at the park, and the commuting modal split for <5 km trips reflects German averages.			
Best-case	Bikes replace 23 % of car trips and 20 % of walking, and bus share increases by 2.1 percentage points due to reduced car use. 100 % of shared bikes are assumed to be e-bikes.			
Worst-case	Bikes replace only 2 % of car trips but 54 % of walking, and bus share increases by one percentage point. The fleet is assumed to be split 50 % e-bikes and 50 % conventional bikes.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	24	19	24	2.5
CED [MJ-eq]	351	282	349	35
RMI [kg]	29	24	30	2.5
Land Use [-]	123	100	123	11
Water Use [m^3-eq]	2.9	2.5	2.9	0.2
Miscellaneous				
Coherence notes	This action interacts with other mobility actions (e.g. offer discounted public transport ticket or ride sharing and especially supporting e-scooter sharing stations).			
Associated R-strategy	Rethink			

Figure C 10: Fact sheet of the action: supporting bike sharing stations.

C 3.10.3 Supporting e-scooter sharing stations

Overview and applicability

Providing shared e-scooter stations aims to shift short commuting trips from cars and walking to e-scooters and public transport (Weschke et al. 2022; Wang et al. 2023). A consortium commissions a provider to install and operate stations. E-scooters are typically used for ~2 km trips (Gebhardt et al. 2022; Follmer 2025).

Assumptions and data

Commuting modal split for <5 km trips (27 % of total (Statistisches Bundesamt 2022)) is adjusted to 2 km average trip length. The ecoinvent database includes large e-scooter processes (~122 kg mass), whereas electric kick scooters weight approximately 11.6 kg (Cano-Moreno et al. 2024). To estimate impacts, we use literature GWP per pkm and scenario-dependent operating conditions (Severengiz et al. 2020) rather than mass scaling,

acknowledging that manufacturing and collection for charging dominate GWP (Hollingsworth et al. 2019) and that outcomes depend on implementation (Arbeláez Vélez 2024).

Scenarios

- Status quo: no e-scooter stations are present and the commuting modal split reflects German averages.
- Best-case scenario: e-scooters replace 11 % of car trips (Weschke et al. 2022; Gebhardt et al. 2022), reduce walking distances by 30 % (Wang et al. 2023), and substitute few bikes (~9 % (Wang et al. 2023)). The e-scooter GWP is set to 0.064 kg CO_2-eq/pkm (Severengiz et al. 2020) with 2-year lifespan, interchangeable battery, e-bike-based battery swap, and electric collection vehicles.
- Worst-case scenario: only 3.5 % of car trips are substituted (Gebhardt et al. 2022), walking substitution reaches 60 % (Wang et al. 2023), and bike substitution is 11 % (Weschke et al. 2022). The e-scooter GWP is set to 0.237 kg CO_2-eq/pkm due to 6-month lifespan, higher vandalism, diesel-based battery swap and collection (Severengiz et al. 2020).

Table C 31 summarizes the modal split by scenario.

Table C 31: Scenario modal split for work commuting: supporting e-scooter sharing stations.

Modal split for work-commuting	Status quo [%]	Best-case scenario [%]	Worst-case scenario [%]
Car, Petrol	26.5	23.6	25.6
Car, Diesel	12.7	11.3	12.2
Car, BEV	1.8	1.6	1.7
Tram	2.9	2.9	2.9
Bus	2.3	2.3	2.3
Train	2.9	2.9	2.9
Bike (electric)	13.0	11.8	11.6
Bike (non-electric)	13.0	11.8	11.6
Walking	25.0	17.5	10.0
E-scooter	0.0	14.4	19.3

Table C 32 reports activity per full-time employee per year (FTE/a). Distance is the annual commuting activity below 5 km used for scaling (Appendix C 2).

Table C 32: Per-FTE annual activity and LCI inputs by scenario: supporting e-scooter sharing stations.

Process	Status quo	Best-case	Worst-case	Unit
Car Diesel DE	0.127	0.113	0.122	km
Car Electric DE	0.018	0.016	0.017	km
Car Petrol DE	0.265	0.236	0.256	km
Transport Train DE	0.029	0.029	0.029	pkm
Transport bike	0.130	0.118	0.116	pkm
Transport electric bike DE modified	0.130	0.118	0.116	pkm
Transport Bus	0.023	0.023	0.023	pkm
Transport Tram DE modified	0.029	0.029	0.029	pkm
E-scooter (kick roller) BC	0.000	0.144	0.000	pkm
E-scooter (kick roller) WC	0.000	0.000	0.193	pkm
Walking	0.250	0.175	0.100	pkm
Distance	216	216	216	km

Fact sheet

Figure C 11 summarizes the action in an action fact sheet.

Supporting e-scooter sharing stations				
Category	Sharing concepts and industrial symbiosis			
Intervention/ goal of the action	Providing shared e-scooter stations aims to shift short commuting trips from cars and walking to E scooters and public transport. A consortium commissions a provider to install and operate stations.			
Operative indicator	Passenger-kilometers (pkm)			
Functional unit (FU) / scaling	Full-time employee (FTE)			
Description of each scenario				
Status quo	No e-scooter stations are present and the commuting modal split reflects German averages.			
Best-case	E-scooters replace 11 % of car trips, reduce walking distances by 30 %, and substitute few bikes (~9 %). The e-scooter GWP is set to 0.064 kg CO_2 eq/pkm with 2 year lifespan, interchangeable battery, e-bike based battery swap, and electric collection vehicles.			
Worst-case	Only 3.5 % of car trips are substituted, walking substitution reaches 60 %, and bike substitution is 11 %. The e-scooter GWP is set to 0.237 kg CO_2 eq/pkm due to 6 month lifespan, higher vandalism, diesel-based battery swap and collection.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	24	23	31	-3.2
CED [MJ-eq]	351	343	476	-59
RMI [kg]	29	30	46	-8.6
Land Use [-]	123	122	174	-25
Water Use [m^3-eq]	2.9	3.1	5.3	-1.4
Miscellaneous				
Coherence notes	This action interacts with other mobility actions (e.g. offer discounted public transport ticket or ride sharing and especially supporting bike sharing stations).			
Associated R-strategy	Rethink			

Figure C 11: Fact sheet of the action: supporting e-scooter sharing stations.

C 3.10.4 Use of smart and shared parking spaces

Overview and applicability

Shared, reservation-enabled parking systems can increase occupancy, reduce built area, and cut search distances (Xie et al. 2023; Cai et al. 2025), addressing common oversupply with an average of 65 % (Weinberger and Karlin-Resnick 2015). A park-wide smart software facilitates allocation and reservations (Cai et al. 2025; ParkHere GmbH). Environmental benefits arise from reduced driving, search, and optimized land use (Zhao et al. 2021), though social and economic outcomes are not guaranteed (Ye et al. 2020).

Assumptions and data

A standard parking space in Germany is 2.65 m × 5.2 m (~14 m^2) (Forschungsgesellschaft für Straßen- und Verkehrswesen 2023). Regulations in North Rhine-Westphalia (NRW) require one space per 40 m^2 of floor area (Ministerium für Heimat, Kommunales, Bau und Gleichstellung 3/14/2022), yielding ~0.7 spaces/FTE at 28 m^2/workplace (Stolze and Ricci 2022), which is consistent with ~68 % car commuting (Statistisches Bundesamt 2022). Parking pavement materials are estimated from LCA: 10 cm hot-mix asphalt (density 2,565 kg/m^3) and 15 cm crushed stone (density 1,949 kg/m^3) (Glick et al. 2013) with a service life of ~35 years (Wang et al. 2022). Status-quo parking search is assumed 0.3 km/day per FTE (lower than urban 1.5 km/day (Zhao et al. 2021), as parking searches in industrial parks are considered less complex compared to urban areas).

Scenarios

- Status quo: conventional parking without sharing/reservations yields ~0.7 spaces/FTE and 0.3 km/day search distance.
- Best-case scenario: smart parking with reservations raises occupancy to 90 % (ParkHere GmbH), reducing spaces to ~0.37/FTE and eliminating search distance.
- Worst-case scenario: a conventional app without reservations raises occupancy to ~30 % (ParkHere GmbH), reducing spaces to ~0.54/FTE. Search distance remains at 0.3 km/day.

LCI summary

Table C 33 reports activity per full-time employee per year (FTE/a). Distance is the annual commuting activity below 5 km used for scaling (Appendix C 2).

Table C 33: Per-FTE annual activity and LCI inputs by scenario: use of smart and shared parking spaces.

Process	Status quo	Best-case	Worst-case	Unit
Car Diesel DE	0.210	0.210	0.210	km
Car Electric DE	0.030	0.030	0.030	km
Car Petrol DE	0.440	0.440	0.440	km
Distance	60	0	60	km/a
Parking Space	9.80	5.18	7.56	m^2

Fact sheet

Figure C 12 summarizes the action in an action fact sheet.

Use of smart and shared parking spaces				
Category	Sharing concepts and industrial symbiosis			
Intervention/ goal of the action	Shared, reservation enabled parking systems can increase occupancy, reduce built area, and cut search distances, addressing common oversupply with an average of 65 %. A park wide smart software facilitates allocation and reservations. Environmental benefits arise from reduced driving, search, and optimized land use, though social and economic outcomes are not guaranteed.			
Operative indicator	Parking space area (m^2)			
Functional unit (FU) / scaling	Full-time employee (FTE)			
Description of each scenario				
Status quo	Conventional parking without sharing/reservations yields ~0.7 spaces/FTE and 0.3 km/day search distance.			
Best-case	Smart parking with reservations raises occupancy to 90 %, reducing spaces to ~0.37/FTE and eliminating search distance.			
Worst-case	A conventional app without reservations raises occupancy to ~30 %, reducing spaces to ~0.54/FTE. Search distance remains at 0.3 km/day.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	17	3.8	16	7.6
CED [MJ-eq]	480	177	404	190
RMI [kg]	174	86	137	63
Land Use [-]	100	26	89	43
Water Use [m^3-eq]	3.9	1.5	3.2	1.5
Miscellaneous				
Coherence notes	This action interacts with other mobility actions (e.g., offering discounted public transport tickets or ridesharing), which affect the number of people who commute by car.			
Associated R-strategy	Rethink			

Figure C 12: Fact sheet of the action: use of smart and shared parking spaces.

C 3.10.5 Sharing of daycare center

Overview and applicability

Constructing a shared daycare center within the industrial park can reduce travel distances to daycare and optimize daily travel patterns (Lowe 2001; Nahlik and Chester 2014; Raimbault et al. 2020). Applicability depends on demand, siting, and capacity. Building impacts are not quantified here because it is assumed that the total number of built daycare centers remains constant with the implementation of this action.

Assumptions and data

The baseline daycare trip distance is derived from average driving time (4.7 min) at mean urban speed (27.8 km/h), yielding ~2.2 km one way (Diermeier et al. 2023; Statista GmbH 2025a). A woman in Germany has an average of 1.35 children (Statistisches Bundesamt

2025a), or ~0.675 children per employee. Daycare duration is ~4.5 years and working lifetime ~40 years (Eurostat 2025b), so daycare time accounts for ~11 % of working years. However, data on the potential for distance reduction for shared daycare centers could not be identified in the literature and were assumed.

Scenarios

- Status quo: employees drive children to off-site daycare (average 2.2 km one way).
- Best-case scenario: an on-site daycare accommodates all children of daycare age, saving ~80 % of travel distance (detours remain possible).
- Worst-case scenario: ~50 % of children attend the on-site daycare (others remain enrolled elsewhere), saving ~60 % of travel distance.

Table C 34 reports activity per full-time employee per year (FTE/a). Distance is the annual commuting activity below 5 km used for scaling (Appendix C 2).

Table C 34: Per-FTE annual activity and LCI inputs by scenario: sharing of daycare center.

Process	Status quo	Best-case	Worst-case	Unit
Car Diesel DE	0.210	0.210	0.210	km
Car Electric DE	0.030	0.030	0.030	km
Car Petrol DE	0.440	0.440	0.440	km
Transport Train DE	0.050	0.050	0.050	pkm
Transport bike	0.055	0.055	0.055	pkm
Transport electric bike DE modified	0.055	0.055	0.055	pkm
Transport Bus	0.040	0.040	0.040	pkm
Transport Tram DE modified	0.050	0.050	0.050	pkm
Walking	0.070	0.070	0.070	pkm
Distance	65.34	13.07	26.14	km/a

Fact sheet

Figure C 13 summarizes the action in an action fact sheet.

Sharing of daycare center				
Category	Sharing concepts and industrial symbiosis			
Intervention/ goal of the action	Constructing a shared daycare center within the industrial park can reduce travel distances to daycare and optimize daily travel patterns. Applicability depends on demand, siting, and capacity.			
Operative indicator	Passenger-kilometers (pkm)			
Functional unit (FU) / scaling	Full-time employee (FTE)			
Description of each scenario				
Status quo	Employees drive children to off site daycare (average 2.2 km one way).			
Best-case	An on site daycare accommodates all children of daycare age, saving ~80 % of travel distance (detours remain possible).			
Worst-case	~50 % of children attend the on site daycare (others remain enrolled elsewhere), saving ~60 % of travel distance.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	12	2.4	4.7	8.3
CED [MJ-eq]	171	34	68	120
RMI [kg]	14	2.8	5.6	10
Land Use [-]	59	12	24	41
Water Use [m^3-eq]	1.33	0.27	0.53	0.93
Miscellaneous				
Coherence notes	This action interacts with other mobility actions (e.g., offering discounted public transport tickets or ridesharing), which affect the number of people who commute by car.			
Associated R-strategy	Rethink			

Figure C 13: Fact sheet of the action: sharing of daycare center.

C 3.10.6 Sharing of canteen

Overview and applicability

A shared canteen within the industrial park can reduce lunchtime travel distances by enabling on-site dining, with potential environmental benefits (Lowe 2001; Nahlik and Chester 2014; Raimbault et al. 2020). Building impacts are not quantified here because it is assumed that the total number of built canteens remains constant with the implementation of this action. Only canteens that are already planned or available will be opened to other companies.

Assumptions and data

In Germany, 10 % of employees often or nearly always visit a supermarket during their main break and 12 % go to bakeries, butchers or snack bars (Huschik et al. 2024). 88 % of people can reach a grocery store within 5 minutes' drive (Neumeier and Osigus 2024), at 27.8 km/h average speed, ~2.3 km one way (Statista GmbH 2025a). We apply the

commuting modal split for trips under 5 km and a vehicle occupancy of 1.4 (Umweltbundesamt 2023), assuming one person can collect food for multiple colleagues.

Scenarios

- Status quo: 22 % of employees make an additional 2.3 km trip during the main break to buy food (Huschik et al. 2024).
- Best-case scenario: an on-site cafeteria is used by ~80 % of those who would otherwise eat out. Trips are replaced by short walks on site.
- Worst-case scenario: ~25 % of those who would otherwise eat out use the on-site canteen and walk.

LCI summary

Table C 35 reports activity per full-time employee per year (FTE/a). Distance is the annual commuting activity below 5 km used for scaling (Appendix C 2).

Table C 35: Per-FTE annual activity and LCI inputs by scenario: sharing of canteen.

Process	Status quo	Best-case	Worst-case	Unit
Car Diesel DE	0.127	0.127	0.127	km
Car Electric DE	0.018	0.018	0.018	km
Car Petrol DE	0.265	0.265	0.265	km
Transport Train DE	0.029	0.029	0.029	pkm
Transport bike	0.130	0.130	0.130	pkm
Transport electric bike DE modified	0.130	0.130	0.130	pkm
Transport Bus	0.023	0.023	0.023	pkm
Transport Tram DE modified	0.029	0.029	0.029	pkm
Walking	0.250	0.250	0.250	pkm
Distance	202.4	40.48	151.8	km

Fact sheet

Figure C 14 summarizes the action in an action fact sheet.

Sharing of canteen				
Category	Sharing concepts and industrial symbiosis			
Intervention/ goal of the action	A shared canteen within the industrial park can reduce lunchtime travel distances by enabling on site dining, with potential environmental benefits. Building impacts are not quantified here because it is assumed that the total number of built canteens remains constant with the implementation of this action. Only canteens that are already planned or available will be opened to other companies.			
Operative indicator	Passenger-kilometers (pkm)			
Functional unit (FU) / scaling	Full-time employee (FTE)			
Description of each scenario				
Status quo	22 % of employees make an additional 2.3 km trip during the main break to buy food.			
Best-case	An on site cafeteria is used by ~80 % of those who would otherwise eat out. Trips are replaced by short walks on site.			
Worst-case	~25 % of those who would otherwise eat out use the on site canteen and walk.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	23	4.5	17	12
CED [MJ-eq]	329	66	246	172
RMI [kg]	27	5,5	21	14
Land Use [-]	115	23	86	60
Water Use [m^3-eq]	2.69	0.54	2.01	1.41
Miscellaneous				
Coherence notes	This action interacts with other mobility actions (e.g., offering discounted public transport tickets or ridesharing), which affect the number of people who commute by car.			
Associated R-strategy	Rethink			

Figure C 14: Fact sheet of the action: sharing of canteen.

C 3.10.7 Desk sharing

Overview and applicability

Desk sharing increases office space utilization by sharing workplaces across employees and across firms, reducing the floor area required per employee and associated energy use (Kim et al. 2016). This action can be implemented within a single company or at park level among several firms. Given its potential for cross-company implementation, this action is classified as a meso-level action.

Assumptions and data

Due to limited ecoinvent office processes, we model office space using “building construction, hall” with 30 % wood and 70 % steel. Office height is assumed 3.5 m (Utami et

al. 2017) (vs. hall height 7 m), reducing impacts by a factor of ~2. The mean annual global warming impact of building construction in Germany is 8.7 kg CO_2-eq/m^2 per year (Braune et al. 2021). This value assumes a building lifetime of 50 years and is used as the basis for scaling the ecoinvent building-construction dataset to the corresponding German annual impact, resulting in a scaling factor of 21.14.

New office buildings in Germany have ~75 kWh/m^2·a heat demand (European Commission 2020c) with heat pumps. Office electricity demand is ~16.1-28.2 kWh/m^2·a (Bagherian et al. 2021) and we assume 22 kWh/m^2·a. Baseline area per workplace is 28 m^2 (Stolze and Ricci 2022). Current German utilization is ~31-41 % (Drees & Sommer SE 2022) and we assume 35 % baseline utilization of workplaces.

Scenarios

- Status quo: utilization is 35 % and area per employee is 28 m^2. Therefore, heat demand is 2,100 kWh/workplace per year and electricity demand 616 kWh/workplace per year.
- Best-case scenario: industrial park level desk sharing raises utilization to 80 %, enabling a load increase of 2.3 and reducing area to ~12 m^2/employee. Therefore, heat demand is 900 kWh/workplace per year; electricity demand 264 kWh/workplace per year.
- Worst-case scenario: establishing desk sharing at the industrial park level is challenging and is mostly limited to company-wide desk sharing, which raises utilization to 60 %, enabling a 1.7 load increase and reducing space to ~16 m^2/employee. Therefore, heat demand is 1,200 kWh/workplace per year; electricity demand 352 kWh/workplace per year.

LCI summary

Table C 36 reports activity per full-time employee per year (FTE/a).

Table C 36: Per-FTE annual activity and LCI inputs by scenario: Desk sharing.

Process	Status quo	Best-case	Worst-case	Unit
Office space (modified)	28	12	16	m^2
Heat demand, heat pump, DE	2,100	900	1,200	kWh/a
Electricity mix DE (Germany)	616	264	352	kWh/a

Fact sheet

Figure C 15 summarizes the action in an action fact sheet.

Desk sharing				
Category	Sharing concepts and industrial symbiosis			
Intervention/ goal of the action	Desk sharing increases office space utilization by sharing workplaces across employees and across firms, reducing the floor area required per employee and associated energy use.			
Operative indicator	Floor space (m^2)			
Functional unit (FU) / scaling	Full-time employee (FTE)			
Description of each scenario				
Status quo	Utilization is 35 % and area per employee is 28 m^2. Therefore, heat demand is 2,100 kWh/workplace per year and electricity demand 616 kWh/workplace per year.			
Best-case	Industrial park level desk sharing raises utilization to 80 %, enabling a load increase of 2.3 and reducing area to ~12 m^2/employee. Therefore, heat demand is 900 kWh/workplace per year; electricity demand 264 kWh/workplace per year.			
Worst-case	Establishing desk sharing at the industrial park level is challenging and is mostly limited to company-wide desk sharing, which raises utilization to 60 %, enabling a 1.7 load increase and reducing space to ~16 m^2/employee. Therefore, heat demand is 1,200 kWh/workplace per year; electricity demand 352 kWh/workplace per year.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	858	368	491	429
CED [MJ-eq]	14,951	6,407	8,543	7,475
RMI [kg]	1,544	662	882	772
Land use [-]	5,152	2,208	2,944	2,576
Water use [m^3-eq]	201	86	115	100
Miscellaneous				
Coherence notes	This action interacts with other energy actions (e.g., use of renewable energies). If furniture/IT equipment influences are modeled, treat them as separate actions.			
Associated R-strategy	Rethink			

Figure C 15: Fact sheet of the action: desk sharing.

C 3.11 Case-specific (micro + meso level)

These actions are tailored to the soil treatment case as well as detergent manufacturer and affect both micro (company) and meso (industrial park) levels. Each action is quantified using shared parameters from Appendix C 2 (e.g., background processes, electricity mixes, functional units).

C 3.11.1 Soil treatment

The case of soil treatment focuses on a company planning to build a soil treatment plant. The soil is sourced from construction projects in the Aachen region. Currently, this soil is landfilled in Aldenhoven, located approximately 31.2 km away from the construction

sites. In the future, the establishment of a soil treatment plant is intended to recycle the soil and reduce transport distances.

C 3.11.2 Treatment of soil instead of landfill

Overview and applicability

Treating excavated soil for recycling instead of landfilling can deliver substantial environmental benefits by reducing both primary material demand and landfill disposal (Magnusson et al. 2015; Hale et al. 2021). Locating the treatment plant closer to excavation sites additionally reduces average transport distances and can significantly lower the environmental burdens of logistics (Greschner Farkavcova et al. 2018). This action combines two effects: the introduction of a mechanically operated soil-treatment plant and its optimized location relative to the construction sites. It is applicable where sufficient volumes of excavated soil arise and where siting a treatment plant near the soil source is feasible.

Assumptions and data

In the status quo, excavated soil from construction sites in Aachen is landfilled in Aldenhoven, approximately 31.2 km away. Site refilling requires 85 % of the original excavated mass as primary backfill, which is transported from Aldenhoven to Aachen. Two vehicle types are used: 3/4-axle rigid trucks (maximum payload 15 t, typical load 11 t) and tractor-trailers (maximum 28 t, typical load 24 t). Fuel consumption (diesel) is scaled to the assumed loads and directions: 3/4-axle 30 l/100 km loaded and 23 l/100 km unloaded; tractor-trailer 38 l/100 km full, 36 l/100 km at 24 t, and 26 l/100 km unloaded. Diesel truck emission and consumption factors are consistent with European handbook values for comparable vehicle classes and driving conditions (McKinnon 2018; Notter et al. 2025). Ecoinvent diesel processes are adjusted to EU (excl. CH) and scaled to these intensities.

In the treatment scenario, a ST plant is located near Aachen and performs mechanical treatment (sorting, conditioning) rather than soil washing or chemical treatment, as this was deemed most appropriate by the company. Electricity demand for mechanical treatment is 13.5 kWh/t in the best case. Other literature reports a diesel demand of 21 kWh/t for soil washing (Grimison et al. 2023) and 420 kWh/t for complex chemical treatment (Deng et al. 2023), but these are not directly comparable and are therefore only used qualitatively. In the worst case, treatment electricity demand increases by 10 % to 14.85 kWh/t, while the mass balances remain the same. Electricity is modeled with the German grid mix; renewable electricity procurement is treated in a separate action (use of renewables energies).

For primary material, we model “gravel, crushed” (CH) as the proxy for imported backfill; for landfill operations, we use the inert material landfill process (CH). In the treatment scenario, 20 % of the original mass is required as primary material, 35 % is landfilled as residue, and 45 % is recycled on-site or regionally as treated soil. The mass balances connecting to transport are those from this treatment action: 45 % treated soil remains in the region (not modeled as long-haul transport), 35 % becomes landfill residue, and 20 % is imported primary material.

Scenarios

- Status quo: Excavated soil is transported from Aachen to Aldenhoven (31.2 km) by 3/4-axle trucks at 75 % load and fully landfilled there. Site refilling requires 85 % of the original mass as primary backfill (gravel, crushed) imported from Aldenhoven to Aachen. Limited on-site storage leads to an average load factor of 75 %.
  Route: Aachen ↔ Aldenhoven, 3/4-axle, 75 % load, 31.2 km one way.
- Best-case scenario: All excavated soil is treated at the newly located ST plant near Aachen. Electricity demand is 13.5 kWh/t and mass balances are 20 % primary, 35 % landfill, 45 % treated soil recycled. Excavated soil and backfill are transported between Aachen and ST (17.6 km one way) using 3/4-axle trucks at 75 % load. 10 % of the mass (residues) is transported from ST to Aldenhoven (21.7 km one way) using tractor-trailers, with outbound trips at 100 % load and return trips empty.
  Routes: Aachen ↔ ST, 3/4-axle, 75 % load, 17.6 km one way; ST ↔ Aldenhoven, tractor-trailer, 21.7 km one way, 100 % out / 0 % back.
- Worst-case scenario: The treatment plant operates with 10 % higher electricity demand (14.85 kWh/t), while the mass balances (20 % primary, 35 % landfill, 45 % recycled soil) remain identical to the best case. Residues cannot be disposed at Aldenhoven and must be landfilled in Horm, increasing the residue transport distance to 44.1 km. Transport between Aachen and ST is the same as in the best-case scenario.
  Routes: Aachen ↔ ST, 3/4-axle, 75 % load, 17.6 km one way; ST ↔ Horm, tractor-trailer, 44.1 km one way, 100 % out / 0 % back.

LCI summary

Table C 37 reports the soil treatment activity per mass of soil.

Table C 37: Per mass annual activity and LCI inputs by scenario: treatment of soil instead of landfill.

Process	Status quo	Best-case	Worst-case	Unit
Gravel, crushed, CH	0.750	0.200	0.200	t/t
Landfill, CH	1.000	0.350	0.350	t/t
Electricity mix DE (Germany)	0.000	13.50	14.85	kWh/t
Mass of soil	100,000	100,000	100,000	t/a

Table C 38 reports activity per transport kilometer depending on the mass of soil.

Table C 38: Per transport kilometer depending on the mass of soil annual activity and LCI inputs by scenario.

Process	Status quo	Best-case	Worst-case	Unit
Transport Aachen -> Aldenhoven -> Aachen, 3/4A 75 % load, Diesel	5.673	0.000	0.000	km/t
Transport Aachen -> ST 3/4A, 75 % load, Diesel	0.000	1.600	1.600	km/t
Transport ST -> Aachen 3/4A, 75 % load, Diesel	0.000	1.600	1.600	km/t
Transport ST -> Aldenhoven, TT 100 % load, Diesel	0.000	0.078	0.000	km/t
Transport Aldenhoven -> ST, TT 0 % load, Diesel	0.000	0.078	0.000	km/t
Transport ST -> Horm, TT 100 % load, Diesel	0.000	0.000	0.158	km/t
Transport Horm -> ST, TT 0 % load, Diesel	0.000	0.000	0.158	km/t
Mass of soil	100,000	100,000	100,000	t/a

Fact sheet

Figure C 16 summarizes the action in an action fact sheet.

Treatment of soil instead of landfill				
Category	Case-specific: soil treatment			
Intervention/ goal of the action	Treating excavated soil for recycle instead of landfilling can deliver substantial environmental benefits by reducing both primary material demand and landfill disposal. In the soil treatment case, without the treatment plant, excavated soil from Aachen is landfilled in Aldenhoven, and primary backfill is transported from Aldenhoven to Aachen. Site refilling typically requires 85 % of the original excavated mass.			
Operative indicator	Mass of soil (t)			
Functional unit (FU) / scaling	Mass of soil excavated by construction works (t)			
Description of each scenario				
Status quo	Excavated soil is transported from Aachen to Aldenhoven (31.2 km) by 3/4 axle trucks at 75 % load and fully landfilled there. Site refilling requires 85 % of the original mass as primary backfill (gravel, crushed) imported from Aldenhoven to Aachen. Limited on site storage leads to an average load factor of 75 %. Route: Aachen ↔ Aldenhoven, 3/4 axle, 75 % load, 31.2 km one way.			
Best-case	All excavated soil is treated at the newly located ST plant near Aachen. Electricity de-mand is 13.5 kWh/t and mass balances are 20 % primary, 35 % landfill, 45 % treated soil recycled. Excavated soil and backfill are transported between Aachen and ST (17.6 km one way) using 3/4 axle trucks at 75 % load. 10 % of the mass (residues) is transported from ST to Aldenhoven (21.7 km one way) using tractor-trailers, with outbound trips at 100 % load and return trips empty. Routes: Aachen ↔ ST, 3/4 axle, 75 % load, 17.6 km one way; ST ↔ Aldenhoven, tractor-trailer, 21.7 km one way, 100 % out / 0 % back.			
Worst-case	Worst-case scenario: The treatment plant operates with 10 % higher electricity demand (14.85 kWh/t), while the mass balances (20 % primary, 35 % landfill, 45 % recycled soil) remain identical to the best case. Residues cannot be disposed at Aldenhoven and must be landfilled in Horm, increasing the residue transport distance to 44.1 km. Transport between Aachen and ST is the same as in the best case scenario. Routes: Aachen ↔ ST, 3/4 axle, 75 % load, 17.6 km one way; ST ↔ Horm, tractor-trailer, 44.1 km one way, 100 % out / 0 % back.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	14.0	11.7	12.4	2.0
CED [MJ-eq]	220	206	221	6.1
RMI [kg]	794	218	219	575
Land use [-]	164	67	69	97
Water use [m^3-eq]	12.4	4.5	4.6	7.8
Miscellaneous				
Coherence notes	This action interacts with other energy actions (e.g., use of renewable energies). The functional unit for scaling the effects of the action is mass of soil excavated by construction works. The specified values are calculated by dividing the absolute effects by the excavated mass of 100,000 t/a. Consequently, these values may not be universally applicable due to their dependence on this specific case study.			
Associated R-strategy	Recycle			

Figure C 16: Fact sheet of the action: treatment of soil instead of landfill.

C 3.11.3 Use of a shared storage to increase load of transports

Overview and applicability

Establishing a cross-company shared storage area near construction sites facilitates transport consolidation and increases load factors, leading to a reduction in the number of transport rides and their associated impacts (Validi et al. 2020; Allen et al. 2012; Guisson et al. 2023). For the soil treatment company, storage is located in Aachen (average 5.6 km from sites and 16.1 km to the treatment plant). No new storage construction is required, as the storage of another company is used, which intensifies its use.

Assumptions and data

3/4-axle trucks are used for transport between construction sites and the storage area, because many sites cannot accommodate larger vehicles. Additionally, the literature indicates that turning radii often restrict 40-ton tractor-trailers, necessitating the use of smaller rigid trucks for first and last mile transports (Bosona 2020; Sanchez-Diaz et al. 2020). Tractor-trailers are used for transport between the storage area and the treatment plant. In this action, all vehicles are diesel-powered, as electrification is addressed separately in the “Use of electric transport vehicles” action.

Scenarios

- Status quo: no storage is used and excavated soil is transported directly site → ST by 3/4-axle at 75 % load.
- Best-case scenario: consolidation is optimal: site → storage uses 3/4-axle at 75 % load, and storage → ST uses tractor–trailers at 100 % load.
- Worst-case scenario: demand and supply variability reduce consolidation effectiveness; tractor–trailer load factor between storage and ST averages 85 %.

LCI summary

Table C 39 reports activity per transport kilometer depending on the mass of soil.

Table C 39: Per transport kilometer depending on the mass of soil annual activity and LCI inputs by scenario: use of a shared storage to increase load of transports.

Process	Status quo	Best-case	Worst-case	Unit
Transport Aachen -> ST, 3/4A, 75 % load, Diesel	1.600	0.000	0.000	km/t
Transport ST -> Aachen, 3/4A, 75 % load, Diesel	1.600	0.000	0.000	km/t
Transport Aachen -> Storage, 3/4A, 75 % load, Diesel	0.000	0.509	0.509	km/t
Transport Storage -> Aachen, 3/4A, 75 % load, Diesel	0.000	0.509	0.509	km/t
Transport Storage -> ST, TT, 100 % load, Diesel	0.000	0.575	0.000	km/t
Transport ST -> Storage TT, 100 % load, Diesel	0.000	0.575	0.000	km/t
Transport Storage -> ST, TT, 85 % load, Diesel	0.000	0.000	0.671	km/t
Transport ST -> Storage TT, 85 % load, Diesel	0.000	0.000	0.671	km/t
Mass of soil	100,000	100,000	100,000	t/a

Fact sheet

Figure C 17 summarizes the action in an action fact sheet.

Use of a shared storage to increase load of transports				
Category	Case-specific: soil treatment			
Intervention/ goal of the action	Establishing a shared storage area near construction sites facilitates transport consolidation and increases load factors, leading to a reduction in the number of transports and their associated impacts. For soil treatment, storage is located in Aachen (average 5.6 km from sites and 16.1 km to the treatment plant). No new storage construction is required (existing industrial site).			
Operative indicator	Transport kilometer			
Functional unit (FU) / scaling	Transport kilometer per mass of soil excavated by construction works (km/t)			
Description of each scenario				
Status quo	Excavated soil is transported directly site → NSW by 3/4 axle at 75 % load.			
Best-case	Consolidation is optimal: site → storage uses 3/4 axle at 75 % load, and storage → NSW uses tractor–trailers at 100 % load.			
Worst-case	Demand and supply variability reduce consolidation effectiveness; tractor–trailer load factor between storage and NSW averages 85 %.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	3.5	2.7	2.8	0.7
CED [MJ-eq]	50	38	41	10
RMI [kg]	1.8	1.4	1.5	0.4
Land use [-]	7.4	5.3	5.7	1.9
Water use [m^3-eq]	0.10	0.07	0.08	0.02
Miscellaneous				
Coherence notes	This action interacts with other actions such as use of electric transport vehicles and requires the execution of the action “treatment of soil instead of landfill”. The functional unit for scaling the effects of the action is transport kilometer per mass of soil excavated by construction works. The specified values are calculated by dividing the absolute effects by the excavated mass of 100,000 t/a. Consequently, these values may not be universally applicable due to their dependence on this specific case study.			
Associated R-strategy	Rethink			

Figure C 17: Fact sheet of the action: use of a shared storage to increase load of transports.

C 3.12 Detergent manufacturer

The case of a detergent manufacturer focuses on the production process of the bottles. One action involves changing how the detergent is provided, while the other action pertains to using secondary materials in the production process.

C 3.12.1 Refill concentrate plastic pouch instead of conventional plastic bottle

Overview and applicability

There is a multitude of reuse models for fast-moving consumer goods to promote the transition towards a CE (Muranko et al. 2021). According to Henkel’s online product

description, they manufacture detergent (concentrate) and package it either in plastic bottles or plastic stand-up pouches. The concentrate pouch is lighter due to lower packaging mass and lower water content. It is designed for refilling the empty conventional bottle, diluting and mixing it with water to obtain a formulation, functionality and volume identical to the conventional detergent bottle (Henkel AG & Co. KGaA 2024).

Assumptions and data

Only primary low-density polyethylene (LDPE) is used in the production of the 120 ml stand-up pouches for packaging detergent concentrate (Henkel AG & Co. KGaA 2024). The bottle for packaging the conventional liquid is made of a recycled polyethylene terephthalate (PET) corpus, polypropylene (PP) label and high-density polyethylene (HDPE) cap and has a volume of approximately 450 ml (Henkel AG & Co. KGaA 2024). Since formulation and functionality of both products are identical (cleaning of 180 place sets), the two main differences are the packaging and the life cycle stage in which the detergent is diluted. The latter effectively only influences transport processes when modeling for LCA which are cut off due to comparably insignificant contributions to the overall results (Nolte et al. 2025). This leaves the comparison of the two plastic packaging designs as the focus. It is assumed that 100 million of these packaged detergents are produced at the site each year based on the production volume of another type of product at that site (Henkel AG & Co. KGaA 2025b).

The action is intended to save packaging material through selling a thin pouch filled with concentrate instead of a comparably thick plastic bottle with a higher volume including diluting water. Theoretically, 84 % of initial material input can be avoided (see Table C 40) with a shift from pouch to bottle though a conventional bottle is still needed as a container to be refilled (Henkel AG & Co. KGaA 2024). Energy demand and plastic manufacturing processing are altered for each scenario based on the varied amount of plastic processed. The compositions of the packaging compositions are also summarized in Table C 40.

Table C 40: Compositions of examined packaging designs.

Background information	Amount	Share	Total packaging weight
PET bottle	12.6 g	86 %	14.6 g
HDPE cap	1.6 g	11 %	
PP label	0.4 g	3 %	
LDPE pouch	2.4 g	100 %	2.4 g
Mass saving if one bottle is replaced by one pouch	-12.2 g	-84 %	-

Scenarios

- Status quo: the status quo is the conventional detergent liquid being packaged in a plastic bottle comprising 86 % secondary material (PET) for its corpus, besides 11 % primary HDPE for the cap and 3 % PP label (see Table C 40).
- Best-case: as best-case scenario we assume that the conventional bottle is reused and refilled five times. This results in a shift of product sales – 83 % less bottles are therefore produced and replaced by LDPE refill pouches.

- Worst-case: in contrast, for worst-case scenario it is assumed that on average only one refill cycle is conducted leading to a reduction of 50 % less bottles sold and replaced with refill pouches.

LCI summary

The effects of the action on the manufacturing and end-of-life process and the LCI are summarized in the following Table C 41. To keep the LCI clear and concise, both packaging are assumed to be incinerated at the end-of-life. The functional unit to scale the effects of the action is defined as *one packaging unit for detergent liquid needed to clean 180 place sets*.

Table C 41: Summary of the LCI of the action: refill plastic pouch instead of conventional plastic bottle.

Process	Status quo	Best-case	Worst-case	Unit
Recycled PET	12.600	2.100	6.300	g/n
HDPE	1.600	0.267	0.800	g/n
PP	0.400	0.067	0.200	g/n
LDPE	0.000	2.000	1.200	g/n
Electricity mix DE (Germany)	0.002	0.001	0.001	kWh/n
Extrusion	0.400	2.067	1.400	g/n
Injection moulding	14.200	2.367	7.100	g/n
Stretch blow moulding	12.600	2.100	6.300	g/n
Treatment of mixed plastic waste	14.600	4.433	8.500	g/n
Amount of detergent	100,000,000	100,000,000	100,000,000	n/a

Fact sheet

Figure C 18 summarizes the action in an action fact sheet.

Refill concentrate plastic pouch instead of conventional plastic bottle				
Category	Case-specific: detergent manufacturer			
Intervention/ goal of the action	Produce a reuseable plastic pouch instead of a conventional plastic bottle.			
Operative indicator	Mass of each material used and how often the plastic pouch is reused			
Functional unit (FU) / scaling	One packaging unit for detergent liquid needed to clean 180 place sets			
Description of each scenario				
Status quo	The status quo is the conventional detergent liquid being packaged in a plastic bottle comprising 86 % secondary material (PET) for its corpus, besides 11 % primary HDPE for the cap and 3 % PP label.			
Best-case	As best-case scenario we assume that the conventional bottle is reused and refilled five times. This results in a shift of product sales – 83 % less bottles are therefore pro-duced and replaced by LDPE refill pouches.			
Worst-case	In contrast, for worst-case scenario it is assumed that on average only one refill cycle is conducted leading to a reduction of 50 % less bottles sold and replaced with refill pouches.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	0.007	0.022	0.041	0.038
CED [MJ-eq]	0.975	0.359	0.602	0.495
RMI [kg]	0.038	0.013	0.023	0.020
Land use [-]	0.292	0.077	0.163	0.172
Water use [m^3-eq]	0.025	0.008	0.015	0.013
Miscellaneous				
Coherence notes	This action interacts with the action “refill plastic pouch made of secondary materials”, if the used material for production is changed. These values may not be universally applicable due to their dependence on this specific case study.			
Associated R-strategy	Reuse			

Figure C 18: Fact sheet of the action: refill concentrate plastic pouch instead of conventional plastic bottle.

C 3.12.2 Refill plastic pouch made of secondary materials

Overview and applicability

This action is based on refill plastic pouches as product system (reuse bottle by refilling it with concentrate packed in a stand-up pouch). The key difference from the previous action is that the pouch is produced using recyclate instead of virgin LDPE. Therefore, this action can be linked to the use of plastic pouches. If a production plant already manufactures plastic pouches from primary materials, this action can also be considered independently.

Assumptions and data

The shift from the conventional detergent bottle to a refill pouch leads to a minimization of plastic packaging mass as outlined in the previous action but replaces secondary

material input (recycled PET) by primary material (LDPE). To overcome this trade-off, the LDPE pouch could be produced using secondary LDPE, although it must be noted that recycled LDPE processing may be challenging (Pawar et al. 2024).

Scenarios

- Status Quo: the pouch is produced using 100 % virgin feedstock.
- Best-case scenario: it is assumed that the pouch can be technically manufactured with 100 % recycled LDPE (Schulte et al. 2023).
- Worst-case scenario: based on the circularity potential of recycled LDPE preserving quantity and quality sustainably, a share of 30 % recycled feedstock is assumed for mechanically recycled LDPE leaving a primary material share of 70 % (Schulte et al. 2023).

LCI Summary

The effects of the action and the LCI are summarized in the following Table C 42. Any LCI that remains unchanged is excluded for clarity. The functional unit to scale the effects of the action is defined as *one packaging unit for detergent liquid needed to clean 180 place sets*.

Table C 42: Summary of the LCI of the action: refill plastic pouch made of secondary materials.

Process	Status quo	Best-case	Worst-case	Unit
LDPE	2.400	0.000	1.680	g/n
Recycled LDPE	0.000	2.400	0.720	g/n
Amount of detergent	100,000,000	100,000,000	100,000,000	n/a

Fact sheet

Figure C 19 summarizes the action in an action fact sheet.

Refill plastic pouch made of secondary materials				
Category	Case-specific: detergent manufacturer			
Intervention/ goal of the action	The pouch is produced using recyclate instead of virgin LDPE.			
Operative indicator	Share of recycled material			
Functional unit (FU) / scaling	One packaging unit for detergent liquid needed to clean 180 place sets			
Description of each scenario				
Status quo	The pouch is produced using 100 % virgin feedstock.			
Best-case	It is assumed that the pouch can be technically manufactured with 100 % recycled LDPE.			
Worst-case	Based on the circularity potential of recycled LDPE preserving quantity and quality sus-tainably, a share of 30 % recycled feedstock is assumed for mechanically recycled LDPE leaving a primary material share of 70 %.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	0.006	0.000	0.004	0.004
CED [MJ-eq]	0.205	0.011	0.147	0.126
RMI [kg]	0.007	0.000	0.005	0.004
Land use [-]	0.017	0.018	0.017	0.000
Water use [m^3-eq]	0.002	0.000	0.002	0.001
Miscellaneous				
Coherence notes	This action interacts with the action “refill concentrate plastic pouch instead of conventional plastic bottle”, if before no refill concentrate plastic pouch is used. These values may not be universally applicable due to their dependence on this specific case study.			
Associated R-strategy	Recycle			

Figure C 19: Fact sheet of the action: refill plastic pouch made of secondary materials.

C 3.13 Electronics industry

The case in the electronics industry focuses on one of the plastics used at the site: PA 6.6, which is utilized in the production process. The case-specific action aims to enhance internal recycling of production waste material.

C 3.13.1 Closed-loop blending of PA 6.6 regranulate in injection-molded housings

Overview and applicability

This action builds on case study 2 (electronics industry). Blending in-plant PA 6.6 regranulate with virgin PA 6.6 for injection-molded housings reduces primary material use and landfill while maintaining sector-typical quality and approvals through controlled shares and process observation (Mönikes 2025). The target scope comprises housings and covers in the electrical industry, with component families differentiated by color tolerance and mechanical requirements (Mönikes 2025). Constraints from the safety regulation

Underwriters Laboratories (UL) for regranulate use and the company's internal quality assurance must be respected (Mönikes 2025).

Assumptions and data

Regranulate obtained via mechanical-thermal processing provides more stable dosing and melt flows than raw regrind and reduces variability when blended with virgin material (Mönikes 2025). Default target blends lie between 25 % and 50 % regranulate by mass; higher shares require case-specific validation and approvals (Mönikes 2025). In line with UL 746D, regrind up to about 25 % of the waste mass is typically permitted by default, whereas regranulate usually requires special qualification (material identification, flammability/mechanical verification, recycler qualification) (Mönikes 2025). For regranulation, an electricity demand of 0.18–0.24 kWh/kg regranulate is used; 0.18 kWh/kg is applied in the best-case and 0.24 kWh/kg in the worst-case scenario ((Volk et al. 2021), based on (Großmann 2011)). In the status quo, waste PA 6.6 is assumed to be transported 50 km to an external recycler (Garcia-Gutierrez et al. 2023); in the closed loop, in-plant regranulation avoids these external transports. For 10,000 t/a of PA 6.6 output, a production waste share of 0.6 % is assumed in line with the ecoinvent "injection moulding" process, i.e., around 60 t/a are available for regranulation.

Scenarios

- Status quo: Housings are molded from 100 % virgin PA 6.6. Parts meet mechanical and color requirements. Process KPIs are stable under standard recipes. No internal recyclate is used. Rejects are transported 50 km to an external recycler.
- Best-case: Housings in the selected family are molded with a 50 %/50 % blend (regranulate/virgin). Regranulate is pre-dried to the processing moisture, screened and supplied in sealed packaging. Injection parameters are tuned to maintain dosing, pressure and cushion stability. Regranulation electricity demand is 0.18 kWh/kg regranulate.
- Worst-case: Housings in the selected family are molded with a 25 %/75 % blend (regranulate/virgin). Regranulate is pre-dried and screened. Minor adjustments to dosing/injection stabilize material use. Regranulation electricity demand is 0.24 kWh/kg regranulate.

Table C 43 summarizes the processes by scenario.

Table C 43: Scenario processes: closed-loop blending of PA 6.6 regranulate in injection molded housings.

Process	Status quo	Best-case	Worst-case	Unit
PA 6.6 granulate (virgin)	1.000	0.500	0.750	kg/kg waste PA 6.6
PA 6.6 regranulate (in-plant)	0.000	0.500	0.250	kg/kg waste PA 6.6
Electricity demand for regranulation	0.000	0.180	0.240	kWh/kg regranulate
Transport of waste PA 6.6	50.00	0.000	0.000	Km/transport

LCI summary

The production of polyamide 6.6 will use the nylon 6-6 production process from ecoinvent as its basis, as it is the closest available process. Transport assumptions are based on the soil treatment case study, utilizing a truck with a 24-ton load for the journey to the recycling plant and an empty truck for the return trip.

Table C 44 reports activity per mass of produced waste PA 6.6.

Table C 44: Per mass annual activity and LCI inputs by scenario: closed-loop blending of PA 6.6 regranulate in injection molded housings.

Process	Status quo	Best-case	Worst-case	Unit
PA 6.6 production	1.000	0.500	0.750	kg/kg waste PA 6.6
Electricity demand, DE (electricity demand for regranulation)	0.000	0.090	0.060	kWh/kg waste PA 6.6
Transport production plant -> recycling plant, TT 100 % load, Diesel	2.083	0.000	0.000	km/t waste PA 6.6
Transport recycling plant -> production plant, TT 0 % load, Diesel	2.083	0.000	0.000	km/t waste PA 6.6
Mass of waste PA 6.6	60	60	60	t/a

Fact sheet

Figure C 20 summarizes the action in an action fact sheet.

Closed-loop blending of PA 6.6 regranulate in injection molded housings				
Category	Case-specific: electronics industry			
Intervention/ goal of the action	This action builds on case study 2 (electronics industry). Blending in plant PA 6.6 regranulate with virgin PA 6.6 for injection molded housings reduces primary material use and landfill while maintaining sector typical quality and approvals through controlled shares and process gating. The target scope comprises housings and covers in the electrical industry, with part families differentiated by colour tolerance and mechanical requirements. Underwriters Laboratories (UL) constraints for regranulate use and the company's internal quality assurance gates must be respected).			
Operative indicator	Share of usable waste PA 6.6			
Functional unit (FU) / scaling	Mass of produced waste PA 6.6 (t)			
Description of each scenario				
Status quo	Housings are molded from 100 % virgin PA 6.6. Parts meet mechanical and colour requirements. Process KPIs are stable under standard recipes. No internal recyclate is used. Rejects are transported 50 km to an external recycler.			
Best-case	Housings in the selected family are molded with a 50 %/50 % blend (regranulate/virgin). Regranulate is pre dried to the processing moisture, screened and supplied in sealed packaging. Injection parameters are tuned to maintain dosing, pressure and cushion stability. Regranulation electricity demand is 0.18 kWh/kg regranulate.			
Worst-case	Housings in the selected family are molded with a 25 %/75 % blend (regranulate/virgin). Regranulate is pre dried and screened; minor adjustments to dosing/injection stabilize material use. Regranulation electricity demand is 0.24 kWh/kg regranulate.			
Effects for each scenario (LCIA)				
Impact [/a·FU]	**Status quo**	**Best-case**	**Worst-case**	**Mean benefit**
GWP [kg CO_2-eq]	8,229	4,150	6,193	3,057
CED [MJ-eq]	140,368	70,922	105,740	52,037
RMI [kg]	3,174	1,622	2,403	1,161
Land use [-]	90	139	126	-43
Water use [m^3-eq]	9,725	4,870	7,299	3,640
Miscellaneous				
Coherence notes	These values may not be universally applicable due to their dependence on this specific case study.			
Associated R-strategy	Recycle			

Figure C 20: Fact sheet of the action: closed-loop blending of PA 6.6 regranulate in injection molded housings.