Forschungsberichte

IPEK
Institut für Produktentwicklung
am Karlsruher Institut für Technologie

Michael Jäckle

Sustainability in Product Engineering – A Guide for Decision Makers to Initiate Targeted Action

Nachhaltigkeit in der Produktentstehung – Ein Leitfaden für Entscheidungsträger zum Initiieren zielgerichteten Handelns

Band 201

Systeme ▪ Methoden ▪ Prozesse

Univ.-Prof. Dr.-Ing. Dr. h.c. A. Albers
Univ.-Prof. Dr.-Ing. S. Matthiesen
(Hrsg.)

Forschungsberichte

Institut für Produktentwicklung
am Karlsruher Institut für Technologie

Michael Jäckle

Sustainability in Product Engineering – A Guide for Decision Makers to Initiate Targeted Action

Nachhaltigkeit in der Produktentstehung – Ein Leitfaden für Entscheidungsträger zum Initiieren zielgerichteten Handelns

Band 201

Herausgeber Univ.-Prof. Dr.-Ing. Dr. h.c. A. Albers
Univ.-Prof. Dr.-Ing. S. Matthiesen

ISSN 1615-8113

Sustainability in Product Engineering – A Guide for Decision Makers to Initiate Targeted Action

Zur Erlangung des akademischen Grades eines

DOKTORS DER INGENIEURWISSENSCHAFTEN (Dr.-Ing.)

von der KIT-Fakultät für Maschinenbau des

Karlsruher Instituts für Technologie (KIT)

angenommene

DISSERTATION

von

Michael Jäckle, M.Sc.

Tag der mündlichen Prüfung:	28.04.2026
Hauptreferent:	Univ.-Prof. Dr.-Ing. Dr. h. c. Albert Albers
Korreferent:	Prof. Dr. Orestis Terzidis

Vorwort der Herausgeber

Wissen ist einer der entscheidenden Faktoren in den Volkswirtschaften unserer Zeit. Der Unternehmenserfolg wird mehr denn je davon abhängen, wie schnell ein Unternehmen neues Wissen aufnehmen, zugänglich machen und verwerten kann. Die Aufgabe eines Universitätsinstitutes ist es, hier einen wesentlichen Beitrag zu leisten. In den Forschungsarbeiten wird ständig Wissen generiert. Dieses kann aber nur wirksam und für die Gemeinschaft nutzbar werden, wenn es in geeigneter Form kommuniziert wird. Diese Schriftenreihe dient seit mehr als 20 Jahren als eine Plattform zum Transfer und macht damit das Wissenspotenzial aus aktuellen Forschungsarbeiten am IPEK - Institut für Produktentwicklung Karlsruhe* am Karlsruher Institut für Technologie (KIT) verfügbar. Die Forschung des IPEK ist dabei strukturiert in die Kategorien Systeme, Methoden und Prozesse, um so der Komplexität heutiger Produktentwicklung ganzheitlich gerecht zu werden. Erst die Verknüpfung dieser drei Kategorien ermöglicht die Synthese innovativer Systeme durch Nutzung neuester Methoden und Prozesse. Gleichzeitig werden durch die Systemsynthese die erforschten neuen Methoden und Prozesse validiert und deren Mehrwert für die Praxis abgesichert. Dieses Forschungskonzept prägt nicht nur das IPEK-Leitbild, sondern auch den Charakter dieser Schriftenreihe, da immer alle drei Kategorien und deren Wechselwirkungen berücksichtigt werden. Jeder Band setzt hier individuelle Schwerpunkte und adressiert dabei folgende Forschungsgebiete des IPEK:

- das Entwicklungs- und Innovationsmanagement,
- die Entwicklungs- und Konstruktionsmethodik,
- der Leichtbau von der Ebene des ganzen Systems bis hinunter zur Optimierung des Bauteils,
- die Validierung technischer Systeme auch unter Berücksichtigung der NVH Aspekte (Noise, Vibration, Harshness) mit dem Fokus auf Schwingungen und Akustik an Komponenten und in den Gesamtsystemen sowie deren subjektiver Beurteilung durch den Menschen,
- die Antriebssystemtechnik mit den Schwerpunkten komplette Antriebslösungen für Fahrzeuge und Maschinen,
- das Design, die Tribologie und Erprobung von Kupplungen und Bremsen sowie
- die Gerätetechnik mit dem Schwerpunkt auf Power-Tools.

Die Forschungsberichte stellen Ergebnisse unserer Forschung sowohl anderen Wissenschaftlern als auch den Unternehmen zu Verfügung, um damit die Produktentwicklung in allen ihren Facetten mit innovativen Impulsen zu optimieren.

Albert Albers und Sven Matthiesen

* Eh.: Institut für Maschinenkonstruktionslehre und Kraftfahrzeugbau, Universität Karlsruhe (TH)

Vorwort zu Band 201

Die gesellschaftliche, politische und wirtschaftliche Diskussion um Nachhaltigkeit hat sich in den vergangenen Jahren deutlich intensiviert. Spätestens mit der Agenda 2030 und den 17 Sustainable Development Goals (SDGs) der Vereinten Nationen ist Nachhaltigkeit nicht mehr nur als allgemeines normatives Leitbild zu verstehen, sondern als ein zahlreiche konkrete Handlungsfelder betreffender Orientierungsrahmen. Die SDGs fordern in ihrer ganzen Breite ökologische, ökonomische und soziale Beiträge ein und machen damit deutlich, dass Nachhaltigkeit kein singuläres Ziel darstellt, wie es oft in der verkürzten Diskussion in der Gesellschaft, aber auch in der Politik, um die ökologische Nachhaltigkeit verstanden wird. Vielmehr ist Nachhaltigkeit als ein in zahlreiche konkrete Handlungsfelder auszudifferenzierender Ansatz zu verstehen. Daraus ergibt sich, dass der Aspekt der Nachhaltigkeit hinführt zu einem mehrdimensionalen Ziel- und Anforderungsgefüge in den unterschiedlichsten gesellschaftlichen und industriellen Kontexten. Besonders relevant ist in diesem Zusammenhang auch, dass die Vereinten Nationen nachhaltige Entwicklung ausdrücklich mit verantwortungsvollen Produktions- und Konsummustern, Ressourcenschonung, Emissionsminderung und langfristiger Transformationsfähigkeit verbinden, diese aber gleichzeitig auch eine Nachhaltigkeit in den Lebensbedingungen des Menschen und ein vergleichbares Wohlstandsniveau beinhaltet.

Für Unternehmen des produzierenden Gewerbes bedeutet diese Entwicklung, dass Nachhaltigkeit heute nicht mehr als randständige Kommunikationsaufgabe oder nachgelagerte Compliance-Frage behandelt werden kann. Vielmehr wirkt sie zunehmend in die strategische und operative Aufstellung von Produktentwicklung und Produktion hinein. Entscheidungen über Zielsysteme, Produktprogramme, Technologien, Werkstoffe, Prozesse, Lieferketten, Produktionssysteme und Produktionsstandorte stehen heute in einem deutlich engeren Zusammenhang mit Fragen der Ressourceneffizienz, der Zirkularität, der Klimaverträglichkeit und der gesellschaftlichen Verantwortbarkeit. Eine tatsächliche ganzheitliche Betrachtung des Aspekts der Nachhaltigkeit bedeutet also zwingend die Berücksichtigung eines System of Systems (SoS), das wir auch hier wiederfinden. Es gibt viele unabhängig voneinander agierende Teilsysteme, die aber trotzdem ganzheitlich zum Ziel der Nachhaltigkeit geführt werden müssen. Die auf Basis der Forderung nach Nachhaltigkeit entstandenen regulatorischen Anforderungen drängen auch immer stärker in Richtung nachhaltiger Produkte und Produktionsweisen. Ein Ausdruck dieser Entwicklung ist etwa die Europäische Verordnung zu Eco-Design-Anforderungen für nachhaltige Produkte, mit der Zirkularität, Energieeffizienz und weitere Nachhaltigkeitsaspekte von Produkten systematisch gestärkt werden sollen. Inwieweit dies aber dann zu Wettbewerbsnachteilen der Unternehmen auf den internationalen Märkten führt, ist immer mit zu bedenken. Dafür gibt es nach heutigem Stand noch keine Lösung, da solche Regularien nicht wirklich einheitlich in allen Teilen der Welt umgesetzt werden. Hinzu kommt, dass die Transformation unter sich zugleich verschärfenden Markt- und Wettbewerbsbedingungen erfolgt. Die internationale Wettbewerbsdynamik, volatile Energie- und Rohstoffkosten, Abhängigkeiten in den Lieferketten, beschleunigte Innovationszyklen sowie die fortschreitende Internationalisierung erhöhen den Handlungsdruck auf alle individuellen Unternehmen zusätzlich. Nachhaltigkeit ist damit nicht nur ein gesellschaftlich eingefordertes, oder regulatorisch gerahmtes Thema, sondern zunehmend auch ein Faktor unternehmerischer Wettbewerbsfähigkeit, Resilienz und Zukunftssicherung. Die Unternehmen müssen sich die Frage stellen: „Wie viel Nachhaltigkeit können wir ganzheitlich unter diesen Randbedingungen und zu einem bestimmten Zeitpunkt umsetzen, ohne im Markt ins Hintertreffen zu gelangen?“ Gerade für die Produktentwicklung entsteht daraus eine doppelte Herausforderung. Sie muss einerseits Antworten auf neue Nachhaltigkeitsanforderungen finden und andererseits unter globalem Wettbewerbsdruck wirtschaftlich tragfähige, technologisch realisierbare und marktfähige Lösungen hervorbringen. Die Europäische Kommission verweist in diesem Zusammenhang ausdrücklich darauf, dass Wettbewerbsfähigkeit, Resilienz und Nachhaltigkeit zunehmend zusammen betrachtet werden müssen und dass insbesondere hohe Energiepreise, Lieferkettenabhängigkeiten und internationaler Wettbewerbsdruck die industrielle Handlungsfähigkeit signifikant herausfordern.

Vor diesem Hintergrund gewinnt die wissenschaftliche Auseinandersetzung mit dem Thema Nachhaltigkeit - ganzheitlich verstanden - in der Produktentstehung erheblich an Bedeutung. Gerade in der Produktentwicklung und den, mit ihr eng verbundenen Bereichen der Produktplanung und der Produktion, werden wesentliche Weichenstellungen für die spätere ökologische, ökonomische und soziale Wirkung technischer Systeme kreiert. Zugleich stehen Entscheidungsträger in den Unternehmen vor der Herausforderung, vielfältige dynamische und teilweise widersprüchliche Ziele und Anforderungen in tragfähige unternehmerische Handlungslogiken zu überführen. Die vorliegende Dissertation von Herrn Dr.-Ing. Michael Jäckle greift genau dieses Spannungsfeld auf. Herr Jäckle widmet sich der Frage, wie Entscheidungsträger in der Produktentstehung dabei unterstützt werden können, unter Unsicherheiten zielgerichtetes nachhaltigkeitsbezogenes Handeln zu verstehen, zu operationalisieren und in den Unternehmenskontext zu implementieren. Sein Ansatz berücksichtigt dabei auch die Wirkung auf die Entwicklung des Unternehmens im Sinne einer auch ökonomischen Wettbewerbsfähigkeit. Damit behandelt die Arbeit ein hoch aktuelles, für die Wissenschaft wie industrielle Unternehmenspraxis gleichermaßen relevantes Thema.

April 2026 Albert Albers

Abstract

Decision makers in product engineering face a high degree of uncertainty about targeted action on sustainability demands. Diverse, potentially inconsistent, and dynamic sustainability demands can expose companies to overlooked risks and untouched opportunities emerging from these demands if they do not act in a targeted manner.

Although product engineering and sustainability have been extensively researched, no consensus on sustainability in product engineering could be found in the existing literature. In particular, support for decision makers that addresses their uncertainty and helps them to act on diverse and dynamic sustainability demands in a targeted manner represents a gap. To bridge this gap, the challenge of developing broad, yet context-specific and actionable support must be overcome.

Therefore, a Guide for decision makers to initiate targeted sustainability action was developed as part of this problem-centered thesis. Systematic literature reviews informed an interview study with 25 participants, including seven consultants and 18 decision makers from four manufacturing companies. Using a grounded theory approach based on the Gioia Methodology, generalizable aspects – in terms of transferability to other contexts – of targeted sustainability action were identified based on the interview data. Based on these findings, the guide was iteratively developed and successfully applied in three studies consisting of company workshops, expert discussions, and a company project.

Generalizable aspects describe the understanding, operationalization, and implementation of targeted sustainability action in product engineering through challenges, success criteria, and the practices that constitute targeted sustainability action. The Guide supports decision makers in (1) understanding targeted sustainability action based on context-specific risks and opportunities to identify company-specific objectives, (2) operationalizing targeted sustainability action in product engineering through practices to create clarity on action, and (3) implementing targeted sustainability action by pragmatically establishing and facilitating practices until they become fully integrated routines.

The generalizable aspects and thus the Guide oppose the unreflected adoption of pre-fixed sustainability conceptions and emphasize the entrepreneurial character of sustainability action. To support decision makers in addressing their uncertainty and initiating targeted sustainability action, these results suggest a material understanding of targeted sustainability action from a company perspective, conscious decision-making for clarity in action, and pragmatism in implementation. The thesis concludes with a reflection on the limitations and implications of the results on the development of support for decision makers.

Kurzfassung

Entscheidungsträger in der Produktentstehung sehen sich mit einem hohen Maß an Unsicherheit hinsichtlich eines zielgerichteten Umgangs mit Nachhaltigkeitsbedarfen konfrontiert. Vielfältige, potenziell widersprüchliche und dynamische Nachhaltigkeitsbedarfe können Unternehmen übersehenen Risiken und ungenutzten Chancen aussetzen, wenn sie nicht zielgerichtet handeln.

Obwohl Produktentstehung und Nachhaltigkeit bereits intensiv wissenschaftlich untersucht wurden, konnte in der vorhandenen Literatur kein Konsens über Nachhaltigkeit in der Produktentstehung gefunden werden. Insbesondere eine Unterstützung für Entscheidungsträger, die ihre Unsicherheit adressiert und ihnen hilft, zielgerichtet bezüglich vielfältigen und dynamischen Nachhaltigkeitsbedarfen zu handeln, stellt eine Lücke dar. Um diese Lücke zu schließen, muss die Herausforderung überwunden werden, eine umfassende, aber dennoch kontextspezifische und handlungsorientierte Unterstützung zu entwickeln.

Daher wurde im Rahmen dieser problemorientierten Arbeit ein Leitfaden für Entscheidungsträger zur Initiierung zielgerichteten nachhaltigkeitsbezogenen Handelns entwickelt. Systematische Literaturrecherchen bildeten die Grundlage für eine Interviewstudie mit 25 Teilnehmern, darunter sieben Unternehmensberater und 18 Entscheidungsträger aus vier produzierenden Unternehmen. Unter Verwendung eines Grounded-Theory-Ansatzes basierend auf der Gioia-Methodik wurden anhand der Interviewdaten generalisierbare Aspekte – im Sinne der Übertragbarkeit auf andere Kontexte – von zielgerichtetem nachhaltigkeitsbezogenem Handeln in der Produktentstehung identifiziert. Auf der Grundlage dieser Ergebnisse wurde iterativ ein Leitfaden entwickelt und erfolgreich in drei Studien bestehend aus Unternehmensworkshops, Expertendiskussionen und einem Unternehmensprojekt angewendet.

Die generalisierbaren Aspekte beschreiben das Verständnis, die Operationalisierung und die Implementierung zielgerichteten nachhaltigkeitsbezogenen Handelns in der Produktentstehung anhand von Herausforderungen, Erfolgskriterien und der Praktiken, die zielgerichtetes nachhaltigkeitsbezogendes Handeln in der Produktentstehung beschreiben. Der Leitfaden unterstützt Entscheidungsträger dabei, (1) zielgerichtetes nachhaltigkeitsbezogenes Handeln auf der Grundlage kontextspezifischer Risiken und Chancen zu verstehen, um unternehmensspezifische Ziele zu identifizieren, (2) zielgerichtetes nachhaltigkeitsbezogenes Handeln in der Produktentstehung durch Praktiken zu operationalisieren, um Klarheit im Handeln zu schaffen, und (3) zielgerichtetes nachhaltigkeitsbezogenes Handeln zu implementieren, indem Praktiken pragmatisch eingeführt und begleitet werden, bis sie zu vollständig integrierten Routinen werden.

Die generalisierbaren Aspekte und damit auch der Leitfaden sprechen gegen eine unreflektierte Übernahme vordefinierter Nachhaltigkeitskonzepte und betonen den unternehmerischen Charakter von nachhaltigkeitsbezogenem Handeln. Um Entscheidungsträger darin zu unterstützen, ihre Unsicherheit zu adressieren und zielgerichtetes nachhaltigkeitsbezogenes Handeln in der Produktentstehung zu initiieren, legen diese Ergebnisse ein konkretes Verständnis von zielgerichtetem nachhaltigkeitsbezogenem Handeln aus Unternehmensperspektive, eine bewusste Entscheidungsfindung für Klarheit im Handeln, sowie Pragmatismus in der Implementierung nahe. Die Arbeit schließt mit einer Reflexion der Limitationen und Implikationen dieser Ergebnisse auf die Entwicklung von Unterstützung für Entscheidungsträger.

Use of Artificial Intelligence

DeepL and Writefull were used by the author to ensure concise translations as well as to improve wording, spelling, and grammar of this thesis. The use of Trint to transcribe the interview recordings is described as part of the research methodology of this thesis.

Contents

List of Figures

List of Tables

List of Abbreviations

CBAM	Carbon Border Adjustment Mechanism
CoC	Center of Competence
CSR	Corporate Social Responsibility
CSRD	Corporate Sustainability Reporting Directive
DfX	Design for X
DRM	Design Research Methodology
DSI	Descriptive Study I
DSII	Descriptive Study II
ERP	Enterprise Resource Planning
ESG	Environmental, Social, Governance
FSSD	Framework for Strategic Sustainable Development
GRI	Global Reporting Initiative
ID	Identifier
iDSDM	integrated Design Support Development Model
iPeM	integrated Product engineering Model
KaSPro	Karlsruhe School of Product Engineering
KPIs	Key Performance Indicators
LCA	Life Cycle Assessment
n/a	no answer
NDC	Nationally Determined Contribution
NGOs	Non-Governmental Organizations
OEM	Original Equipment Manufacturer
PS	Prescriptive Study
RC	Research Clarification

SBTi	Science Based Targets initiative
SDGs	Sustainable Development Goals
SGE	System Generation Engineering
SLR	Systematic Literature Review
TBL	Triple Bottom Line
TSA	Targeted Sustainability Action
WCED	World Commission on Environment and Development

1 Introduction

1.1 Motivation

In recent years, sustainability has become a major strategic pillar for many companies (Doherty, Kampel, Koivuniemi, Pérez, and Rehm, 2023; Granskog, Ahlawat, Kalavar, and Agarwal, 2024; KPMG, 2024). Driven by regulation, market demands, and other drivers, sustainability targets have been publicly set at the global, country, and company levels (Science Based Targets initiative, 2024; Bland, Corb, Granskog, Nauclér, and Siccardo, 2023; Llanos et al., 2022), and industrial alliances have been formed (Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, n.d.; Bland et al., 2023).

As time progresses, these (public) commitments are increasingly raising expectations among some company stakeholders about implementation and fulfillment (Department of Economic and Social Affairs, 2024; e.g., United Nations Development Programme, 2019; von der Gathen et al., 2024). At the same time, in many markets, the economic situation has changed, e.g., due to geopolitical reasons (Grant et al., 2023) and/or regulatory insecurity (Crispeels et al., 2023), forcing companies to take a short-term perspective and a focus on cost reduction (Corb et al., 2023; Cavaciuti-Wishart et al., 2024), while also fragmenting stakeholder priorities in a non-linear way (Cavaciuti-Wishart et al., 2024).

Under these volatile circumstances, uncoordinated sustainability action within companies can carry multiple risks involving unknown blind spots, with potential negative impacts of action on these blind spots (Kravchenko et al., 2021; Hallstedt et al., 2020), and even greenwashing in the organization (Urbański and ul Haque, 2020). At the same time, if companies do not act, they risk missing targets (Hallstedt et al., 2020), increasing their talk-walk gap (Bland et al., 2023) and could face a loss of scope of action (Hallstedt et al., 2020). Thus, to counteract such risks, companies must act in a targeted manner on sustainability demands relevant to them (Corb et al., 2023; Petersen, 2021; Granskog et al., 2024).

In this targeted action on relevant sustainability demands, product engineering is expected to play an important role in leveraging opportunities such as competitive advantages, technological advancement, growth, and synergies with cost targets, if done successfully (Billing et al., 2021; Doherty et al., 2023; Cavaciuti-Wishart et al., 2024; Bohnsack et al., 2020; Diaz et al., 2022). In addition, long development cycles (Liu et al., 2021) further increase the pressure for early action in product engineering, as they can delay fulfilling demands and cause inertia with changing circumstances.

However, decision makers who perform product engineering and shape its conditions face a high degree of uncertainty about sustainability action (Shu, 2022; Petersen, 2021; Hallstedt et al., 2020). Sustainability demands do not only amplify objective technological, market, and regulatory uncertainties emerging from the external environment, but also create additional subjective uncertainty among decision makers (Shu, 2022) within and beyond product engineering (Kravchenko et al., 2021). This becomes evident in hesitation (Hallstedt et al., 2020; Kortus and Gutmann, 2023), deferred decisions (Hallstedt et al., 2020), firefighting (Missimer and Mesquita, 2022) and unclear guidance for engineers (Delaney, Liu, Zhu, Xu, and Dai, 2022). Thus, these uncertainties limit decision makers in their ability to take advantage of the opportunities that emerge from sustainability demands. “Hence, to allow companies to successfully navigate the opportunities and risks emerging from … sustainability [demands] and initiate sustainability action in a targeted manner, decision makers need support to understand and address … [objective and subjective] uncertainties appropriately” (Jäckle et al., 2025, p. 1). (see also Jäckle et al., 2025)

This need to address the uncertainty of decision makers about sustainability action and to support them, was initially identified through the industry experience of the author, and was confirmed in eight exploratory expert discussions[1] conducted as part of the research clarification, with four senior product engineering decision makers from manufacturing companies and four experienced consultants. During the discussions, the experts emphasized the uncertainties of decision makers about prioritizing demands, operationalizing sustainability action, and achieving sustainable change within their respective organizations, among other things. The acquired insights further motivated and detailed the focus of this thesis.

[1] The eight exploratory expert discussions were conducted in 2022 and 2023, with a duration of 30 to 60 minutes and documented through note-taking by the author.

1.2 Focus of This Thesis

This thesis aims to address the uncertainty of decision makers about sustainability action in product engineering. By synthesizing the findings into a suitable support for decision makers, the overarching objective of this thesis is to enable decision makers to take advantage of opportunities and mitigate risks emerging from sustainability demands through targeted action (or inaction); in other words, to initiate targeted sustainability action.

Through its problem focus and, therefore, decision makers' perspective, this thesis can be located at the intersection of the research disciplines of engineering and organization sciences. In terms of content, this thesis connects the two fields of product engineering and sustainability, starting from a product engineering conception based on the KaSPro – Karlsruhe School of Product Engineering (see Chapter 2.1). Moral judgments and the topic of responsibility are explicitly delimited from this thesis, acknowledging the background of the author in engineering sciences and the limitations of his expertise (see also Chapters 2.2 and 3.1). Thus, this thesis addresses decision makers in product engineering and collaborators facing uncertainties about action on sustainability demands, as well as researchers studying sustainability action in product engineering.

1.3 Structure of This Thesis

The structure of this thesis is described below and summarized in Figure 1.1. To start from a common ground, the foundational terms and conceptions of product engineering and sustainability, as the adjacent fields of research to the objective of this thesis, are discussed in Chapters 2.1 and 2.2. Then, the perspective of decision makers in product engineering on the existing literature at the intersection of both fields is considered (Chapter 2.3). Therefore, an extensive body of literature was collected and analyzed in multiple steps. First, existing conceptions of sustainability in product engineering were identified and are discussed in Chapter 2.3.1. As no consensus on terminology could be found, the underlying understanding of sustainability in product engineering was analyzed in this body of literature (Chapter 2.3.2). Then, the existing support relevant to the objectives of this thesis was analyzed (Chapter 2.3.3).

Based on the remaining gap in the support provided by the literature with respect to the practical problem outlined in Chapter 1.1, the main challenge to be overcome to bridge this gap was derived: Broad, yet context-specific and actionable support for decision makers on targeted sustainability action in product engineering. The two respective research needs to be addressed are, (1) identifying generalizable aspects of targeted sustainability action and, (2) supporting decision makers on its initiation by addressing their uncertainty (Chapter 3). The objective of this thesis is to overcome this challenge and address these two research needs. To structure further research, the needs are broken down into four research questions. They cover the first research need, generalizable aspects of targeted sustainability action, in three parts, each with one question: Understanding, operationalization, and implementation. The support for decision makers, as the second research need, is covered by the fourth research question.

To answer these research questions and achieve the objective of this thesis, a systematic but problem-centered research methodology was needed, which is described in Chapter 4. Selected elements of the Design Research Methodology (DRM) by Blessing and Chakrabarti (2009) to provide an overall structure to the thesis and the integrated Design Support Development Model (iDSDM) by Marxen (2014) to structure the research activities were combined (Chapter 4.1). The overarching empirical and literature-based methods are described in Chapter 4.2, while aspects of the analyses that are specific to the research questions are discussed in the respective results chapters.

The results of this thesis are organized along the two research needs (generalizable aspects and support for decision makers) and the four research questions. Addressing the first research need represents the core part of the Descriptive Study I (DS I), which is based on literature reviews and an interview study. In this context, Chapter 5 addresses the understanding of targeted sustainability action, by answering the first research question covering the first part of the generalizable aspects. Chapter 6 addresses the second part of the generalizable aspects, the operationalization of targeted sustainability action, by answering the second research question. Chapter 7 addresses the third part of the generalizable aspects, the implementation of targeted sustainability action, by answering the third research question. Chapter 8 covers the second research need, the support aimed at addressing the uncertainty of decision makers and helping them initiate targeted sustainability action. The DS I is concluded by consolidating a system of objectives for the support to be developed, which is then operationalized and describes the intended support (Chapter 8.1). The support is realized as a Guide that is developed and evaluated in three studies (Chapters 8.2 to 8.4), parallelizing the prescriptive study (PS) and the descriptive study II (DS II) in an iterative way. The developed Guide itself can be found in the Appendix A.1. Finally, overarching conclusions are drawn and the outlook is discussed in Chapter 9.

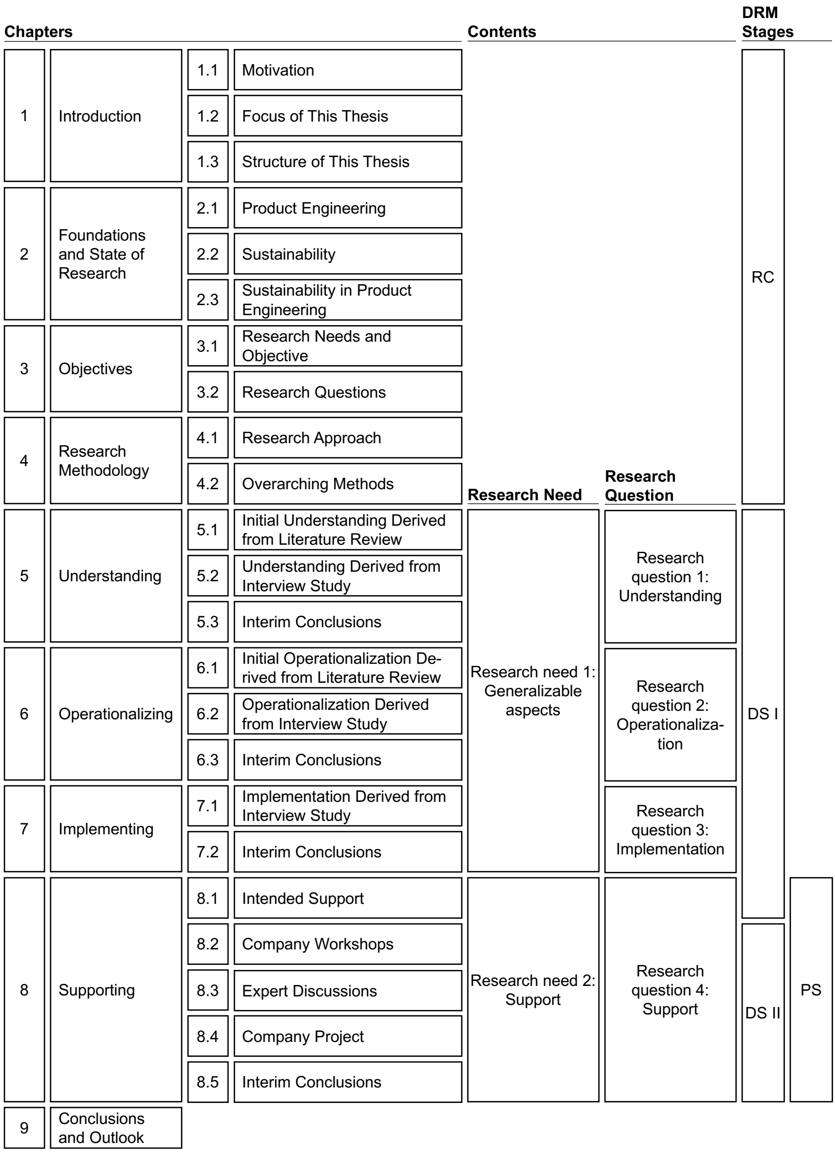

Figure 1.1: Structure of This Thesis

2 Foundations and State of Research

In this chapter, the foundations referenced in this thesis and the relevant state of research are discussed. It is divided into three sections. First, the foundations of product engineering are covered in Chapter 2.1, and second, the field of sustainability is covered in Chapter 2.2. For both areas, relevant conceptions are outlined and discussed as part of the respective interim conclusions, before their intersection – sustainability in product engineering – and its state-of-the-art is analyzed based on systematic literature reviews (SLRs) in Chapter 2.3. An overview of the adjacent research fields and the chapter structure can be found in Figure 2.1.

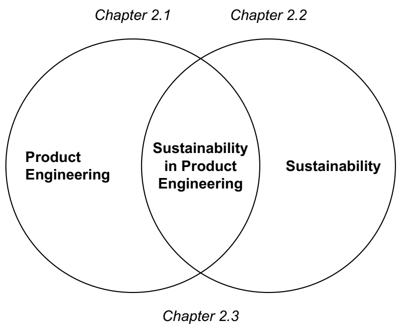

Figure 2.1: Research Fields Adjacent to the Focus of This Thesis and Structure of Chapter 2

2.1 Product Engineering

As described in Chapter 1.1, product engineering can play a key role in capturing opportunities emerging from sustainability demands, while at the same time it is subject to uncertainty, amplified through these demands. Thus, to openly explore sustainability action in product engineering, a conception of product engineering is required that acknowledges the lack of clarity concerning this action at the beginning of this research project. Therefore, using the KaSPro – Karlsruhe School of Product Engineering as starting point, relevant action-oriented conceptions of product engineering from engineering and organization sciences are discussed in Chapter 2.1.1, before the key terms in this thesis are defined on the basis of these conceptions as part of the interim conclusions in Chapter 2.1.2. The structure of Chapter 2.1 and the key conceptions discussed are summarized in Figure 2.2.

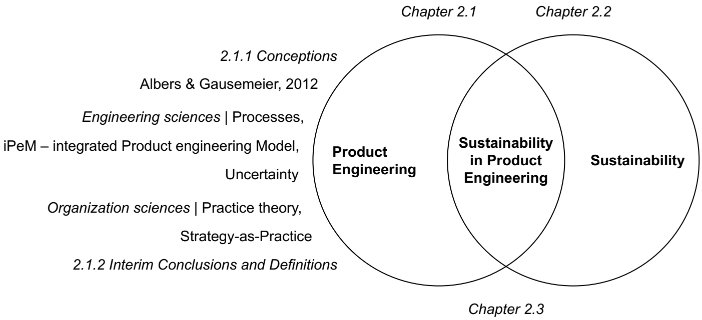

Figure 2.2: Key Conceptions of Product Engineering Relevant to This Thesis and Resulting Structure of Chapter 2.1

2.1.1 Conceptions

According to Albers and Gausemeier (2012), product engineering can be described through “the three main task areas, strategic product planning, product development, and production system development” (p. 18). In this conception, strategic product planning comprises activities to create “the economic basis of a product” eventually resulting in a development order (Albers and Gausemeier, 2012, p. 18). Product development encompasses creating a concept of the product and designing it by involving and integrating all relevant disciplines. Similarly and closely interlinked, the activities of the production system development cover the concept and design of the production system (Albers and Gausemeier, 2012).

Albers and Gausemeier (2012) further classify product engineering as “part of the product life cycle” (p. 18) and provide a respective life cycle model from a product perspective, where product engineering is followed by manufacturing, distribution, use, and return. Such product life cycle models can be based on various perspectives (e.g., resource-based or economically market-focused, Verein Deutscher Ingenieure, 2019), and are a common conception, e.g., used for product sustainability considerations (Östlin, Sundin, and Björkman, 2009; Sakao and Sundin, 2019; see also Chapter 2.3.2, Jäckle et al., 2023, and Tusch, Jäckle, and Albers, 2024).

Within that product life cycle, Albers and Gausemeier (2012) describe product engineering as “the basic process from the product or business idea to the start of production” (p. 18) describing product engineering itself also as a process. Comparable process descriptions of varying degrees of formalization are a common conception of product engineering in engineering sciences (Verein Deutscher Ingenieure, 2019; Wynn and Clarkson, 2024). The widespread description of product engineering from a process perspective (Wynn and Clarkson, 2024) has resulted in various process models being available. They can be differentiated from each other in degree of detail and degree of formalization (Verein Deutscher Ingenieure, 2019). Examples are the 3-cycle model of product creation with a low degree of formalization and a medium degree of detail, and the sector-specific V model (see also Verein Deutscher Ingenieure, 2021) with a medium degree of formalization and detail (Verein Deutscher Ingenieure, 2019).
The iPeM – integrated Product engineering Model (see Figure 2.3) by Albers et al. (2016) is characterized by a high degree of detail, while at the same time a low degree of formalization compared to other models (see Verein Deutscher Ingenieure, 2019).

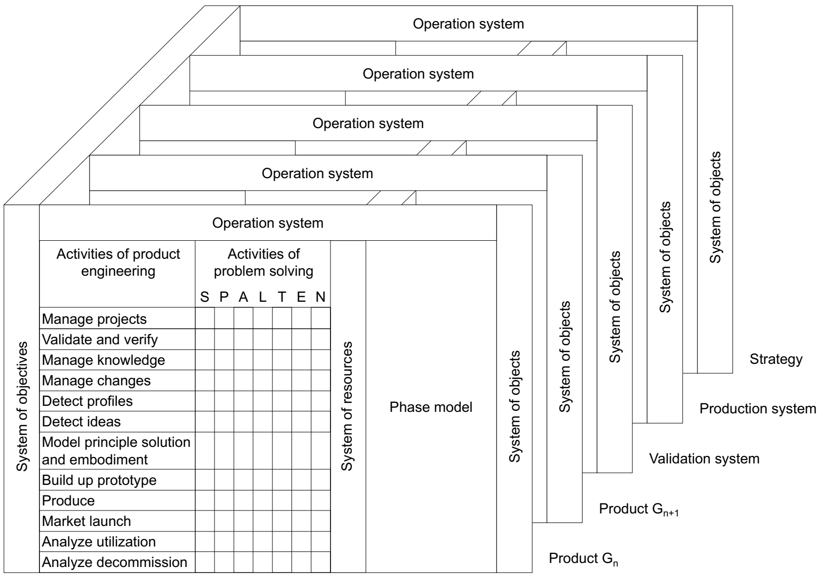

Figure 2.3: iPeM – integrated Product engineering Model (adapted from Albers et al., 2016)

The initial version of the iPeM by Albers (2010) is based on five hypotheses of product engineering that form the fundamental concepts of the iPeM as part of the KaSPro – Karlsruhe School of Product Engineering: The uniqueness of engineering processes, the system triple of product engineering, the validation, the objective description in problem solving, and the functional description. The system triple of product engineering structures the iPeM based on the system theory by Ropohl (1999). Thus, it introduces a systems perspective to the process conception of product engineering, which enables the iPeM's meta-model character motivated by the uniqueness of engineering processes. The three systems comprising the system triple are the system of objectives, the operation system, and the system of objects. The operation system continuously interacts in cycles of analysis and synthesis with the system of objectives and the system of objects. The operation system is modeled through an activity matrix that includes the activities of product engineering (see Figure 2.3) and the activities of problem solving (based on the SPALTEN problem solving process; see Albers, Burkardt, Meboldt, and Saak, 2005 for details), as well as the resource system and the phase model. From the activity matrix, a unique product engineering process can be derived and modeled in the phase model, considering the available resources, such as capital, employees, or energy, which are summarized as the system of resources. (Albers, 2010)

Albers et al. (2016) introduce a second version of the iPeM, which details additional aspects of product engineering based on the KaSPro and, in its illustration, expand it to a three-dimensional model spanning several layers (see Figure 2.3). The layers are connected through a single system of objectives and a single system of resources, but have distinct operation systems and systems of objects. The product layers now integrate the generational aspect of product engineering based on the Model of SGE – System Generation Engineering, which describes that systems, in this case products, are developed based on reference systems through three types of variation: Carry-over, attribute, and principle variation (Albers, Bursac, and Wintergerst, 2015; Albers and Rapp, 2022). Thus, the development of each product generation is represented through a layer, for example, a product generation currently in development G_n, or the subsequent generation G_{n+1}. In addition, the validation system, the production system and the underlying strategy are modeled through separate layers, again with their operation system and system of objects. (Albers et al., 2016)

Building on the iPeM, Arslan, Haug, Heitger, Kraemer, and Albers (2016) develop an initial proposal to detail the strategy layer through an activity-based framework to support the management of strategic complexity. They derive activities similar to the product layer and divide them into two phases. In the first phase, “Identification & Evaluation”, they start from trends that result in product variations and derive their impact on four categories: Competencies, infrastructure, processes, and organization. In a second phase, “Implementation”, they describe the derivation of measures and

their implementation. (Arslan et al., 2016)
Arslan, Bursac, Killer, and Albers (2018) further detail the strategy layer of the iPeM by describing the “strategic development of the system of resources” (p. 12). Here, Arslan et al. (2018) propose seven subsystems to detail the system of resources: Organization, processes, capacities, competencies, finance, infrastructure, and cooperations, which are to be adjusted in generations through activities described in the strategy layer. In addition, they emphasize the interaction between the layers of iPeM through the system of resources and the system of objectives and describe it through requirements and measures. Moreover, they introduce a generational character in strategy development similar to the product layers. (Arslan et al., 2018)
Stammnitz (2025) details a strategy process in the context of medium-sized companies based on the generational character of strategy development and the activities of the SPALTEN problem solving process, which are also found in the iPeM (see above). Moreover, Stammnitz (2025) introduces the concept of assets to describe “all elements that a company needs to operate a business unit” (p. 21) and also links them to the system of resources in the iPeM.
While the broader context of product engineering is often modeled as influencing factors, which are structured along various categorizations and levels (see, e.g., Hales and Gooch, 2004; Albers and Gausemeier, 2012; Wilmsen, Dühr, and Albers, 2019; Verein Deutscher Ingenieure, 2019), the authors above use and augment the iPeM meta-model from a strategy perspective to describe interdependencies within product engineering, as well as between product engineering and its conditions through the system of resources. Thus, for example, the organization (e.g., the company) in which product engineering is performed can be modeled as an influencing factor or as a subsystem to the system of resources depending on the respective purpose.

In parallel to the expansion of the iPeM itself, Albers, Lohmeyer, and Ebel (2011) extend the system triple as part of the KaSPro, taking a people-centered perspective. Albers et al. (2011) interpret the operation system as designers that analyze and synthesize the system of objectives and the system of objects in iterative cycles. Moreover, they highlight the subjective perspective that designers have on potential action and the uncertainty under which designers act (Albers et al., 2011). Thus, they link uncertainty and action in their description through a lack of knowledge in analysis and a lack of definition in synthesis (Albers et al., 2011).
The uncertainty in product engineering has already been addressed more broadly by Muschik (2011), who defines uncertainty in product engineering from a systems perspective as “a state in which several potential outcomes are possible” (p. 34). Muschik (2011) further describes that uncertainty in its basic character can be reducible or irreducible and that the effects of uncertainty are risks and opportunities

that can be coped with by “reducing uncertainty or by protecting the respective system” (p. 34). Alquist and Baumeister (2024) distinguish subjective uncertainty from objective uncertainty in a psychological context, where subjective uncertainty can be reduced by seeking information, and objective uncertainty, similarly to Muschik (2011), describes a situation with multiple outcomes not yet determined.

In organization sciences, multiple perspectives are prevalent that might serve as a lens on organization and product engineering within an organization, such as the resource-based view (Wernerfelt, 1984), dynamic capabilities (Teece, Pisano, and Shuen, 1997), or complementary assets (Teece, 1986). Another particularly action-oriented perspective on organizations is that of practice theory (Feldman and Orlikowski, 2011; Feldman and Worline, 2016). Practice theory focuses on the actions of people, their relations, and how these actions constitute organizations (Feldman and Orlikowski, 2011). Findings related to these aspects are not universal, however, they allow for a generalization of situated dynamics to understand other contexts (Feldman and Orlikowski, 2011). Thus, practice theory can be used to teach the theory itself, to convey “best practices,” but also to support practitioners to “assess and engage with practices relevant to their organization” (Feldman and Worline, 2016, p. 320).
A common area of application of practice theory is strategy (Feldman and Orlikowski, 2011), forming the research field of strategy-as-practice in which strategy is seen as “something that people do” (Jarzabkowski and Spee, 2009, p. 71) across the levels of an organization (Feldman and Worline, 2016), instead of something static that organizations possess (Feldman and Orlikowski, 2011).

Jarzabkowski and Spee (2009) review the field of strategy-as-practice, outlining relevant concepts. They emphasize focusing on people (groups or individuals) directly or indirectly involved in strategy work, referred to as “strategy practitioners” (Jarzabkowski and Spee, 2009, p. 70). They call the flow of activities in which the strategy is accomplished “praxis” (Jarzabkowski and Spee, 2009, p. 70). This praxis can span across multiple levels, from individual actions (micro actions), over (sub-)organizational patterns or processes, to patterns of action on the industry level (Jarzabkowski and Spee, 2009). Jarzabkowski and Spee (2009) find that there is no common conception of practices in this field of research, however, they characterize practices as “social, symbolic and material tools through which strategy work is done” (p. 70). Jarzabkowski, Kaplan, Seidl, and Whittington (2016) further specify practices as “shared and recognizable ways of doing things” (p. 271), which are enacted by actors depending on their individual context. Moreover, Jarzabkowski and Spee (2009) cite Jarzabkowski and Whittington (2008), who state that practices involve “various routines, discourses, concepts, and technologies through which strategy labor is made possible … [including] those embedded in … material technologies and artifacts" (p. 101). Thus, practice theory takes a new perspective on resources, as "potential resources only become resources when they are used in practice" (Feldman and Worline, 2016, p. 311). The emergence of practice theory also affects the conceptualization of routines and their dynamics (Feldman and Worline, 2016) that can be characterized by "repetition, a recognizable pattern of action, multiple participants, and interdependent actions" (Feldman and Pentland, 2003, p. 103) that are not necessarily documented (e.g., as a process; Feldman and Pentland, 2003). Such routines can retain patterns of action, but can also be sources of change in two ways, as "meta-routines" for renewal (e.g., forming continuous improvement, total quality management, or generating dynamic capabilities), or by their performance (Feldman and Pentland, 2003, pp. 94, 112). And, they "encode organizational capabilities and knowledge" and are therefore the foundation for organizational learning (Feldman and Pentland, 2003, p. 98). Moreover, Feldman and Pentland (2003) highlight the subjectivity and agency associated with such routines that imply the decision of whether and how to act by any actor, as a result of the individual interpretation of interdependent practices that constitute routines.

2.1.2 Interim Conclusions and Definitions

With respect to sustainability action in product engineering, aspects of the two perspectives from engineering and organization sciences are combined to provide a basis for this thesis.

On the one hand, the perspective of engineering sciences clearly delimits the task areas of product engineering and introduces a process conception. With the iPeM – integrated Product engineering Model as a meta-model of product engineering, a systems perspective and foundational activities of product engineering are introduced. Thus, a characterization of product engineering without overly narrowing its conception at an early stage of research is enabled. The discussion not only shows the broad variety of activities, from strategic to operational as well as their dynamic interdependence, but also sheds light on the conditions under which these activities are executed. In addition, complementary research addresses subjective perspectives and the uncertainties under which product engineering takes place.

On the other hand, with practice theory organization science offers a perspective on organizations and action in organizations, and thus an action-oriented lens, that is compatible with the characteristics of the product engineering conception above. Therefore, by combining practice theory with a detailed understanding of product engineering, the fundamental terms used in this thesis can be clearly defined. At the same time, the resulting conception of product engineering enables an open exploration of sustainability action in product engineering.

In this thesis, *product engineering* is defined in line with Albers and Gausemeier (2012), and is thus described as practices related to strategic product planning, product development, and production system development. Therefore, drawing on Jarzabkowski and Spee (2009), product engineering can also be described as a flow of interdependent practices and their entirety as praxis.

Practices are defined as actions of individuals and groups. Following Jarzabkowski and Whittington (2008) and Feldman and Worline (2016) these practices also explicitly describe the provision and use of material and immaterial resources. Moreover, the definition and configuration of such practices is also described as practice and referred to as *operationalization*, while establishing and enacting practices is referred to as *implementation*. Both are closely interlinked. In this thesis, repetitive patterns of interdependent practices are called *routines*, which are not necessarily static or documented (following Feldman and Pentland, 2003).

People acting (individuals and groups, who define and enact practices) are called *decision makers* in this thesis to emphasize their agency and subjectivity in action. With respect to product engineering, the actions and attitudes of decision makers who are involved in product engineering or shape the conditions of product engineering are of special interest.

Uncertainty is understood here from the perspective of these decision makers. Its definition in this thesis therefore follows Muschik (2011) and emphasizes subjectivity according to Alquist and Baumeister (2024). Thus, uncertainty can be caused by both a lack of information and a situation with multiple potential outcomes. The former is called subjective uncertainty, which can thus be addressed through information. Situations with multiple potential outcomes are referred to as objective uncertainty, which, however, is also perceived subjectively by decision makers. In both cases and in combination, this uncertainty may be reducible or irreducible.

With these terms, a decision maker's perspective on product engineering and action in product engineering can be described. The definitions thus provide first foundations for investigating sustainability action in product engineering. Sustainability-related foundations will be discussed in the following Chapter 2.2.

2.2 Sustainability

As described in Chapter 1.1, sustainability demands can pose both opportunities and risks for companies and their decision makers. Thus, fundamental conceptions of sustainability that might relate to such demands are discussed. Although sustainability as a topic is not new (see, for example, von Carlowitz, 1713), its conception in a company context has evolved over the past several decades (Taticchi and Demartini, 2021). Historical overviews of the definition and conception of sustainability have been extensively discussed in the literature, for example, by Taticchi and Demartini (2021), Geissdoerfer, Savaget, Bocken, and Hultink (2017) or Purvis, Mao, and Robinson (2019). Thus, fundamental conceptions with a broader consensus are discussed in this chapter (see also Figure 2.4 for key conceptions), while a more specific perspective on sustainability in product engineering is given in Chapter 2.3.

Potential moral implications and possible responsibilities arising from these conceptions are explicitly not part of this discussion (see also Chapter 3), although some sustainability conceptions discussed below are motivated by such considerations of responsibility.

A short summary of the key conceptions presented in Chapter 2.2.1 has previously been published in Jäckle et al. (2023).

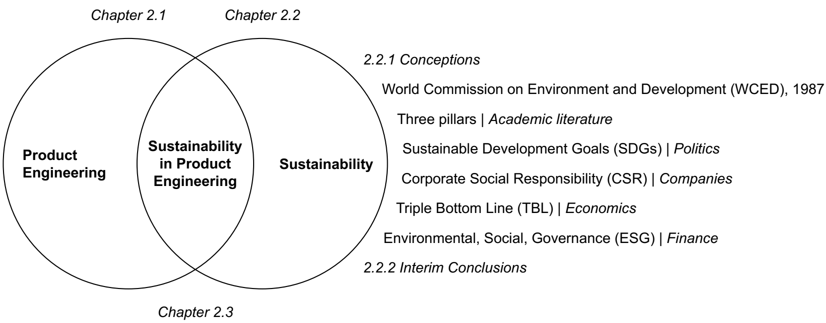

Figure 2.4: Key Conceptions of Sustainability Relevant to This Thesis and Resulting Structure of Chapter 2.2

2.2.1 Conceptions

The arguably most widely accepted definition of sustainable development was established in 1987 by the World Commission on Environment and Development (WCED) in the report “Our Common Future”: “Sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future” (World Commission on Environment and Development, 1987, p. 51).
In the academic literature, the three pillars (also referred to as dimensions, aspects, or perspectives) of sustainability represent a common conception, which introduces the multidimensionality of sustainability (Purvis et al., 2019):

- Economic / economy
- Social / society
- Environmental / environment / ecological

The three dimensions are often illustrated as Venn diagrams or interdependent pillars. However, the interdependencies between the pillars as well as the respective implications remain subject to debate. (Purvis et al., 2019)
In 2015, the three pillars were further detailed by the United Nations in 17 Sustainable Development Goals (SDGs) with 169 targets as part of the Agenda 2030 for Sustainable Development (General Assembly, 2015). Since then, governments have broken down this conception to the national level and further to determine political action (Sachs, Lafortune, Fuller, and Iablonovski, 2025). At the same time, the SDGs are also commonly used as a conception of sustainable development and sustainability in the academic literature (Purvis et al., 2019).
Also in 2015, the Paris Agreement was adopted by the Conference of the Parties, which represents a legally binding treaty between the parties of the United Nations Framework Convention on Climate Change (Framework Convention on Climate Change, 2015). The Paris Agreement aims to address climate change and sets the objective of limiting the increase in global average temperature (Framework Convention on Climate Change, 2015). This objective can be mapped to the SDGs; however, the Paris Agreement represents a separate political process (Dzebo, Janetschek, Brandi, and Iacobuta, 2019), also resulting in national action, through Nationally Determined Contributions (NDC; Framework Convention on Climate Change, 2024). Political action in this context results, for example, in regulations such as the Carbon Border Adjustment Mechanism (CBAM) as part of the European Green Deal (Spain and the European Commission, 2023).
Sustainability in a company context has been discussed for decades, for example in the context of Corporate Social Responsibility (CSR) since the 1950s, followed by a debate on the relationship between business and society (Taticchi and Demartini, 2021). Over time, additional conceptions have been introduced from various

perspectives, such as the Triple Bottom Line (TBL) that refers to the three pillars of sustainability, which in an accounting context are named as profit, people, and planet (Purvis et al., 2019; Taticchi and Demartini, 2021). Driven by a financial markets perspective, another three-dimensional conception of sustainability has been introduced: Environmental, Social, and Governance (ESG; Taticchi and Demartini, 2021). This conception is widely used, for example, by financial institutions for ratings and investments that lead to various sustainability-focused indexes (Taticchi and Demartini, 2021), and has also found a hold in reporting regulations such as the Corporate Sustainability Reporting Directive (CSRD) by the European Parliament and Council (2022).

In addition to reporting regulations, voluntary initiatives have been established that guide companies in disclosing sustainability performance. Examples are the Global Reporting Initiative (GRI), which is based on the three pillars and compatible with the SDGs (Global Reporting Initiative, 2021), or the Science Based Targets initiative (SBTi), which refers to the Paris Agreement (Science Based Targets initiative, 2024).

2.2.2 Interim Conclusions

The conceptions show the close connection between the political, economic, and academic debates on the conception of sustainability and sustainable development (see also Purvis et al., 2019). The conceptions are specified and detailed to varying degrees from varying perspectives with varying purposes. At the same time, all of these conceptions are well established, applied, and accepted in their respective contexts, and thus can be relevant to companies and their decision makers.

Thus, with respect to the focus of this thesis, this discussion raises the question of how these conceptions relate to the sustainability demands faced by companies and decision makers and how a product engineering and/or decision maker perspective relates to these conceptions. Therefore, sustainability in product engineering and related conceptions will be discussed in more detail in the following Chapter 2.3.

2.3 Sustainability in Product Engineering

Following the discussion of the foundations in the fields of product engineering and sustainability as relevant to this thesis in Chapters 2.1 and 2.2, the state of research regarding sustainability in product engineering is reviewed in this chapter from a decision makers' perspective. This will narrow the focus of the thesis to define its objectives (Chapter 3) and to derive a research approach (Chapter 4). Thus, a comprehensive body of literature was collected to capture relevant publications at the intersection of product engineering and sustainability. The body of literature comprised 174 publications, with 116 additional publications added in September 2024 for updated analyses in Chapters 2.3.1 and 2.3.3. A detailed description of data collection including search strings and filters can be found in Chapter 4.2.1.
The literature analysis was conducted in three steps, which are described in the following chapters (see Figure 2.5): First, existing conceptions of sustainability in product engineering were identified, which are discussed in Chapter 2.3.1. Because no consensus on the terminology proposed by the literature could be found, a second analysis was conducted. The collected body of literature was analyzed in its entirety with respect to an underlying, potentially implicitly shared, understanding of sustainability in product engineering. The results of this analysis and their implications are described in Chapter 2.3.2. Based on these findings and as a third step, publications that propose support that could address the uncertainty of decision makers and the initiation of targeted sustainability action were individually reviewed to derive the research gap (see Chapter 2.3.3). The results of these steps are summarized and discussed in Chapter 2.3.4, while the structure of Chapter 2.3 is illustrated in Figure 2.5.

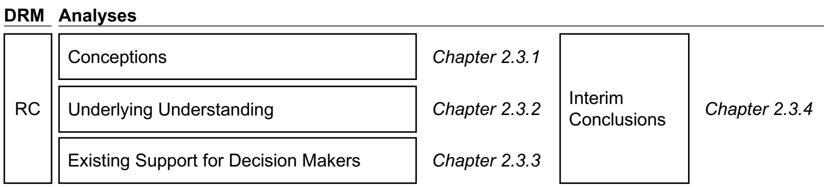

Figure 2.5: Literature-based Analyses of Sustainability in Product Engineering and Resulting Structure of Chapter 2.3

2.3.1 Conceptions

The body of literature was searched for conceptions of sustainability in product engineering. Although multiple conceptions have been proposed, no consensus on terminology for sustainability in product engineering could be found (see also Chatty, Harrison, Ba-Sabaa, Faludi, and Murnane, 2022; Jäckle et al., 2023). An update of this review in September 2024 yielded the same insights. To illustrate this impression, some of these proposals for conceptions of sustainability in product engineering are summarized below.

On a company level, for example, Taticchi and Demartini (2021) propose a definition for Corporate Sustainability that "is an integral approach to business aimed at enhancing competitive positioning and profitability through the sustained creation of shared value, co-creation practices with stakeholders and the integration of ESG factors in decision-making" (p. 73). Multiple publications introduce or refer to a technology dimension as part of sustainability conceptions. Examples are, Feng, Huang, and Chen (2022) who introduce a design requirements model, Oliveira et al. (2021) and Glönkler, Reick, Stetter, Till, and Pfeil (2022). In a similar vein, Kattwinkel and Bender (2020) refer to Charter and Tischner (2001) who model the relationship between product design and sustainable development by adding environmental and social/ethical aspects to a definition of product design that previously included only economic, function, aesthetic, and safety aspects. For example Schulte and Knuts (2022) cite Hallstedt and Isaksson (2017), who define sustainable product development as "a strategic sustainability perspective [that] is integrated and implemented into the early phases of the product innovation, including life cycle thinking" (p. 42). Moreover, they refer to Broman and Robèrt (2017) who introduce a Framework for Strategic Sustainable Development (FSSD) that is based on a principled definition of sustainability attempting to coordinate the use of conceptions of sustainability (see Chapter 2.2), however, without direct links to product engineering. Vilochani, McAloone, and Pigosso (2024) for example define sustainable product development as "systematic incorporation of environmental, economic and social considerations into the … [product development process] to fulfill the elementary needs of society, while improving the environmental and economic performance" (p. 116).

In this sense, scholars continue to publish definitions and conceptions of sustainability related to areas of product engineering without any recognizable convergence of terminology. This leaves the choice of an appropriate conception up to decision makers and thus does not support addressing the uncertainty of decision makers as intended in this thesis (see Chapter 1). However, this raises the question whether there is a shared underlying understanding or consensus on terminology that could be implicitly prevalent and might help support decision makers on sustainability action in product engineering. Therefore, as a subsequent step this underlying understanding was analyzed, and is discussed in the following Chapter 2.3.2.

2.3.2 Underlying Understanding

As no consensus on a conception of sustainability in product engineering could be found, the collected literature was reviewed again to identify a potentially implicitly shared underlying understanding of sustainability in product engineering.

This analysis has previously been published in Jäckle et al. (2023). Thus, Chapters 2.3.2.1 and 2.3.2.2 represent a direct citation (pp. 772–774). The citation style and references to chapters, figures, and tables, as well as the figure formatting and title capitalization, have been adjusted to match this thesis. Additional adjustments and additions are indicated by brackets. Chapter 2.3.2.3 represents an indirect citation, where direct citations (p. 774) are indicated by quotation marks.

[The analysis of the literature body is guided by the following initial guiding question:]
How is sustainability in product engineering currently understood in the literature and what are the implications to support consistent further research and practice?
Following a hermeneutic approach, a general understanding may be obtained and sharpened iteratively. Since no established, comprehensive understanding of sustainability in product engineering could be found, the … question [above] … was iteratively refined and answered based on the publications analyzed. Three results could be obtained by this process: As a first result, a … set of guiding questions with evaluation criteria detailing the … [initial guiding] question could be identified [(Chapter 2.3.2.1)]. The second result is the current understanding of sustainability in product engineering, … [consisting] of the answers to these guiding questions given by the analyzed publications [(Chapter 2.3.2.2)]. Building on this, an explication framework to describe … [an] understanding of sustainability in product engineering could be extracted from the analysis [, which is introduced as part of the implications in Chapter 2.3.2.3]. This process is shown in Figure 2.6.
[For the traceability of the analysis, this chapter uses the terms that emerged from this process and have thus been derived inductively from the analyzed literature (e.g., conceptions are referred to as description models).]

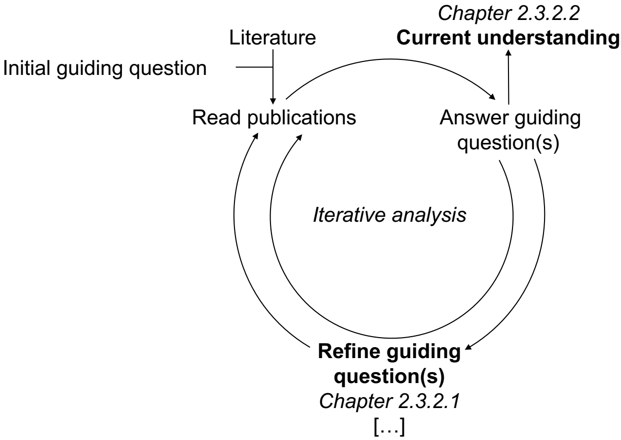

Figure 2.6: Process of [the Hermeneutic] Analysis [of the Underlying Understanding in the Literature] (adapted from Jäckle et al., 2023)

2.3.2.1 Refined Guiding Questions to Analyze the Current State of Sustainability Understanding in Product Engineering

The refined [guiding] questions as a result of the iterative process [comprise] four … questions, which target specific evaluation criteria allowing [the] categorization of publications. Guiding questions, evaluation criteria, and categories were iteratively refined according to the knowledge gained on differences in the underlying understanding of sustainability in product engineering. The final set can be found in Table 2.1. The contributions analyzed differ in their rationale behind the need for sustainability in product engineering by the either reactive … or proactive … character of the arguments [, where arguing for sustainability in product engineering based on drivers (e.g. demands) represents a rather reactive stance of the authors, and highlighting benefits (e.g. market potential) of sustainability in product engineering represents a rather proactive stance of the authors]. The description of sustainability differs in the description models used and focus areas stated, which both can be either reasoned for or assumed as given. Variations in the description of the application area of sustainability considerations were also observed (e.g., company, product, or specific aspect) and can be classified by their respective description models. Another difference between publications can be found in cited approaches that mark the foundation for their respective contributions, as well as the employed description of the respective approach (e.g., as concept, tool).

Table 2.1: Refined Guiding Questions and Evaluation Criteria with Example Categories [of the Underlying Understanding in the Literature] (adapted from Jäckle et al., 2023)

Guiding Question	Evaluation Criteria	Example Categories
How do authors argue the need for sustainability in product engineering?	Drivers	Stakeholder req., responsibility
	Benefits	Specific benefits, …
How do authors describe sustainability … [as well as] its area of application … [and] how are delimitations done?	Description model (Sust.)	TBL, SDGs, …
	Focus area (Sust.)	Environmental, …
	Reasoning (Sust.)	Yes, no
	Area of application	Product, company, specific aspect, …
	Description model company	Process, function, …
	Description model product	Product life cycle
Which approaches do authors refer to and how do they describe them?	Approach	Circular product design, …
	Description	Concept, tool, …

… [This set, as a result of this literature analysis, by nature of the hermeneutic text analysis, cannot be exhaustive. However, reflecting the analysis conducted, it can be useful to examine existing publications regarding their understanding of sustainability in product engineering. Further implications are discussed in Chapter 2.3.2.3.]

2.3.2.2 Current Understanding of Sustainability in Product Engineering

[The identified understanding of sustainability in product engineering is structured along the three guiding questions and presented on the basis of the evaluation criteria and categories found (see also Chapter 2.3.2.1 and Table 2.1), before the results are discussed with respect to each question.]

How do authors argue the need for sustainability in product engineering?

52% of publications do not explicitly reason why they see a need for sustainability in product engineering and the remaining 48% argue ... [based on] related drivers and/or benefits. 27% cite drivers pushing product engineering to strive for sustainability (reactive [stance]), and 13% outline the beneficial implications of sustainability in product engineering (proactive [stance]). A share of 8% uses both benefits and drivers in their reasoning (see Figure 2.7).

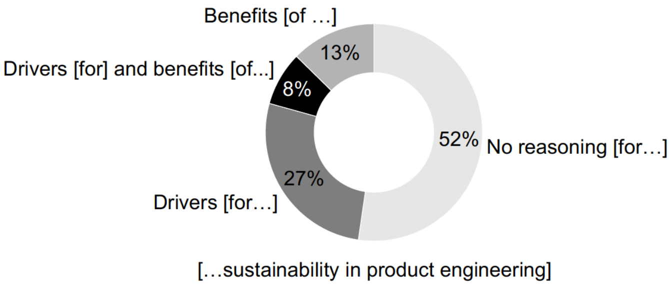

Figure 2.7: Reasons Cited by Authors to Argue for Sustainability in Product Engineering [as Part of the Underlying Understanding in the Literature] (adapted from Jäckle et al., 2023)

Cited drivers are in over 38% generic stakeholder requirements (stakeholder not explicitly stated or requirements not directly related to product engineering, e.g., societal demand), while 34% give specific stakeholder requirements (e.g., purchase criteria of the customer) and 28% refer to an inherent responsibility (e.g., need for intervention against climate change). Stated benefits of sustainability in product engineering vary in their level of detail: 44% are rather generic (e.g., market potential), while 56% provide specific benefits, such as increased employee motivation.

The range of given drivers and benefits of sustainability considerations in product engineering reflects the general relevance of this topic. However, there is a significant share of publications that do not state their reasoning for the need for sustainability in product engineering. This could be due to various causes, e.g., that reasons are commonly clear for the intended addressees, that this reasoning could be part of literature that has not been reviewed, or that there is a [gap] … marking an opportunity to foster understanding. The literature predominantly uses drivers (instead of benefits) as motivation for sustainability, which reflects a rather reactive position. The variety and, in many cases, generic description of drivers also suggest a broad perspective on influencing factors for sustainability in product engineering. To further understand these stakeholders and the implications of their requirements for product engineering, a more detailed analysis should be conducted.

How do authors describe sustainability … [as well as] its area of application … [and] how are delimitations done?

As shown in Figure 2.8, 40% of analyzed publications refer to the Triple Bottom Line [(TBL) or a related conception] as a description model for sustainability. This also includes alternative wordings [for the three dimensions as a whole (e.g., three pillars) or the individual dimensions] (e.g., ecologic … or environmental) and four instances where another dimension was added to the TBL (e.g., technology). [The term TBL was used in this analysis due to its frequent mention, while its relation to the three pillars is described in Chapter 2.2.] SDGs are also cited regularly (7%), while others are only used on a few occasions. However, 49% of the publications refer to the concept of sustainability but do not explicitly use a description model. Even more interestingly, those publications that refer to a description model tend to use a more comprehensive approach toward sustainability (70% of the TBL-based publications cover all three dimensions). Those who do not refer to such a description model narrow their focus to individual dimensions or leave their focus unclear. In only 6% of the cases where the focus is narrowed, a reason is provided. Moreover, publications that address single or two dimensions of the TBL most often relate to the environmental dimension (over four times more than the social dimension).

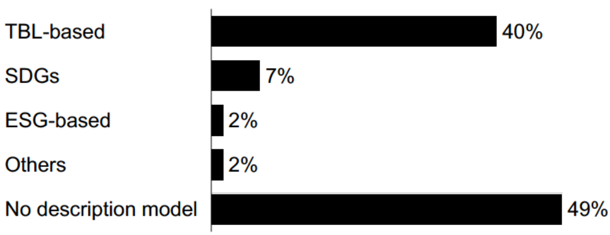

Figure 2.8: Description Models Used for Sustainability Aspects [as Part of the Underlying Understanding in the Literature] (adapted from Jäckle et al., 2023)

Therefore, [the] TBL can be regarded as the predominant basis for description models in a comprehensive view of sustainability in product engineering. In most cases, a narrower focus is neither delimitated using a broader description model for sustainability nor reasoned, which might make the interpretation and application of corresponding findings more difficult. The focus of the literature lies on comprehensive and environmental sustainability, while dedicated social sustainability is comparably underrepresented. Overall, the used models only provide a high-level description of sustainability, … [while] detailing (e.g., by indicators) depending on the area of application can be necessary, and should be analyzed further.

The described sustainability considerations can be applied in different areas of product engineering and its context, with different implications for product engineering. Therefore, the intended area of application of these sustainability considerations is analyzed in the following. 43% of publications identified apply their sustainability considerations completely on products, taking a comprehensive view of the product as the result of product engineering. 16% address the company running the product engineering process in their sustainability considerations. Only 2% of publications address both explicitly. 16% address a specific area of application within a company or product (e.g., supply chain management of a company, material selection for products), while in 22% of cases, a delimited area of application could not be identified (see Figure 2.9).

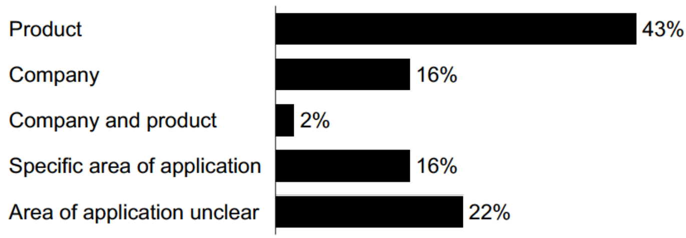

Figure 2.9: Area of Application of Sustainability Considerations [as Part of the Underlying Understanding in the Literature] (adapted from Jäckle et al., 2023)

The description models used for companies are dominated by process related descriptions with 31%, while only 6% use functional descriptions, 2% hierarchies, and others. However, 61% do not use a company description model at all. For product descriptions, in 22% the product life cycle is used, while 8% use systems as description models. 1% use other descriptions and 61% do not specify the product further.

Summarizing these findings, the current … literature on sustainability in product engineering strongly focuses on product sustainability, where the product is described by its life cycle [if at all]. Addressing the company's sustainability explicitly or even a combination of company and product sustainability is currently less common. Nevertheless, for both areas, significant relevance can be stated, suggesting their relationship should be analyzed in further research. Description models for companies are dominated by process descriptions, while functional views are less common. Since the latter could be particularly interesting for [decision makers] … depending on their respective organizational structures, this aspect should be analyzed in more depth.

Which approaches do authors refer to and how do they describe them?

45 different approaches to sustainability in product engineering with 24 different descriptions (e.g., concept, method, strategy) that served as an immediate basis for the contributions could be identified in the analyzed literature. As shown in Table 2.2, the most common approaches were "Design for ..." (grouped), circular economy, and life cycle assessment (LCA).

Table 2.2: Sustainability Approaches Used as a Basis for Publications [as Part of the Underlying Understanding in the Literature] (adapted from Jäckle et al., 2023)

Approach	**Mentions, #**
Design for … (e.g., X, Sustainability, Circularity, …)	11
Circular economy	8
Life Cycle Assessment (LCA)	8
Eco-design	6
Corporate Social Responsibility (CSR)	5
…	…

The variety of approaches seen in the literature suggests that a deeper analysis of underlying understandings, their relations, and their area of application would be beneficial. Since linguistic terms for the identified approaches also vary, overlap and misunderstandings cannot be ruled out. Hence, … [this] analysis should be based on a contextualized understanding with a clear purpose and scope. According to Johansson and Sundin (2014), a synergetic reduction of approaches could lead to simplification and support application in practice. [In this analysis] … the description "approach" [is used] because it was used the most in the literature.

2.3.2.3 Implications of the Underlying Understanding

These literature-based findings are based on explicit statements within the reviewed publications, which are subject to interpretation and do not allow conclusions about the potentially implicit intentions of the authors of these publications. However, the analysis in Chapter 2.3.2.2 "shows that the current literature on sustainability in product engineering typically covers explicit approaches (e.g., DfX, LCA) and the area of application of sustainability considerations (e.g., product, company), while the purpose (benefits or drivers) and description of sustainability (e.g., TBL-based, SDGs) is explicated more rarely and rather generic." Therefore, no shared understanding of sustainability in product engineering could be identified, while the conceptions used are related to the foundational conceptions described in Chapter 2.2. Assuming consistency within each publication, the variety of approaches, terms, application areas, sustainability conceptions, and reasons for sustainability action suggest a context-dependent understanding of sustainability in product engineering.

Thus, without explicit purpose and scope of sustainability considerations in publications, e.g., by a delimitation of addressed sustainability aspects or explicit area of application in product engineering, the applicability can remain unclear to decision makers seeking support in the literature. "This can lead to inconsistent sustainability efforts that might fail to support the intended … purpose. Inconsistencies might include mismatches between selected approaches, their area of application, addressed sustainability aspects, and the intended purpose."
However, scholars can allow for a more targeted application of their findings, for example, to address a specific sustainability demand faced by a decision maker, by creating transparency on the understanding of sustainability in product engineering underlying their publication. Based on the guiding questions and the findings in this chapter, a framework can be summarized that can support scholars in doing so but might also help decision makers to explicate their intentions. The framework is illustrated in Figure 2.10 and is based on two suggestions for additions to the findings on sustainability in product engineering, or approaches for sustainability action proposed in a publication:

First, the *purpose* of published sustainability considerations should be explicated to allow decision makers to compare it with their own intentions and to help understand any scope definition. According to the literature, this purpose of sustainability action in product engineering can be rooted in potential drivers for sustainability action, such as societal demands or customer purchase criteria, as well as expected benefits, in terms of intended impact, of sustainability action, such as capturing market potential or employee motivation.
Second, the *scope* of the publication or approach should also be explicated with respect to sustainability and product engineering. This can be done by delimiting the addressed aspects using existing description models. This scope should be consistent with the purpose based on the individual context and can be described based on the sustainability aspects covered in the literature (e.g., the environmental dimension based on the TBL or SDGs) as well as their area of application, which might be comprehensively company- or product-related or relate to specific aspects within those (e.g., material selection).

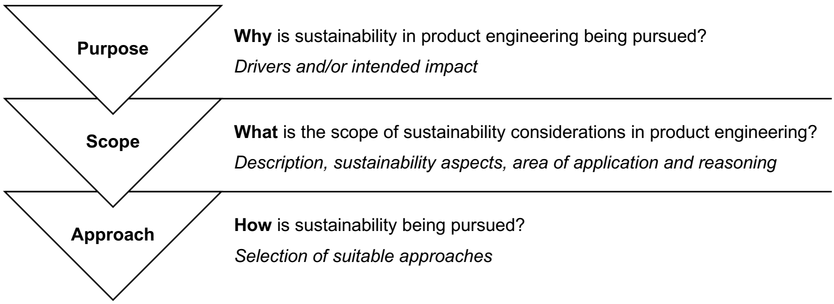

Figure 2.10: Explication Framework Derived from the Hermeneutic Analysis [of the Underlying Understanding in the Literature] (adapted from Jäckle et al., 2023)

With transparency in purpose and scope, addressees can better evaluate the applicability of findings and proposed approaches, such as implementing circular economy principles, using Design-for-X approaches, or applying ecodesign methods in product engineering.
Although these findings may help to navigate the existing literature, they suggest a context-dependent understanding of sustainability in product engineering. Thus, the findings provide an initial step towards addressing the (literature-related) uncertainty

of decision makers but do not support the initiation of targeted sustainability action. Therefore, publications providing relevant support with respect to the focus of this thesis will be discussed individually in the following chapter.

2.3.3 Existing Support for Decision Makers

Although the analyzed literature in its entirety does not yet address the uncertainty of decision makers about sustainability action (see Chapters 2.3.1 and 2.3.2), individual publications may offer support in addressing the uncertainty of decision makers about sustainability action in product engineering, and thus be relevant with respect to the focus of this thesis. Therefore, individual publications in the body of literature (see Chapter 4.2.1 for details on data collection) and their potential support for decision makers to initiate such targeted sustainability action in product engineering are discussed below.

Many publications on sustainability in product engineering emphasize decision making in the early phase, such as choosing between alternative solutions at the product level (Vilochani, McAloone, and Pigosso, 2024). Examples of such publications are Kwok, Schulte, and Hallstedt (2020), Albers, Tusch, Jäckle, Seidler, and Kempf (2024), and T. Wang and Yang (2023). T. Wang and Yang (2023) explicitly address the topics of uncertainty and ambiguity, providing decision support that combines grey relational analysis and fuzzy quality function deployment to derive design parameters. Upadhyay and Kumar (2020) focus on the design phase by adapting the house of quality concept to incorporate sustainability dimensions, linking enterprise goals with product variables. S. Wang and Su (2022) propose a framework for Sustainable Product Development and Services that incorporates the TBL and life cycle thinking into Product Service Systems development, using life cycle assessments for implementation on the Product Service Systems level. Chatty et al. (2022) discuss a case study on integrating sustainable design in product development practices, presenting a framework that incorporates sustainable design stages at the system level. They note generalizable aspects but recognize the limited transferability of the framework's content, emphasizing the importance of co-creation (Chatty et al., 2022). Relich, Adamczyk, Dylewski, and Kister (2024) present a case-based reasoning method using company cases to guide product-level sustainability decisions and achieve sustainability targets based on identified opportunities. F. Rusch, Demke, Willems, and Mantwill (2024) developed a framework for Sustainable Context Engineering to help developers identify and trade-off sustainability requirements at the product level.

However, scholars also highlight the conditions required for successful sustainability action at the operational level, which include other actors and decision makers within and outside the organization (e.g., Delaney et al., 2022; Hallstedt et al., 2020). For example, Schulte and Hallstedt (2018b) and Kravchenko et al. (2021) indicate that top management and middle management buy-in is such a condition. Mesquita and Missimer (2021), and Missimer and Mesquita (2022), suggest that organizational complexities must be understood for successful implementation of sustainability action. Therefore, to initiate sustainability action, not only the actions of operational engineers are relevant but also those of all other decision makers that shape the conditions under which product engineering takes place (see also Chapter 2.1). These decision makers and the conditions under which product engineering takes place also become focal objects of publications that investigate practices (e.g., Vilochani, McAloone, and Pigosso, 2024; Hallstedt et al., 2020), and their implementation for sustainability action (e.g., Schulte and Hallstedt, 2018b). These publications are of special relevance for addressing the uncertainty of decision makers and initiating targeted sustainability action in product engineering, and thus, for the focus of this thesis. Therefore, their support will be discussed in detail in the following.

The remainder of this Chapter has previously been published in Jäckle et al. (2025) and thus represents a direct citation (pp. 2962–2964). Where useful, more detailed discussions and additional publications were added, given the space constraints in the previous publication. These adjustments are indicated by brackets and are also reflected in the adapted Figure 2.11, which provides an overview of the publications discussed.

[The literature can be organized] … along two relevant dimensions (see Figure 2.11): The dimension “type of support” (descriptive insights vs. prescriptive advice) and the dimension “scope of sustainability action in product engineering”. The scope of sustainability can be narrow or broad [(see Chapter 2.3.2)]. Publications with a narrow scope focus on selected aspects of product engineering and/or selected aspects of sustainability action, e.g., one aspect of [the TBL] …, a small selection of the SDGs, or otherwise narrow conceptualizations of sustainability action fields. Choosing a narrow scope comes with the advantage of complexity reduction on the conceptual level, but at the same time does not sufficiently acknowledge the uncertainty [that] decision makers face due to highly diverse and changing external sustainability demands [(see Chapter 1.1)]. Publications with a broad scope embrace a greater number of product engineering aspects and/or broader, more holistic conceptualizations of sustainability. Choosing a broad scope means that support on how to implement sustainability can acknowledge and address the uncertainty [that] decision makers face due to highly diverse and changing external sustainability demands. As some studies summarized below show, broad scope in currently existing prescriptive advice comes with limitations as well: [decision makers] … have difficulties in applying such support since it is not sufficiently context-specific.

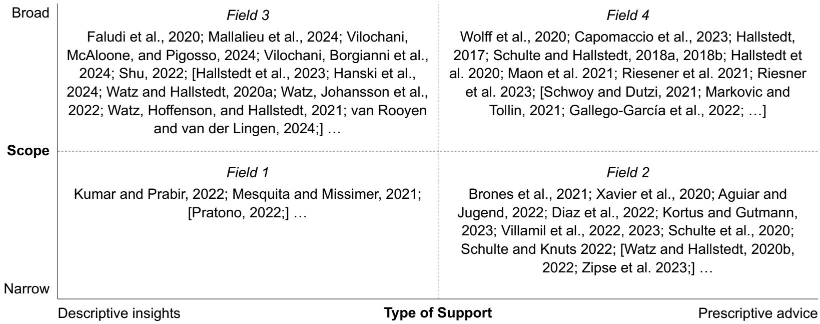

Figure 2.11: Overview of Existing Publications [Offering Support for Decision Makers with Respect to the Focus of This Thesis] by Scope and [Type of] Support (adapted from Jäckle et al., 2025)

Descriptive insights with narrow scope (Field 1)

[Publications in this field span from e.g.,] Kumar and Prabir (2022) [who] evaluate key enablers for ecodesign practices, and Mesquita and Missimer (2021) who conduct an empirical study on the motivation behind and implementation of social sustainability in product development [to publications like Pratono (2022), who evaluates the effect of an entrepreneurial culture on sustainable competitive advantage.]
Those studies collect knowledge on selected fields of interest, but do not offer concrete guidance on how to implement sustainability action. [Hence, detailed discussion is omitted, but their findings may provide valuable insight when addressing these fields.]

Prescriptive advice with narrow scope (Field 2)

Brones, Zancul, and Carvalho (2021), and Xavier, Reyes, Aoussat, Luiz, and Souza (2020) also show a focus on ecodesign [and eco-innovation respectively], adding recommendations for ecodesign integration [through maturity frameworks that cover multiple organizational levels and aspects.] … [Aguiar and Jugend (2022) also provide a maturity framework which focuses on circularity. Similarly Diaz et al. (2022) describe managerial factors that are also compiled into a framework to support the implementation of value retention strategies.] Kortus and Gutmann (2023) focus on

environmental aspects of sustainability and develop a framework of dynamic capabilities an organization should develop to successfully meet environmental requirements. They suggest that companies continuously evaluate sustainability demands and define a process model [with facilitators and barriers to build these capabilities] (Kortus and Gutmann, 2023).
Villamil, Schulte, and Hallstedt (2022, 2023) choose a rather broad scope of sustainability, but are narrow in that they focus on specific aspects of product engineering. They propose a method for the integration of sustainability in portfolio management and offer support for implementation. In a similar vein, Schulte, Villamil, and Hallstedt (2020), develop a conceptual approach to risk management [to cope with a societal sustainability transition (see also Field 4)] and Schulte and Knuts (2022) derive practical support for decision makers [at the product level. The proposed tool incorporates a strategic perspective from an operational point of view in product-level decisions between alternatives (Schulte and Knuts, 2022). Similarly, Watz and Hallstedt (2020b, 2022) develop a profile model from a requirements management perspective.]

All those studies in Field 2 offer explicit, action-oriented support for decision makers on selected issues. [Some publications refer to broader scopes on the strategic level (also e.g., Zipse et al., 2023), but their practical support remains limited to selected aspects of sustainability and/or product engineering. And] since they remain narrow in scope, they do not offer comprehensive support on how to deal with great diversity and uncertainty in sustainability demands in all areas relevant to product engineering. [The developed support can serve as a reference for others, but its content requires contextual reflection.]

Descriptive insights with broad scope (Field 3)

Literature in this field shares one central finding: When scope is broad, a significant theory-practice-gap exists. While research-based insights or suggestions on how sustainability integration in product engineering may be done exist, [decision makers] … pay little to no attention to those insights because when scope becomes broader, support on how to address this scope becomes less context- and company-specific. Faludi et al. (2020) identify a misalignment between sustainable design and business strategies, which is supposed to explain why sustainable design methods and tools are not applied in product development. [They set the vision of integrating the SDGs into the strategies and objectives of industry practitioners by overcoming multiple barriers identified (Faludi et al., 2020).]
Mallalieu, Hallstedt, Isaksson, Watz, and Almefelt (2024) report 53 factors that influence the adoption of sustainable design practices through design methods, and identify implementation barriers. A major barrier to support adoption is a mismatch

between proposed design methods and context-specific aspects which define a situation or existing practices in a company. [They summarize this mismatch in a paradox and emphasize the need to bridge this contextual gap, for which they propose a sustainable design thinking method to develop respective methods (Mallalieu et al., 2024). Moreover, they state that prescriptive support is needed on how to bridge this contextual gap (Mallalieu et al., 2024).]
Vilochani, McAloone, and Pigosso (2024) summarize … [61] management practices for sustainable product development in a … [SLR and map them to relevant … [product development process] phases, focus areas and organizational functions, but do not cover how to implement them. In a survey on the current state of implementation of these management practices,] Vilochani, Borgianni, McAloone, and Pigosso (2024) find low levels of implementation capability in companies. Hence, they recommend more collaboration between academia and industry to close the theory-practice gap (Vilochani, Borgianni, et al., 2024).
Shu (2022) highlights the uncertainty, ambiguity, and complexity of sustainable new product development that leads to paradoxical tensions, setting a focus on the framing activities of managers. Shu (2022) also finds that a holistic and integrated view of sustainable innovation is needed and that its unique challenges must be linked to management decisions.
[Other publications in this field range from company case studies, such as Hallstedt, Isaksson, Nylander, Andersson, and Knuts (2023), and Hanski, Uusitalo, Rantala, and Hemilä (2024), who cover company case studies, or causal loop diagrams as a result of group model building approaches (Watz and Hallstedt, 2020a; Watz, Johansson, Bertoni, and Hallstedt, 2022; Watz, Hoffenson, and Hallstedt, 2021), to, for example, van Rooyen and van der Lingen (2024) who address uncertainty in technology innovation by linking success factors of innovation management.]

In summary, the literature in Field 3 describes the central challenge for researchers who seek to develop applicable support for [decision makers:] … to offer context-specific support which considers company-specific situations and perspectives while at the same time taking a broad scope … . Only when a broad scope does not come with limitations to context specificity, support becomes actionable for … [decision makers. Therefore, this literature provides valuable insights for the development of a support for decision makers on targeted sustainability action in product engineering.]

Prescriptive advice with broad scope (Field 4)

Prescriptive advice with a broader scope often refers to SDGs (e.g., Wolff, Bronner, Held, and Lienkamp, 2020), or CSR (e.g., Capomaccio, Reyes Carrillo, and Richet, 2023) as a basis for support. Wolff et al. (2020) propose SDG owners (similar to

product owners) [to address transformation barriers] and drive operational measures for sustainability implementation. Capomaccio et al. (2023) introduce a maturity model to assess the level of capabilities for CSR integration into the product development process [and provide questionnaires to assess the current and envisioned state.]
Hallstedt (2017), Schulte and Hallstedt (2018a, 2018b), Schulte et al. (2020), and Hallstedt et al. (2020) offer support for sustainability integration based on the Framework for Strategic Sustainable Development (FSSD) and the conceptually related definition of sustainability [with eight principles] by Broman and Robèrt (2017) [, similar to previous publications by the authors such as Hallstedt, Ny, Robèrt, and Broman (2010) and Hallstedt, Thompson, and Lindahl (2013, not added to Figure 2.11). Hallstedt (2017) developed an approach to identify sustainability criteria and derives a sustainability compliance index and the respective matrices to support decision making of design teams during product development. Schulte and Hallstedt (2018a) use the FSSD to define sustainability risks and derive implications for company risk management assuming an inevitable sustainability transition. They find a need for support to address these risks in practice (Schulte and Hallstedt, 2018a). Schulte et al. (2020, see also Field 2) further develop a conceptual approach to manage these risks and use it as the basis for Schulte and Knuts (2022, see also Field 2), while this risk management perspective in principle also offers the possibility of describing broader implications for companies resulting from the societal sustainability transition mentioned. Moreover, Schulte and Hallstedt (2018b) developed a FSSD-based self-assessment method that addresses key elements to implement sustainability in product innovation. Hallstedt et al. (2020) highlight the uncertainty of decision makers and recommend incorporating complex contexts in engineering research. They propose a framework covering resources for sustainability implementation, informed by trends in digitization, sustainability, and servitization (Hallstedt et al., 2020).]
All of these studies derive their support from and for fixed sustainability target states, which means that they do not account for [the] uncertainty decision makers face due to changing external sustainability demands. Other studies take a more dynamic approach and aim to help companies react to changing demands:
Maon, Lindgreen, and Swaen (2021) present a "conceptual framework [to] understand … the development of a CSR strategic agenda" (p. 4). They emphasize the need for each organization to develop a company-specific understanding of CSR based on stakeholder demands and provide a descriptive dual-loop model. This model comprises, and at the same time is limited to, a continuous stakeholder dialogue loop and an integration loop with a focus on managerial perceptions. [Schwoy and Dutzi (2021) show that materiality analyses offer standard solutions but lack context specificity and guidance, while Markovic and Tollin (2021) emphasize the need for research on dynamic managerial capabilities to drive business model innovations for sustainability. Similarly, Gallego-García, Ren, Gallego-García, Pérez-García, and

García-García (2022) promote dynamic capabilities and propose a project evaluation scheme and a digital ecosystem based on the Plan-Do-Check-Act cycle, however, this requires advanced digital infrastructure for application (Gallego-García et al., 2022).] Riesener, Kuhn, Tittel, and Schuh (2021), and Riesener, Kuhn, Tittel, Singh, and Schuh (2023) address organizational resilience … [, outlining] five steps which are supposed to help to set up product development departments in a beneficial way.

In summary, the literature in Field 4 provides basic support on how to approach sustainability integration when a broad scope is chosen. Some [authors] even take a dynamic approach, and hence provide the grounds for development of support which helps to adjust sustainability action to changing sustainability demands. However, existing support does not yet provide detailed advice on how to implement sustainability action in all areas relevant to product engineering. Furthermore, the challenge to offer context-specific support while offering a broad scope remains to be tackled (see the literature in Field 3).

2.3.4 Interim Conclusions

In Chapter 2.3 the existing literature was discussed from the perspective of decision makers who face uncertainty about sustainability action in product engineering, in order to provide a starting point for further research.
The review of the literature for existing definitions and conceptions of sustainability in product engineering revealed various conceptions, but no consensus or convergence was found (see also Chapter 2.3.1), raising the question of an implicitly shared understanding.
The analysis of the underlying understanding in the literature (Chapter 2.3.2) did not reveal an implicitly shared understanding of sustainability in product engineering beyond the use of the fundamental conceptions presented in Chapter 2.2. However, assuming consistency within the publications, the analysis suggested a context-dependent scope, narrowing for sustainability considerations in product engineering aligned with the purpose of these considerations. The derived explication framework is intended to support the navigation of the existing literature and thus is limited to addressing uncertainties related to the literature.
Nevertheless, these findings could be used to discuss the existing support for decision makers with respect to the focus of this thesis in Chapter 2.3.3. To acknowledge the uncertainty that decision makers face about targeted action on diverse and dynamic sustainability demands in volatile circumstances (see Chapter 1.1), support with a broad scope with respect to sustainability and product engineering is needed. To address this uncertainty, this support must be actionable for decision makers. It was

found that this support only becomes actionable if it is context-specific in a sense that not only relates the action (how) to the scope (what) and purpose (why) of this action (see also Chapter 2.3.2), but also acknowledges the individual circumstances in which a decision maker acts at a given point in time (see Chapter 2.3.3, Field 3). Moreover, the findings reveal a gap in the literature, as the existing prescriptive support does not resolve this, and, in addition, was found to either cover a broad (i.e., also dynamic) scope or offer detailed prescriptive (i.e., actionable) advice to decision makers in product engineering, but not both (see Chapter 2.3.3, Field 4). In summary, these findings pose the challenge of developing broad, yet context-specific and actionable support to bridge this gap and address the uncertainty of decision makers, in order to adequately support them in initiating targeted sustainability action in product engineering.

3 Objectives

This chapter provides a description of the identified research need and the objectives set for this thesis (Chapter 3.1), as well as the derived research questions (Chapter 3.2), while the research approach taken to answer those research questions is described in Chapter 4.

3.1 Research Needs and Objective

As described in Chapter 1.1, companies and decision makers face diverse and dynamic sustainability demands, and experience a non-linear fragmentation of stakeholder priorities in many markets. To mitigate risks and exploit opportunities emerging from these demands in such volatile circumstances, companies must act in a targeted manner on these demands; hence, initiate targeted sustainability action. Product engineering can play a pivotal role in this targeted sustainability action, and the exploitation of opportunities such as competitive advantages, growth, and synergies with cost targets. However, these sustainability demands also amplify objective uncertainties and cause additional subjective uncertainty among decision makers, which limits their ability to initiate targeted sustainability action, potentially leaving opportunities untapped and companies exposed to risks.

Thus, to take advantage of opportunities and mitigate the risks that emerge from sustainability demands in a targeted manner, decision makers must be enabled to initiate targeted sustainability action. And therefore, their uncertainty needs to be addressed (see Chapter 1.2).

To grasp this uncertainty, potential support for decision makers to initiate targeted sustainability action needs to be broad in scope with respect to product engineering and sustainability, thus also recognizing the dynamic nature of sustainability demands. To address this uncertainty, this support must be actionable for decision makers, thus providing prescriptive advice while acknowledging the specific context in which they act. Such support, capable of grasping and addressing the uncertainty of decision makers with respect to targeted sustainability action in product engineering, currently represents a gap in the existing literature (see Chapter 2.3).

Thus, to adequately support decision makers in addressing their uncertainty and initiating targeted sustainability action, the challenge of developing broad, yet context-specific and actionable support must be overcome.

Therefore, the following two research needs must be addressed:

- First, generalizable aspects – in terms of transferability to other contexts – of targeted sustainability action in product engineering that do not compromise overcoming the above challenge must be identified.
- Second, support for decision makers must be developed that consistently combines a broad scope with context-specific and actionable advice.

Addressing these two research needs defines the objective of this thesis, with generalizable aspects being a prerequisite for the support. The term “generalizable” is understood here in accordance with Gioia, Corley, and Hamilton (2013) and Feldman and Orlikowski (2011), which means that generalizable aspects in this thesis are not universal aspects, but situated dynamics that are transferable to other contexts and thus allow their understanding (see also Chapter 2.1). The research needs are broken down into research questions, which are described in the following Chapter 3.2.

In order to clearly separate the set objective from other intentions and reduce possible misunderstandings, the following three aims, which fall outside the scope of this thesis, are delimited.

- First, the thesis does not aim to develop a new “definition” or fixed conception of sustainability, but rather to support decision makers in developing an action-oriented understanding (see also Chapter 5).
- Therefore, the support does not aim to provide a process for implementing a fixed set of sustainability objectives or aspects thereof in product engineering. However, notable traits are highlighted to facilitate future research (see also Chapter 9).
- Third, acknowledging the authors’ background in engineering sciences and the limitations of his expertise, this thesis does not aim to provide support for moral judgments or to provide guidance on possible responsibilities (see also Chapters 1.2 and 2.2).

3.2 Research Questions

The two research needs are broken down into four research questions as described below. The relations between research needs and research questions are illustrated in Figure 3.1. The first research need, namely, identifying generalizable aspects of targeted sustainability action in product engineering, is broken down into three areas of interest based on two considerations.

First, starting from the intention of enabling targeted action on sustainability demands to take advantage of opportunities and mitigate the risks that emerge from them, targeted sustainability action must be understood in more detail for decision makers to initiate it. Thus, based on the findings presented in Chapter 2.3, the first research question aims at an action-oriented understanding of sustainability in product engineering to better understand targeted sustainability action:

Research question 1: How can targeted sustainability action be understood in product engineering?

The second consideration on the first research need employs a practice-theoretical perspective on targeted sustainability action in product engineering (see also Chapter 2.1). Thus, sustainability action, as any action, can be described through practices that are established and enacted. If this action is intended to be targeted, in this case with respect to relevant sustainability demands, these practices must be defined and configured. Consequently, once targeted sustainability action is understood, it needs to be operationalized and implemented, which leads to the second and third research question:

Research question 2: How can targeted sustainability action be operationalized in product engineering?

Research question 3: How can targeted sustainability action be implemented in product engineering?

With answers to the first three research questions and thus generalizable aspects of targeted sustainability action, the first research need is addressed. Based on these findings, the second research need can be addressed and broad, yet context-specific and actionable support for decision makers to initiate targeted sustainability action can be developed. Thus, the uncertainty of decision makers is also addressed by answering the fourth research question:

Research question 4: How can decision makers be supported in addressing their uncertainty about targeted sustainability action and initiating targeted sustainability action in product engineering?

The related methodological structure to answer these research questions is provided by the research approach described in Chapter 4, while the results are structured along the research questions and can be found in Chapters 5 to 8 as indicated in Figure 3.1.

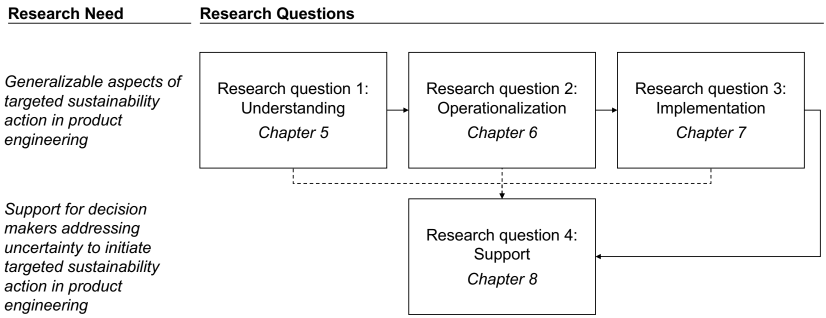

Figure 3.1: Research Needs and Respective Research Questions Addressed in This Thesis

4 Research Methodology

To overcome the challenge and achieve the objective of this thesis, a systematic research approach is required that at the same time allows an open exploration of targeted sustainability action. Therefore, the overarching structure of this thesis adopts the Design Research Methodology (DRM) by Blessing and Chakrabarti (2009), which provides a four-stage structure for the development of support related to design. The integrated Design Support Development Model (iDSDM) by Marxen (2014) provides a compatible framework with additional emphasis on building a credibility case for the support being developed during the course of the research project (see Marxen, 2014). Therefore, the iDSDM is used to structure the research activities within the DRM stages, while the Gioia Methodology by Gioia et al. (2013) with its grounded theory approach is used for empirical research. A complete description of the research approach could also be done in either DRM or iDSDM. However, this combination was chosen because it supported maintaining a decision makers' perspective while ensuring a systematic process for developing credible support. This research approach is described in Chapter 4.1 with an overview in Figure 4.1. The overarching methods used are described in Chapter 4.2.

A short summary of the research approach (Chapter 4), with a focus on the interview study (Chapter 4.2.2) and its context, has previously been published in Jäckle et al. (2025). The description of the systematic literature review (Chapter 4.2.1) has previously been partially published in Jäckle et al. (2023). Details on references and indications can be found in Chapter 4.2.1.

4.1 Research Approach

The objectives in Chapter 3 and the research methodology in Chapter 4 represent the results of the **Research Clarification (RC)** according to the DRM. The objectives and the respective research questions were identified based on initial expert discussions (see Chapter 1) and systematic literature reviews (SLRs; see Chapter 2.3).
To answer the research questions, empirical research based on the Gioia Methodology by Gioia et al. (2013) was carried out as part of the **Descriptive Study I (DS I)**. The methodology was chosen because of its grounded theory approach, which allows an open exploration of the research questions, while allowing the identification of generalizable aspects that are transferable to other contexts (Gioia et al., 2013). This

approach, together with the practice theory-based perspective on product engineering and action in product engineering introduced in Chapter 2.1, enables the required problem focus in this thesis. To balance this problem focus with being informed, two sources for qualitative data were used: SLRs and expert interviews (see Chapter 4.2 for details). The SLR results were primarily used to develop the interview guideline for the subsequent semi-structured expert interviews, as the expert interviews allow consideration of the individual context of the interviewee. This makes expert interviews particularly suitable to identify generalizable aspects of targeted sustainability action, which is why they were considered the main source of data in this thesis. However, the results of the interviews are discussed with respect to the literature findings to draw on existing academic knowledge. The DS I is therefore characterized by a qualitative, predominantly inductive approach based on expert interviews. As part of this DS I all four research questions were addressed in a similar way: First by consulting the literature and deriving the respective part of the interview guideline and then by conducting the expert interviews covering all four research questions. While Chapters 5 to 7 are structured based on the research questions, the structure within these chapters follows this approach. With respect to the development of the support for decision makers presented in Chapter 8, this approach is also reflected in the intended support (Chapter 8.1), which marks the transition from DS I to Prescriptive Study (PS).

In the **Prescriptive Study (PS)** the support to address the uncertainty of decision makers about targeted sustainability action is developed. This stage is split into two parts. The first part describes the intended support by synthesizing an initial system of objectives for the support and its operationalization based on empirical findings for all research questions (see also Marxen, 2014). The second part of the PS is parallelized with the **Descriptive Study II (DS II)** in an iterative way and is carried out in three studies with an increasing maturity of the support (see also Chapter 8 for further details). Version 1 of the support is a workshop concept, where the core elements of the support were applied and evaluated at an early stage in company workshops. The support was then refined to a Version 2, an explanatory Guide in presentation format, which was iterated in expert discussions. Both of these studies combine experimental and transfer studies (see Marxen, 2014). The third and final study was a company project that integrated the development of a Version 3 of the support: A Guide in a document format, and its full application over the course of six months in a company in conjunction with a masters thesis (Herrmann, 2025[2], see Chapter 8). This third version is the final synthesized result of the thesis. It can be found in its entirety in Appendix A.1. The analysis of utilization of this support in

[2] Co-supervised master’s thesis (unpublished)

practice as suggested by Marxen (2014) is consequently intended to be part of future research.

This research project only allows for an initial evaluation of the support as part of the DS II due to time constraints, while the long-term sustainability and success of a company cannot be ensured due to methodological limitations. However, to support decision makers in challenges they are facing today, a pragmatic research approach is needed that identifies generalizable aspects of targeted sustainability action and makes them usable to decision makers in a timely manner. Therefore, a special focus is placed on a rigorous DS I stage and its empirical research, providing a solid basis to develop support that meets the objective of this thesis in line with the challenge described.
Thus, the collection and analysis of qualitative data collected in the DS I through SLRs and expert interviews are described in the following Chapter 4.2, while a research question-specific perspective on the interpretation is taken in the respective sections in Chapters 5 to 8. Figure 4.1 shows an overview of the methodological structure of this thesis.

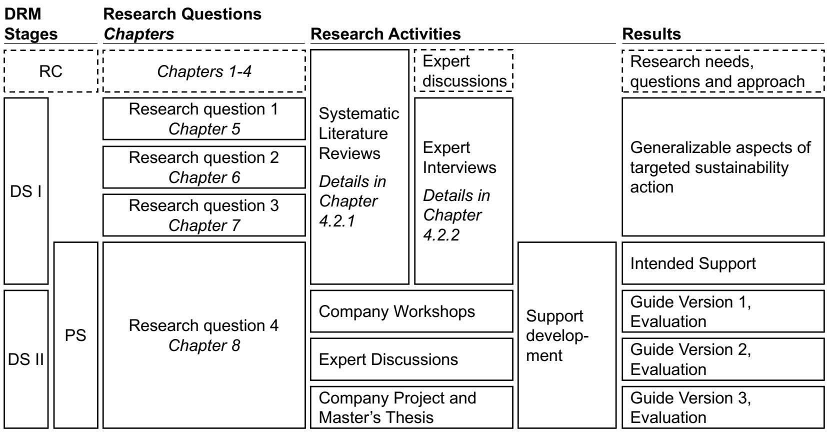

Figure 4.1: Research Approach to Answer the Research Questions and the Resulting Methodological Structure of This Thesis

4.2 Overarching Methods

4.2.1 Systematic Literature Review

Due to the problem focus of this thesis, it was essential not to narrow the literature review too early in the process, which is why a broad literature base was collected and analyzed regarding the research questions that emerged during the process of research clarification. Therefore, the same literature base used for the RC (Chapter 2.3) was also used for the DS I (Chapters 5 to 8), however, it was analyzed specifically with respect to the research questions (see also Figure 4.2 at the end of this chapter). Thus, a description of the data collection, which was inspired by the PRISMA guidelines by Page et al. (2021), can be found below, while details on analysis and interpretation of this data can be found in the respective chapters.

The following two paragraphs have previously been published in Jäckle et al. (2023) and therefore represent a direct citation (pp. 771–772). The citation style and references to chapters, figures, and tables, have been adjusted to match this thesis. Moreover, additional details of the search string were added to Table 4.1 and the process of the SLR was integrated in Figure 4.2.

The [*initial literature body* was collected] … in September 2022 using the two literature databases *Scopus*[3] and *Web of Science*[4]. Since … [this thesis focuses on] the intersection of product engineering and sustainability, these two areas were used as search terms. Related keywords like product development were also included since they are often used synonymously, although, … product development [is understood] as a … [task area] of product engineering [in this thesis] (see Chapter 2.1). Further aspects … were introduced … [by incorporating publication and content perspectives to ensure that relevant contributions, such as definitions, approaches, needs, etc., are captured. But also to include those publications that address less obvious aspects of product engineering relevant to this thesis based on the above understanding, such as strategy] (see Table 4.1). German translations of the respective keywords were included. … The review considered publications from 2020 onwards. The first reason for this limitation was the fast development in this area (Ceschin and Gaziulusoy, 2016; Liu et al., 2021), which suggests a rather short time frame [in favor of a broader coverage] to capture the latest understanding. Furthermore, relevant [publications] … published before 2020 are expected to be [cited by and therefore] reflected in … current literature.

[3] https://www.scopus.com/
[4] https://www.webofscience.com/

Table 4.1: Search String Used to Identify Literature Relevant to the Focus of This Thesis (adapted from Jäckle et al., 2023)

Aspect	**Search Terms**
Product engineering	Product engineering OR Product development
	AND
Sustainability	Sustainab*
	AND
Publication aspects	Defin* OR Descri* OR Research needs* OR Need* OR Approach OR Method*
	OR
Content aspects	Strateg* OR Operationali* OR Production planning
	AND
Publication year	Since 2020

Overall, a total of 933 publications … [were] identified during the systematic literature review, … [with] 708 … left after the removal of duplicates and entries not … [representing] publications. These 708 publications were screened (title and abstract) regarding their relevance. Within this process, two major types of non-relevant publications were identified: Those with deep functional focus (e.g., materials engineering, biomaterials, marketing) or specialized industry character (textile/fashion, tourism, food, construction). The remaining 198 publications were screened in full text for contextual relevance (24 excluded). [This literature body was used for all SLRs in this thesis.]

This body of literature was *updated* in September 2024 using the same search string with adjusted publication years to capture publications published in the meantime, resulting in 1313 documents, of which, after duplicate removal and cleanup, 1040 remained. After a title and abstract screening, an overlap check with the previous search, and an access check, 143 new publications remained. After a full-text screening, 116 of these publications were considered potentially relevant and added to the literature body to update the analyses on existing conceptions of sustainability in product engineering (Chapter 2.3.1) and the existing support for decision makers (Chapter 2.3.3), as suggested by Marxen (2014).

In addition, a dedicated exploratory literature review was conducted in October and November 2023 using the databases *Academy of Management*[5] and *Web of Science* to ensure that publications in *organization sciences* were adequately covered. 35 potentially relevant publications were identified, of which 34 were reviewed in full text and one was inaccessible. Thereof, 22 were added to the literature body, with relevant statements included in the analysis in Chapters 5.1, and 6.1. In these publications, no statements relevant to the analysis in Chapter 8.1 could be identified.

Data analysis and interpretation are specific to the research questions and therefore can be found in Chapters 2.3, 5.1, 6.1, and 8.1, while Chapter 7 draws on the literature analysis in Chapter 6.1. In the analyses in Chapters 2.3.1, 2.3.3, and 6.1, additional literature exploratively identified as relevant was taken into account to make use of existing knowledge and contributions.

5 https://journals.aom.org/

	Initial Literature Body Search String Table 4.1 Jan. 2020 to Sept. 2022	**Organization Sciences** Explorative Until Nov. 2023	**Update** Search String Table 4.1 Sept. 2022 to Sept. 2024
Databases	Scopus and Web of Science	Academy of Management and Web of Science	Scopus and Web of Science
Literature search	933	35	1313
Duplicate removal and clean-up	708		1040
Access check & title and abstract screening	198	34	143
Full-text review	174	22	116
Sustainability in Product Engineering *Chapter 2*	Conceptions *Chapter 2.3.1*		
	Underlying Understanding *Chapter 2.3.2.*		
	Existing Support for Decision Makers *Chapter 2.3.3.*		
Understanding *Chapter 5*	Dependencies *Chapter 5.1*		
Operationalization and Implementation *Chapter 6 and 7*	Suggestions *Chapter 6.1 and 7*		
Support *Chapter 8*	Suggestions *Chapter 8.1*		

Figure 4.2: Overview of the Literature Data Collection Process and Use in Systematic Literature Reviews with Number of Publications Remaining After Each Step of Each Search

4.2.2 Expert Interviews

The main source of information for the DS I and thus to answer the research questions was an interview study conducted with 25 experts in 2024 based on the Gioia Methodology (Gioia et al., 2013; see also Chapter 4.1 and Gioia, 2021). The interviews aimed to capture the perspective of decision makers on sustainability action in product engineering. Semi-structured interviews were prepared using an interview guideline derived from the SLR results to balance openness and targeted research, as suggested by Gioia et al. (2013). Data collection and analysis are described below, while the interpretation can be found in the respective chapters, as this was specific to the research questions.

Data collection

The SLRs cover existing knowledge, while the interviews were intended to identify the relevant aspects and the purposeful complexity of the answers to the research questions from a practical perspective, and therefore create new knowledge. As outlined above, data collection through interviews needs to balance the use of known information to ask relevant questions with not knowing in order to retain the necessary openness and achieve new findings. Starting from the research questions stated in Chapter 3.2, multiple SLRs specific to the research questions were performed to detail the respective part of the interview guideline, which was then compiled and used in the interviews (see also Figure 4.3).

Due to the problem focus of this research and the associated uncertainty, a combined approach of a generic discussion of relevant aspects to targeted sustainability action in product engineering and a case-based discussion was chosen. Therefore, two groups of experts were identified:

- Experienced consultants to share their reflective subject matter expertise across companies and
- Decision makers in product engineering at manufacturing companies to reflect on their work within their company.

Therefore, the semi-structured expert interviews can be classified as problem-centered in the case of consultants and as experience-centered and “episodic” in the case of decision makers (see Marxen, 2014). An overview of the interviews conducted can be found in Table 4.2.

The seven consultants had eight to 14 years of experience in the fields of product engineering and/or sustainability. They have all been based in Europe and were working closely with manufacturing companies.

To identify decision makers, four case companies were selected on the basis of the following criteria to increase the likelihood of relevant insights:

- A sophisticated understanding of sustainability to ensure that the data reflects multiple dimensions, e.g., a strategy referring to multiple sustainability objectives,
- A clear perspective on sustainability, to ensure that the decision makers are able to discuss the operationalization (beyond an initial understanding), e.g., ambitious objectives were communicated,
- A significant product engineering focus, to ensure relevant role of decision makers, e.g., sufficient technological complexity of products, and
- Variation in size, organizational structure, internationality, to identify potentially different aspects.

All four case companies are manufacturing companies with headquarters in Germany, of which two are automotive suppliers, one is an aerospace supplier, and one is a machinery company. The numbers of employees at the time of the interviews ranged from 1,000-5,000 in the case of the automotive tier 2 supplier, 5,000-10,000 for the aerospace supplier, 10,000-50,000 for the machinery company, to 50,000-100,000 in the case of the automotive tier 1 supplier.

In each case, a senior decision maker in product engineering was approached for an initial pre-discussion to introduce the research project and the role of the interviews. Together, with this senior decision maker, relevant perspectives for sustainability action in product engineering were identified. The aim was to cover a minimum of three but potentially up to six perspectives, depending on the case company's organizational structure:

- Functional perspective involving, e.g., a Head of Engineering
- Project perspective involving, e.g., a Head of Project Management
- Sustainability perspective involving, e.g., a Head of Sustainability

In addition, more operational perspectives were added through project leads. An overview of the case companies and experts interviewed can be found in Table 4.2. The number of employees and interviewee roles were anonymized in relation to the considered business unit. The identifiers (IDs) are used for references to the expert statements in Chapters 5 to 8.

Table 4.2: Overview of Company Cases and Interviewed Experts with Details Anonymized in Relation to the Considered Business Unit

Group	**Company Case** *Number of Employees*	**Role**	**ID**
Consultants	-	-	C1-7
Decision makers	Automotive supplier 1 *1,000-5,000*	Head of Sustainability	DM11
		Head of Advanced Engineering	DM12
		Team Lead Product Engineering	DM13
		Head of Industrial Engineering	DM14
		Head of Production Planning	DM15
		Head of Logistics	DM16
	Automotive supplier 2 *50,000-100,000*	Head of Sustainability	DM21
		Head of Advanced Engineering	DM22
		Head of Product Engineering	DM23
		Project Lead Product Engineering	DM24
		Project Lead Industrial Engineering	DM25
		Head of Project Management	DM26
	Aerospace supplier *5,000-10,000*	Head of Sustainability	DM31
		Head of Engineering	DM32
		Head of Industrial Engineering	DM33
	Machinery company *10,000-50,000*	Head of Product Sustainability	DM41
		Head of Engineering	DM42
		Project Lead Engineering	DM43

The 25 interviews were conducted from February to June 2024. They were scheduled for one hour and lasted 26 to 67 minutes depending on the discussion (1260 minutes total). All interviews were conducted virtually via Microsoft Teams or Zoom video conferencing software in English or German, depending on the interviewee's preference. They were recorded after consent, and the recordings were automatically transcribed using the transcription software Trint (Trint, 2024), followed by a word-by-word revision by the author to ensure accuracy.

The interviews were semi-structured using an interview guideline, which included an introduction, a section for each of the research questions, and a closing section (see Figure 4.3). For each of the research questions, the interview guideline contained questions at three levels of detail:

- Open questions
- More specific questions based on information extracted from the SLRs
- Challenging questions to trigger reflection

In addition, examples could be provided if the interviewees asked for further clarification. During the interview, the interviewer (author of this thesis) ensured that all research questions were covered as appropriate by asking open questions. Starting with these open questions, the discussions followed the experts' answers, with spontaneous follow-up questions asked by the interviewer. The more detailed levels of the interview guideline were only used after the related open question was answered or could not be answered before. The English language version of the interview guideline can be found in the Appendix A.2. The German language version, which was also used in the interviews, represents a direct translation.

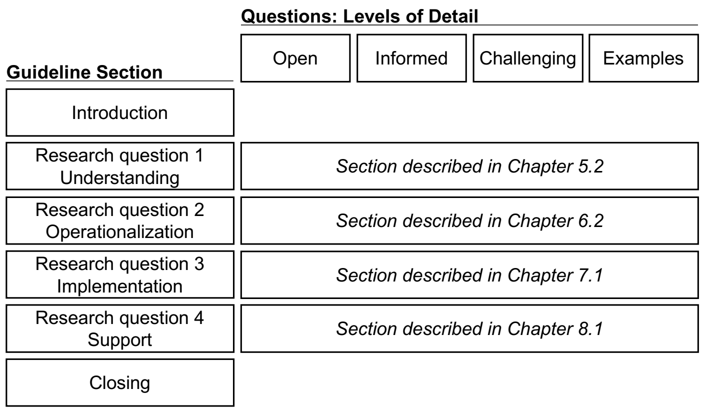

Figure 4.3: Structure of the Interview Guideline Used in the Expert Interviews (see also Appendix A.2)

Analysis

The collected and transcribed data was manually analyzed in five steps based on the Gioia Methodology (see Gioia et al., 2013) using ATLAS.ti software (ATLAS.ti, 2024):

1. Key interview statements were highlighted and paraphrased using interviewees' terms, resulting in 1993 statements, which can be seen as very detailed and initial first-order categories (see Gioia et al., 2013).
2. Where applicable, the statements were additionally inductively categorized by industry context (e.g., “Automotive”), sustainability context (e.g., “Environmental – Circularity”), and type of statement (e.g., “Observation”) to allow for potential comparisons later.
3. The first-order categories were distilled into second-order themes (e.g., “Missing materiality”). During this step, first-order categories and emerging second-order themes were continuously clustered and divided based on similarities and differences (see also Gioia et al., 2013). Moreover, where applicable, actors (e.g., “Competitors”), functions (e.g., “Engineering”), and organizational level (e.g., “Top management”) were inductively identified and added to the statements at that stage to enable comparisons at a later stage.
4. The identified second-order themes were assigned to the research questions or clustered as overarching themes (e.g., “Uncertainty”).
5. The second-order themes and first-order categories of each research question were reviewed again with respect to the overarching second-order themes, resulting in a split into two aggregate dimensions per research question that reflect a problem- and solution-focused perspective: Challenges and success criteria.

The first-order categories, second-order themes, and aggregate dimensions are summarized in “data structures” (e.g., Figure 5.3), which can be found in Chapters 5.2, 6.2, and 7.1. The discussion of the results is based on the individual statements and follows these data structures. An example illustrating this logic that includes two statements can be found in Figure 4.4.

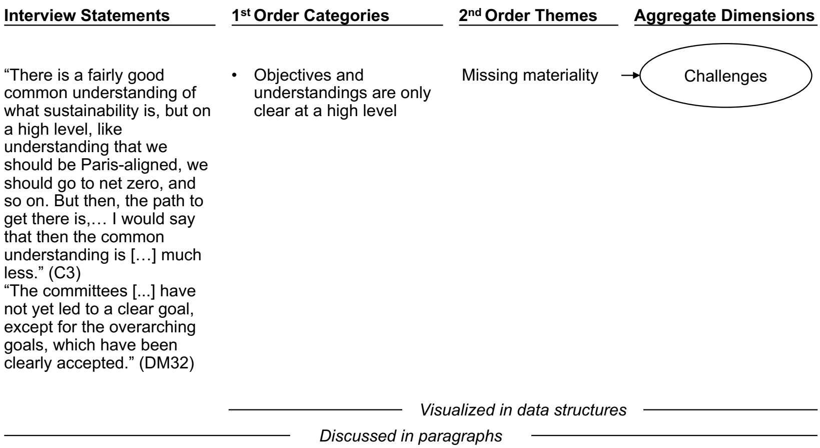

Figure 4.4: Illustration of the Expert Interview Data Analysis and the Discussion of Its Results Based on the Example of the Data Structure in Figure 5.3

5 Understanding Targeted Sustainability Action in Product Engineering

In order to identify generalizable aspects of targeted sustainability action in product engineering, which is the first research need to be addressed by this thesis, targeted sustainability action must first be understood in a way that does not compromise overcoming the challenge outlined in Chapter 3.1.
Therefore, based on the initial findings in Chapter 2.3, this chapter aims to further understand sustainability in product engineering in order to answer the first research question: *How can targeted sustainability action be understood in product engineering?*

The structure of the chapter follows the analyses conducted. First, the results of the literature study that resulted in the interview guideline are presented (Chapter 5.1). Second, the results of the interview study are described and discussed (Chapter 5.2). In Chapter 5.3 an interim conclusion is drawn and the above research question is answered.

A summary of the key findings of this chapter can also be found in the Guide for decision makers in Appendix A.1, as the results in this chapter were incorporated into this support. Specific references are provided throughout this Chapter, while the development of the Guide is described in Chapter 8. An overview of the Guide and the key concepts behind it have previously been published in Jäckle et al. (2025).

5.1 Initial Understanding Derived from Literature Review

The SLR in Chapter 2.3.2 covered the underlying understanding of sustainability in product engineering in the literature based on an hermeneutic analysis, and suggested the context dependence of understanding sustainability in product engineering, resulting in an explication framework with three aspects: Purpose (Why?), scope (What?), and approach (How?), shown in Figure 2.10. Although the interdependence of these three aspects became evident in this analysis, it could not yet be explained. Thus, to understand sustainability in product engineering in more detail, the underlying interdependencies are explored.

To capture what is known about the interdependencies between *Why*, *What* and *How*, the literature body (see also Chapter 4.2.1) was reviewed for statements that describe the **dependencies** between aspects of sustainability and product engineering, resulting in a total of 181 statements. These dependencies were visualized as directed arrows between the aspects, which themselves were described in ovals using the terms of their authors. Each arrow was labeled with the [ID] of the statement that described the dependency, and whether a positive (+) or negative (-) effect was described (see Figure 5.1 for examples). Through this manual visualization exercise, a network could be developed describing the interdependencies between sustainability and product engineering in a broader sense, which in its process is comparable to the identification of initial first-order categories according to Gioia et al. (2013, see also Chapter 4.2.2). This network is shown in the background of Figure 5.1, where exemplary statements are illustrated by their aspects and dependencies as part of the network. These exemplary statements are also part of the discussion below.

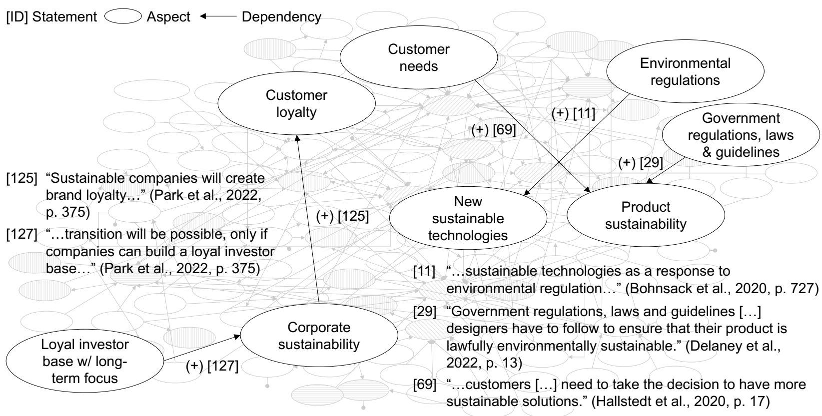

Figure 5.1: Exemplary Visualization of Aspects and Dependencies Identified in the Literature

Building on this network, the aspects were clustered and assigned to the three levels (*Why*, *What*, *How*) identified in Chapter 2.3.2 to describe the interdependence between sustainability and product engineering. The resulting clusters can be found in Figure 5.2, while the characteristics of the interdependencies are discussed in the following. In this discussion, two types of interdependencies are differentiated. First, the interdependencies found between the aspects of purpose and scope at *Why* and

What levels (dashed arrows in Figure 5.2). To understand sustainability in product engineering, the dependencies between product engineering and these aspects are of special interest. Thus, they represent the second type of interdependencies between the levels *How* and *What*/*Why* (solid arrows in Figure 5.2).

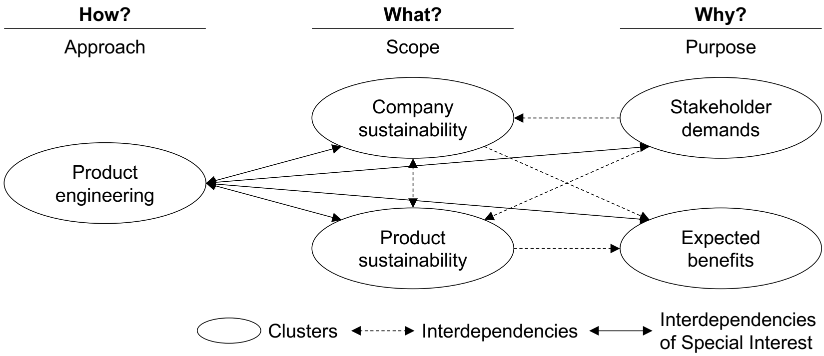

Figure 5.2: Initial Understanding of Sustainability in Product Engineering Derived from the Literature, with Relevant Interdependencies to be Understood in the Interview Study (Solid Arrows)

In Chapter 2.3.2 the *Why* level was divided into drivers and benefits. Based on the network this can be refined to stakeholder demands as a first cluster and expected benefits as a second cluster that interact with the *What* level. At the *What* level, the previous scope consisting of sustainability aspects and the area of application can be described by two clusters that emerged from a product engineering perspective in the network: Company sustainability and product sustainability, both of which depend on each other (e.g., Park et al., 2022).
Moreover, both might contribute to expected benefits and/or might be demanded by stakeholders in various ways leading to a broad and complex network of dependencies (see Figure 5.1). As an example of dependencies found within the network, regulations can affect the sustainability of products in development (Delaney et al., 2022) and the technologies behind them (Bohnsack et al., 2020). Customers can demand more sustainable products (Hallstedt et al., 2020), or an investor base with a long-term focus can promote corporate sustainability, which again can lead to brand loyalty on the customer side as a benefit (Park et al., 2022).

According to the reviewed literature, this breadth of dependencies between *Why* and *What* levels (simplified to dashed arrows in Figure 5.2) also sets itself apart from other demands and benefits, known in product engineering by its long-term orientation (Park et al., 2022; Evrard, Rejeb, Zwolinski, and Brissaud, 2021), which can cause uncertainty (Hallstedt et al., 2020).

Product engineering, in this model on the *How* level, can directly affect the sustainability of products and the company itself (the *What* level). In addition, product engineering might also include direct interactions with stakeholders and their demands or directly address expected benefits (the *Why* level), as the discussion below shows. As outlined, these four interdependencies (solid arrows in Figure 5.2) are of special interest to targeted sustainability action in product engineering and are therefore discussed in more detail below.
In the current literature, these interdependencies between product engineering at the *How* level and *What* and *Why* levels are investigated with respect to the multiple conceptions of and approaches to sustainability in product engineering (also see Chapter 2.3). At the time of this analysis, the sustainability of products and the sustainability of production, as part of the product life cycle and thus from a product sustainability perspective (see also Chapter 2.1), were at the core of the research. The dominant approach of sustainability in product engineering employed to describe the interdependencies between sustainability and product engineering was circular product design (e.g., Aguiar, Mesa, Jugend, Pinheiro, and Fiorini, 2021; Diaz et al., 2022). However, similar research was conducted using, e.g., the approach of eco-design, sometimes even resulting in similar findings. For example Balikci, Borgianni, Maccioni, and Nezzi (2021), and Aguiar et al. (2021), identify user behavior as a barrier to eco-design and circular product design respectively. Therefore, the interdependencies are discussed here across these approaches and the conceptions behind them.

Analyzing the interdependencies between product engineering at the *How* level and company as well as product sustainability at the *What* level, for example, Petersen (2021) states that a thought-out corporate sustainability approach is a major success factor for sustainable product engineering, and Ganji, Shah, and Coutroubis (2020) see a company strategy as a driver for the integration between the development of new products and the circular economy in this case. Watz and Hallstedt (2022) also highlight the importance of early and systematic integration of sustainability in aspects of product engineering. However, for example Diaz, Schöggl, Reyes, and Baumgartner (2021) state that the implementation of high-value “R strategies” in product engineering can “interfere with the corporate competitive strategy” (p. 1041), and Xavier et al. (2020) name strategy as an area of organizational barriers. This indicates that the interaction between corporate strategy and operational product engineering requires special attention, which is in line with, e.g., Diaz et al. (2022) who refer to “strategy implementation as … the bottleneck to … deployment” of circular economy strategies (p. 2).

The interdependencies between *How* and *Why* levels, namely between product engineering and the expected benefits of sustainability or stakeholder demands, show similar breadth and complexity within the network to the interdependencies between the *What* and *Why* levels. For example, Watz and Hallstedt (2020a) suggest that both bottom-up and top-down exchanges within the organization are needed for the implementation of sustainable product development, and Diaz et al. (2022) state that such implementation (in this case of circular economy) is tied to competitive advantages, which Bohnsack et al. (2020) also view as a benefit of sustainable innovation. At the same time, opposing dependencies between these levels can also be found in the literature. For example, Jugend, Fiorini, Pinheiro, Da Silva, and Pais Seles (2020) find that legislation can be a driver and a barrier to circular economy adoption. Also, cost reductions can be a benefit resulting from eco-innovation according to Bierwisch, Huter, Pattermann, and Som (2021), while, e.g., Jugend et al. (2020) state that potential cost increases are a barrier to circular economy adoption in new product development. In addition, product engineering can interact directly with stakeholders (Xavier et al., 2020), e.g., through customer involvement and co-creation (Diaz et al., 2021), or indirectly, e.g., through “perceived as sustainable” product features (El Dehaibi, Herrera, Rattanakongkham, and MacDonald, 2022, p. 12). Moreover, product development departments as social systems themselves can swing between obstructing or promoting product sustainability, further adding complexity to the network and broadening the interdependencies (Petersen, 2021).

In summary, this literature review represents a qualitative analysis of the interdependencies between aspects of sustainability and product engineering. Inductively identified clusters of aspects and interdependencies could be matched to the explication framework developed as part of the Research Clarification in Chapter 2.3.2. The analysis shows the breadth and complexity of these interdependencies in the developed network. The overlaps and opposing dependencies discussed further suggest the context specificity of an action-oriented understanding of sustainability in product engineering.
Thus, these findings provide more detail on the challenge to develop broad, yet context-specific, actionable support for decision makers by further understanding sustainability in product engineering. However, they do not yet provide an action-oriented understanding of sustainability in product engineering that allows for understanding

targeted sustainability action. Consequently, the interview study described in the next chapter revisits these interdependencies.

5.2 Understanding Derived from Interview Study

Developing this action-oriented understanding of sustainability in product engineering represents the focus of the first section of the interview guideline, with four open questions that are detailed by literature-informed questions (based on Chapter 5.1), as well as challenging questions and examples. A summary of this section is provided below, while the structure of the interview guideline with its types of questions can be found in Chapter 4.2, and the interview guideline in Appendix A.2.

Since the interdependencies between product engineering and sustainability identified in the literature could not yet provide an action-oriented understanding of sustainability in product engineering, the interview guideline was designed to cover two areas of interest. First, asking openly how the topic of sustainability and product engineering impact each other at the specific company, and second, referring to potential conceptions, how sustainability in product engineering is understood. The first area was chosen as a starting point as it addresses the experts' observations regarding the interdependencies of interest (solid arrows in Figure 5.2). After an open question, the informed and, therefore, more specific questions address these interdependencies based on Chapter 5.1. Due to the long-term orientation and uncertainty indicated by the literature, they further cover the current as-is status, as well as potential expectations of the experts. As dependencies between sustainability and product engineering can be opposing and also dependent on each other, they also cover the reasons and conditions of these expectations.

The open question of the second area directly addresses the understanding of sustainability in product engineering and, therefore, the sense-making of the interviewees and others based on the observations discussed in the first area, which is a prerequisite to action (see Chapter 2.1). Due to the suggested context dependence of the demands, the questions distinguish between a shared understanding at the company and the personal understanding of the expert. Moreover, more specific questions address the differences and implications of multiple understandings and their origins, if prevalent.

The analysis of the interview data with respect to the first research question (see Chapter 3.2) followed the Gioia Methodology (Gioia et al., 2013; see Chapter 4.2.2 for details), resulting in a data structure with challenges and success criteria as aggregate dimensions. The coding took into account not only the answers to the questions related to the understanding but also all statements with implications for the understanding (see Table 4.2 in Chapter 4.2.2 for an overview of the interviews with identifiers). The data structure is shown in Figure 5.3, with challenges and success criteria as aggregate dimensions.

The analysis of the interview data related to the first research question aimed to understand sustainability in an action-oriented way that supports targeted action in product engineering. In the context of this intention, a problem-oriented perspective emerged from the data, which resulted in the identification of the **challenge** of coping with the *missing materiality* of the understanding amid *complexity* and *uncertainty*.

Missing materiality High-level objectives such as “more circularity,” (C1, trans.) or “we should go to net zero” (C3) are easily aligned, e.g., in exchange with authorities (DM32); however, such unspecific demands and resulting understandings also lead to no or unspecific action (C7; DM32). As one of the consultants put it, “with an objective like: Let’s do more circularity somehow, you can’t do anything. That has no chance.” (C1, trans.). Another consultant describes the situation as follows: “There is a fairly good common understanding of what sustainability is, but on a high level, like understanding that … we should go to net zero and so on. … But then the translation … into ‘How does that play into my specific role as an engineer, as a procurement officer, as a site manager?’ That’s often lacking.” (C3). Moreover, such missing materiality opens the floor for individual interpretations (C2) raising the question, “What’s actually behind all this?” (DM32, trans.), as one Head of Engineering describes the “helplessness” of employees: “There have been various opinions on this, but which opinion is … important and is expedient?” (DM32, trans.). Another project lead summarizes this missing materiality illustratively as, “You can write in the project specifications that we want a sustainable product and then when someone asks ‘What does that mean?’, … their eyes widen, and nobody knows.” (DM43, trans.). This stated lack of materiality in sustainability understandings therefore constitutes an obstacle to targeted action in product engineering, which needs to be overcome.

Complexity However, achieving this materiality is difficult due to the complexity and uncertainty involved in understanding sustainability. The complexity can be described as twofold: First, sustainability as a term can be arbitrarily broad (C1), and an expanding set of topics is observed to be considered for action (DM21). One Head of Sustainability raised the example of an automotive OEM’s priorities, “The accident rate has always been there. And this topic is now expanding even further into other areas.” (DM21, trans.). The broadening of sustainability demands includes more and more topics that are conceptually difficult and not yet fully understood, such as circularity (C1; C6), and even topics that are not immediately evident from a product engineering perspective, e.g., social aspects of raw material extraction (C1).

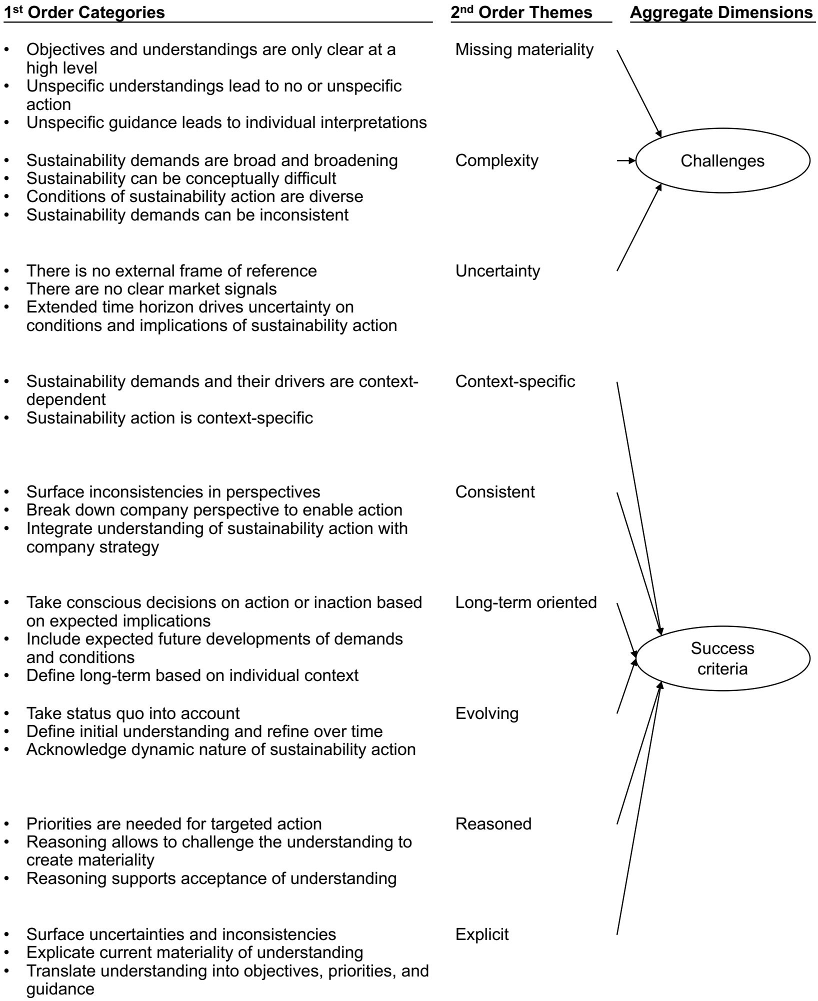

Figure 5.3: Data Structure Derived from the Interviews with Problem- (Challenges) and Solution-oriented (Success Criteria) Findings with Respect to the First Research Question: Understanding Sustainability in Product Engineering

This development complicates targeted action, as understanding these topics is a prerequisite. Secondly, individual topics such as carbon dioxide emissions that can be considered conceptually rather “simple” are only slowly acted on. One consultant describes decarbonization as “simple, CO_2 is incredibly simple. It’s a thing where it’s completely clear what the math is, how you can measure it, how you can integrate it into your system data-wise. It’s absolutely … something that an engineer can very, very easily deal with as one more requirement in their specification. And even that is tentative.” (C1, trans.). This again sets the focus on the conditions under which sustainability action is intended. These conditions, like drivers of sustainability demands, e.g., regulations (C1), or the supply chain of a company (DM32; DM43), can be highly diverse. Therefore, also the (expected) implications of these conditions on sustainability action, such as potential risks (DM22), vary depending on the company context (C1). A summary of potential drivers of sustainability demands (Table A.11), possible sustainability aspects (Table A.12), and their potential application area (Figure A.5) identified during the interviews can be found as part of the Guide for decision makers (Appendix A.1).
Moreover, this variety in demands and conditions also results in differing perspectives leading to conflicting demands and understandings (DM33). One Head of Industrial Engineering describes such a situation as: “Sustainability is also diverse. In these discussions, whether it is legally driven, ecologically driven, or something else, I think everyone has a slightly … different underlying understanding. To be honest, I don’t think it’s broken down or described enough what … the company … understands by sustainability.” (DM14, trans.). This complexity, with broad, conceptually difficult, diverse, and inconsistent demands and their implications, complicates the creation of a material understanding that supports targeted action. As one Head of Sustainability summarized this complexity: “There are no longer simple answers.” (DM31, trans.).

Uncertainty In addition to complexity, there is uncertainty, making it challenging to create materiality, as there is no external frame of reference for the targeted action (C1; C7) and, in many cases, no clear market signals. This becomes evident in multiple statements. “Nobody has very clear signals from the market … ‘What’s considered a sustainable product?’, ‘Is there demand for a sustainable product?’, ‘Is there a premium?’ … ‘Can I get margin for it or is it the cost of doing business?’, ‘What is the real demand from customers?’” (C6), or “It might come the question around: ‘So how much … recycled materials do you have, in your product, for example?’ But it’s unclear for the tier-1 supplier as well: Is this going to be a hard demand soon?” (C3). Moreover, the extended time horizon of sustainability demands leads to additional uncertainties (DM31), especially in product engineering, where long development cycles are prevalent (DM31). Examples are uncertainties on the development of relevant conditions and implications of sustainability action like stakeholder abilities and actions (C3; DM12; DM26), or on the potential value of one's own sustainability action (see statements above; DM13), but also on implied risks of inaction (C1). Waiting for the collective wisdom of stakeholders (C1) might work in some industries (C1), but also may not be enough to take advantage of the opportunities that come from this uncertainty (C1; C6), or might result in a situation of being at mercy (C1). A summary of potential risks and opportunities identified during the interviews can be found in Table A.10 as part of the Guide for decision makers (Appendix A.1).

With respect to the main challenge of this thesis, which is to develop support that is actionable and context-specific, while maintaining a broad perspective (see Chapter 3.1), these results confirm that this challenge not only persists for the development of academic support, but is rooted in the nature of the problem itself.

Supporting targeted sustainability action therefore first of all means supporting decision makers in creating a material understanding of sustainability that acknowledges the described complexity and uncertainty and enables targeted action in product engineering. Therefore, the discussion of the solution-oriented perspective, which emerged from the data as a second aggregate dimension with respect to the first research question (see Figure 5.3), takes into account this nature of the problem in understanding sustainability in product engineering to address the main challenge of this thesis. In this context, six **success criteria** for such an understanding were identified, which will be discussed in the following: An understanding should be *context-specific*, *long-term oriented*, *evolving*, *consistent*, *reasoned*, and *explicit*.

Context-specific First, as outlined under complexity, the interview data shows that drivers and demands for sustainability action strongly depend on the company's context. Similarly to sustainability demands, opportunities and potential actions are also context-dependent (C1). This dependency again includes the industry (C1), a company's size (DM16), its specific supply chain and value chain (C1), footprint (DM21; DM31), products (DM42), markets (C7; DM25) as well as its economic situation (C4), and many more. These conditions therefore define the "solution space" of potential sustainability action (C1, trans.).
Rooting the understanding of sustainability action in these context-specific demands and conditions acknowledges this breadth and complexity of the topic of sustainability in product engineering. At the same time, it allows one to focus on relevant demands with respect to the conditions to create material understanding that supports targeted action. A consultant indicated such an approach to a more material understanding of circularity in a company by raising the following question: "Circularity is a nebulous concept. Based on our business, what does circularity mean?" (C6).
A summary of potential drivers of sustainability demands (Table A.11), potential risks

and opportunities (Table A.10), potential sustainability aspects (Table A.12), and their potential application area (Figure A.5) identified during the interviews can be found in Appendix A.1 as part of the Guide for decision makers.

Consistent Addressing the complexity of sustainability and acknowledging its context-dependent nature also means coping with a variety of perspectives on sustainability (see also *complexity*). These differences in perspectives can range from different priorities (DM23) to inconsistent demands and conflicts in objectives (DM42). To create a material understanding of sustainability, these perspectives need to be assessed and inconsistencies need to be surfaced (DM43). Therefore, and to enable targeted action, a consistent and broken-down company perspective on sustainability is needed (see *complexity*). Developing this perspective distinction is comparable to requirements in product engineering, which are translated into a consistent set of specifications, where usually "more than 100% is desired at the beginning," as one Engineering Project Lead describes it (DM43, trans.). On the one hand, this company perspective allows one to differentiate demands or ambitions (DM31), which include personal and employee perspectives (DM24), from objectives to be acted on. At the same time, this differentiation between perspectives creates clarity for action (DM33; DM43), as priorities can be set (C1) with top management commitment (DM15), while embracing the diversity of perspectives to keep breadth (DM32) and not overdo it (DM24; DM33). This company perspective should also be consistent and integrated with the company's strategy (C5; DM11; DM21). Thus, it should not be an add-on of "what should happen" (C7), to avoid additional inconsistencies with existing objectives leading to deprioritization and no action (C2; C7). One consultant illustrates such an inconsistency with existing objectives that hinders action: "Be … honest on what you think, about the … cost effects, of that, so that there is not a total disconnect between we want to go down 60% in emissions on … this car, but everything needs to be cost neutral." (C3). Another consultant summarizes the value of such consistent integration surfacing an opportunity at the example of circularity: "Most success is where the business believes that actually increased circularity gives them some type of business advantage. … If I am heavily dependent on scarce and valuable raw material, circularity can help decouple me from that." (C6).

Long-term oriented The extended time horizon of sustainability demands (see *uncertainty*) also increases the time horizon of sustainability action and its implications (C3). Despite the long-term orientation of the demands, action might also be required now (e.g., due to a required learning curve, C1) or action now might mitigate risks/create opportunities (C7). Both taking action or not taking action on these demands means making assumptions (C3) that sometimes can only be evaluated later in time (C1). This uncertainty on action is described by a consultant with a procurement example:

"Should I accept this green premium? Should I sign a longer contract, or should I actually wait and see, and so on? But you need a similar point of view, which will be … even more longer-term … in product engineering … as well." (C3). Therefore, to take targeted action, conscious decisions are needed that take into account future developments of demands, conditions, and potential implications of actions with all their uncertainty (C3). This can also mean aiming to anticipate such developments as new regulations (DM26) to avoid additional challenges that occur if transparency is gained too late (C2). Consequently, the understanding of sustainability and action on it should be long-term oriented and allow for a connection to today's actions, e.g., on technologies. However, what is long-term and when to act is again strongly context-dependent. This includes conditions like current development cycles (DM31), product lifetimes (DM32), but also available capacities (DM26; DM31), economic pressure (C1; C5; DM33) and one's own ambition (DM31), which may also lead to ambiguities (DM31). This potentially strategic character of a long-term-oriented understanding requires the involvement of appropriate management levels that can take responsibility for the decisions taken (C5).

Evolving A material understanding of sustainability is needed at the beginning of a transformation and broader action in the organization, for example, in product engineering (see *consistent*). Acknowledging the context dependence (see Context-specific) of such an understanding also means assessing and taking into account prevalent perspectives on it and the current status quo of sustainability action (C7; DM11; DM23; DM25) when starting to create the company perspective (see *consistent*). At the same time, a material understanding is built through experience, as through proactive action, uncertainty about demands, conditions, and implications can be reduced, and complexity can be resolved (C1; DM21; DM23; DM31; DM43). One consultant describes this relation between understanding and acting "if you really want to act now and understand how you improve over time, you need to create that understanding yourself" (C7). In addition, early involvement in understanding and sustainability action fosters a common understanding among employees (DM16; DM32) and promotes acceptance (DM11). Therefore, to initiate targeted sustainability action, an initial understanding must be defined (DM15), which is then iteratively revised and evolves as new knowledge is gained (DM21; DM31). As one Head of Sustainability puts it: "One shouldn't see it as being set in stone. If we come to a different conclusion three or four years down the line through a new project or something similar, then it can always be adjusted or adapted. But initiating it for the first time and then establishing it is, of course, necessary at some point." (DM31, trans.). The relevant demands, conditions and perspectives are not only uncertain, but also not static (see *long-term oriented*). They change over time with an uncertain pace and increasing volatility (DM21). One obvious unidirectional example is the expectation that “the legal requirements will become even stricter” (DM26, trans.), but opposing developments in stakeholder demands, e.g., investors, can also be seen to develop in certain regions (C6). Hence, the evolution of the understanding of sustainability and sustainability action does not necessarily converge to a fixed state of sustainability that can be defined now, but might need to change continuously. Moreover, the long-term orientation might need to be adjusted, e.g., depending on the economic situation of the company (C1). As one Head of Sustainability put this evolving nature: “Who says I have to reach 120% right away? That I can’t achieve over 80%? … And then I can always continue working.” (DM11, trans.). The Head of Sustainability also puts full-blown academic approaches into perspective: “One thinks in black and white. One has such theoretical approaches. But that’s not what a company needs. … It also requires a great deal of knowledge about how it can actually be implemented in the company. How does the company operate?” (DM11, trans.). One Head of Engineering further suggests this nature as reference for future regulations: “It doesn’t matter, … how bad they are at the start. … It would be important that the improvement is then assessed and evaluated from year to year.” (DM42, trans.). Therefore, when creating a material understanding, one should start from the current status quo, acknowledge that this understanding might be subject to changes over time, and refine it as action reduces uncertainties.

Reasoned As outlined under *consistent* and *evolving*, a company’s perspective and, therefore, its understanding of sustainability in product engineering will likely not meet all demands at a given point in time, since this is neither possible nor useful for targeted action (C7). As a Head of Sustainability stated: “I can never be 100% sustainable. But I can do something small every day to get there.” (DM31, trans.). Similarly, one consultant illustrates the focus in action set by companies, compared to theoretically “comprehensive” sustainability conceptions: “There is the full taxonomy. But in the real world, the whole taxonomy does not count.” (C6). Another summarizes: “Consciously act on things that make sense to act on. … And to get there, you need that detailed understanding. You need to understand when should I invest in certain things? Certain things do not make sense to do right now.” (C7). Hence, the understanding of sustainability should be honestly reasoned to allow for targeted detailing, prioritization and action (C1). Moreover, such reasoning allows one to challenge this understanding, which enables a debate with diverse perspectives (see *consistent*) over the best solution (DM32) or option for action (DM32), and makes an evolution of the understanding over time possible (see *evolving*). This debate should also be open for no action if it can be convincingly reasoned (DM41). One Head of Product Sustainability reported on a new machinery component they developed that was very sustainable but not demanded by customers: “It actually … only cost money and had 0.0 effect. Although you can disassemble it in seven steps and only need a cross-head screwdriver." (DM41, trans.). The Head of Product Sustainability summarized this action as the "right idea on the wrong product" (DM41, trans.). Finance can be a constructive challenger in this debate (DM31). In essence, this reasoning and debate create the materiality of the understanding (DM31). In addition, such reasoning makes the understanding and therefore the company perspective comprehensible for others, which increases its acceptance. One Head of Sustainability explains it as follows: "Especially in an engineering-oriented company … it's a must. … If I then come around the corner with scientific topics, then people can comprehend it. And if I make something explainable, it's very comprehensible. If I just say we're doing this and don't explain why, then it offends people. So why is always very important." (DM21, trans.). Therefore, the first element of such an understanding of sustainability action in product engineering should provide this reasoning by answering this *why* from company a perspective, e.g., "Why does this matter for the company?" (C3), "Why is this an issue at all?" (DM31, trans.). These questions are also part of the Guide for decision makers, which can be found in Appendix A.1.

Explicit An understanding of sustainability in product engineering can only lead to targeted action if it is explicit with respect to the described aspects. This might start with clarifying the current company perspective on sustainability in product engineering as well as the complexities and uncertainties that are faced with their interdependencies (see the respective paragraphs). The understanding should surface inconsistencies (see *context-specific*, *consistent*), be clear on assumptions on future developments and commitments (see *long-term oriented*), be transparent on the status quo and evolving character of the understanding (see *evolving*), and be honest on the reasoning (see *reasoning*). Otherwise, these points outlined above will not come into effect and the understanding will not be material enough to enable targeted action (see respective paragraphs). Therefore, as a second element, the understanding should answer the question of what is intended to be achieved through targeted sustainability action, which should be explicated and communicated in the organization, for example, as objectives with clear priorities and guidance for action (C1; DM12; DM14; DM15; DM16; DM32; DM33; also see Chapter 6 for more details).

Summarizing the solution-oriented findings of the interview results, generalizable aspects of a material understanding of sustainability that supports targeted action in product engineering could be identified. Problem-oriented knowledge found in the literature (see Chapter 5.1) was confirmed but also translated in a solution-oriented description of such an understanding. In addition to the known context-dependency of sustainability demands, sustainability action was also found to be *context-specific*. Therefore, an action-oriented understanding of sustainability should be derived from these context-specific demands and conditions. Moreover, these context-specific demands and conditions become a lens that allows one to navigate the complexity of understanding sustainability to initiate action. This approach opposes the application of pre-fixed understandings (mostly aiming for comprehensiveness), which are widely found in the literature (see Chapter 2.3). In addition, inconsistencies between perspectives that were also reflected in the literature (see Chapters 2.3.2 and 5.1) could be understood in more detail and were found to be addressable by introducing a *consistent* company perspective to initiate action as a company. The long-term orientation of sustainability demands could be translated into a long-term orientation of sustainability action, which was also found to be context-specific, also affecting the time horizon of an action-oriented understanding of sustainability. The *uncertainty* regarding targeted sustainability action (see Chapter 1.1) was confirmed and found to be addressable through an *evolving* understanding of sustainability. The development of context-specific sustainability demands was not only uncertain in pace, but also in direction, suggesting an evolving understanding that might change in all aspects including the long- or short-term orientation, which again opposes pre-fixed understandings of sustainability when aiming for action orientation. Moreover, the importance of reasoning the sustainability understanding could be confirmed (see also Chapter 2.3.2) enabling context-specific prioritization for targeted action. It could be found that in all these aspects one needs to be *explicit* to initiate action. Overall, this analysis could identify generalizable aspects of an understanding of sustainability that support targeted action in product engineering and illustrate their relations, which constitutes an entirely new approach to supporting decision makers on targeted sustainability action in product engineering.

This understanding emphasizes a new leeway in dealing with sustainability demands when shaping a company's perspective on sustainability. This leeway should not be confused with "sustainability neglect or breach of conduct/rules out of ignorance" (Jäckle et al., 2025, p. 2965). Instead, it recognizes these demands' uncertain and dynamic nature, acknowledging that information on current and future demands and conditions is incomplete. Thus, with this understanding, even companies with a short-term orientation can begin to address their uncertainties without implicit moral judgments embedded in preconceived ambitions for action. Moreover, this leeway accounts for the entrepreneurial character of sustainability action (DM31), enabling decision makers to seize opportunities and take or mitigate risks through conscious sustainability action or inaction. (see also Jäckle et al., 2025)

5.3 Interim Conclusions

Understanding sustainability in product engineering in an action-oriented way provides the basis to answer the first research question of this thesis: *How can targeted*

sustainability action be understood in product engineering?
As described in the previous chapter, an understanding of sustainability in product engineering that supports targeted sustainability action, and thus an action-oriented understanding of sustainability in product engineering, must be developed from a company perspective and should be context-specific, consistent, long-term oriented, evolving, reasoned, and explicit.

Hence, targeted sustainability action (TSA) can be defined as conscious action or inaction that contributes to such an understanding or is derived from it. When targeted sustainability action replaces sustainability action driven by pre-fixed demands and sustainability conceptions, companies can take advantage of opportunities emerging from sustainability demands and related uncertainties. (see also Jäckle et al., 2025)

This new way of understanding sustainability in product engineering to initiate targeted sustainability action has two implications. On the one hand, it describes generalizable aspects of the individual understanding that decision makers need to develop in order to initiate targeted sustainability action in product engineering and thus addresses the first part of the first research need (see Chapter 3). How such an understanding can be operationalized is discussed in the following Chapter 6. On the other hand, it offers the first step in addressing this thesis’s main challenge by defining the nature of expedient support: Not offering a pre-fixed conception of sustainability (as is common in the literature), but supporting decision makers in developing a context-specific understanding. The development of this support is discussed in Chapter 8, while the Guide, which also summarizes the main findings of Chapter 5, can be found in Appendix A.1.

6 Operationalizing Targeted Sustainability Action in Product Engineering

To turn an understanding of targeted sustainability action into action in product engineering, this understanding (see Chapter 5) must be operationalized. Therefore, based on the understanding of targeted sustainability action, generalizable aspects of its operationalization are identified, without compromising overcoming the main challenge described in Chapter 3.1.
This chapter therefore aims to answer the second research question: *How can targeted sustainability action be operationalized in product engineering?*

The structure of this chapter follows the analyses conducted, which cover the results of a literature analysis in Chapter 6.1 and the interview study in Chapter 6.2. Moreover, interim conclusions are drawn in Chapter 6.3 with respect to the second research question, above.

A summary of the key findings of this chapter can also be found in the Guide for decision makers in Appendix A.1, as the results in this chapter were incorporated into this support. Specific references are provided throughout this Chapter, while the development of the Guide is described in Chapter 8. An overview of the Guide and the key concepts behind it have previously been published in Jäckle et al. (2025).

6.1 Initial Operationalization Derived from Literature Review

In Chapter 5.1, the interdependencies between product engineering aspects and sustainability aspects were analyzed based on existing literature to better understand sustainability in product engineering. To further explore sustainability action in product engineering to potentially affect these interdependencies, the literature body was reviewed again. The literature was searched for **suggestions** on sustainability action in product engineering. These suggestions had two forms, “barriers”, e.g., uncertainty (Hallstedt et al., 2020), to be overcome for sustainability action, and “practice needs”, e.g., encouraging culture (Obal, Morgan, and Joseph, 2020), that need to be met for sustainability action. Again, these suggestions were collected across conceptions of sustainability (see also Chapter 5.1).
Overall, 234 practice needs for and 34 barriers to sustainability action were identified. They were inductively clustered (see Figure 6.1) and are discussed below along these

clusters to prepare the second part of the interview guideline, which is described at the beginning of the following Chapter 6.2. As these suggestions characterize and describe sustainability action in product engineering, they closely relate not only to the operationalization of sustainability action but also to its understanding and implementation. Where applicable, these implications are discussed and referenced throughout the chapter.
The identified suggestions can be further distinguished into two types: first, the practice needs and barriers that characterize sustainability action (Chapter 6.1.1), and second, suggestions that describe this sustainability action (Chapter 6.1.2), which, when clustered, represent potential fields of action. However, it should be noted that these findings refer to general sustainability action, as this analysis was conducted based on the literature prior to the interview study, thus targeted sustainability action was not yet understood. An overview of the identified clusters can be found in Figure 6.1 illustrated as a deep dive into product engineering in the context of Figure 5.2.

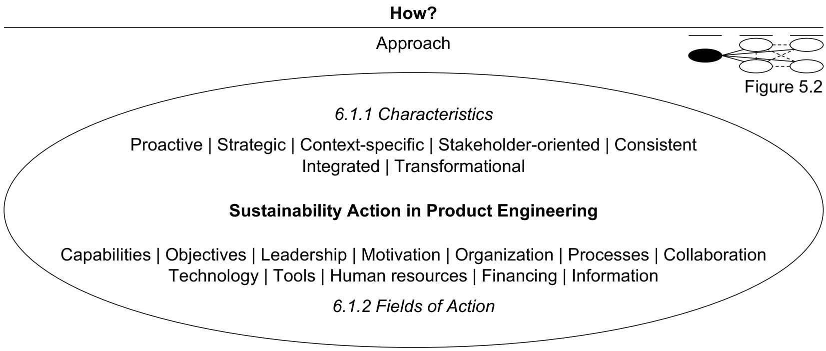

Figure 6.1: Initial Characteristics and Fields of Sustainability Action in Product Engineering Derived from Suggestions Identified in the Literature

6.1.1 Characteristics

Seven clusters of suggestions that characterize sustainability action in product engineering could be identified and are discussed in the following.

Proactive The literature suggests that sustainability action in product engineering should be proactive to keep solution freedom (Hallstedt et al., 2020; Villamil et al., 2022; Benabdellah, Zekhnini, Cherrafi, Garza-Reyes, and Kumar, 2021), for which "awareness, understanding, and … ongoing learning" are stated as prerequisites by Hallstedt et al. (2020, p. 14) similar to Obal et al. (2020). This proactive characteristic further details previous findings that indicated proactive action (see Chapter 2.3.2) and supports the evolving character of understanding in interaction with proactive action (see Chapter 5.2).

Strategic According to the literature, sustainability action in product engineering should also be strategic (Missimer and Mesquita, 2022), with a long-term perspective, which is new and not obvious according to Evrard et al. (2021). This is especially relevant in the early phases of product engineering (Hallstedt and Isaksson, 2017; Villamil et al., 2022) and requires a systems perspective (Villamil and Hallstedt, 2021). However, this long-term orientation should be combined with a short-term perspective (Schulte et al., 2020) to ensure that action is in line with the strategic direction (Villamil et al., 2022). However, this strategic action is often opposed by a solely short-term vision (Schulte et al., 2020; Xavier et al., 2020) and uncertainties (Hallstedt et al., 2020), which are stated as barriers. This characteristic links to the long-term oriented understanding of sustainability for action in product engineering and the uncertainties that accompany it (see Chapter 5.2), and supports the findings of the previous literature reviews (see Chapter 5.1).

Context-specific Sustainability action and its operationalization in product engineering, similar to its understanding in Chapter 5, should be context-specific (e.g., Kwok et al., 2020). For example Schulte et al. (2020) state that companies need to "operationalize what sustainability means for the company" (p. 9), which is in line with the findings in Chapter 5. Lubis, Fathoni, and Lubis (2020) suggest aligning sustainability action with available resources, and Christmann (2000) suggests the implementation of different sustainability practices with different advantages depending on the company's circumstances. These suggestions support the general approach taken in this thesis and connect understanding and operationalizing sustainability action accordingly. As Chang, Yeh, and Li (2020) put it with respect to environmental sustainability: "Companies need to develop their own green strategic development blueprint" (p. 14).

Stakeholder-oriented Strongly connected to the third cluster (*context-specific*), the literature also suggests a stakeholder orientation of sustainability action. This further specifies an aspect of the context dependence of sustainability action and extends the focus of product engineering from customer orientation to a broader set of internal and external stakeholders, as well as from mere orientation to actual interaction (Xavier et al., 2020) and involvement (Costa, Freire, and Reis, 2021; Wurster, Heß, Nauruschat, and Jütting, 2020) in order to innovate (Costa et al., 2021). These interactions and their implications are again strongly dependent on the specific stakeholders and their demands (Ramus, Vaccaro, and Berrone, 2021). For example, Hallstedt et al. (2020) suggest connecting sustainability aspects to customer needs, while Aguiar et al. (2021) state that consumer behavior can also be a barrier. Thus, similarly to the SLR discussed in Chapter 5.1, the concept of stakeholders was again present in publications to conceptualize the drivers of sustainability demands as actors. This concept and stakeholder orientation as characteristic of operationalizing sustainability action, therefore, describes some implications of context-specific demands on product engineering practice.

Consistent Sustainability action in product engineering should be systematic and consistent, with organizational integration of objectives and decision-making processes across organizational levels (Missimer and Mesquita, 2022; Mesquita and Missimer, 2021). These should be connected through top-down and bottom-up alignments between company strategy and operational product engineering (Benabdellah et al., 2021; Ahmadi-Gh and Bello-Pintado, 2021; Benabdellah, Benghabrit, Bouhaddou, and Benghabrit, 2020; see also *strategic*). This means that consistency in corporate approach and its operationalization are critical to successful sustainability action in product engineering (Petersen, 2021; see also Chapter 5). Schweitzer and Meng (2022) also refer to a talk-walk gap that needs to be closed to avoid inconsistency between top-management commitments and actions to avoid internal tensions (see also, Johl and Toha, 2021; Urbański and ul Haque, 2020), and, for example, make consumer marketing work (Park et al., 2022). In contrast, the concept-vagueness of sustainability (Villamil and Hallstedt, 2021), and a missing clear cohesive direction for designers (Delaney et al., 2022) are stated as consistency-related barriers to sustainability action in product engineering. This further specifies and illustrates the implications of consistent versus inconsistent understandings of sustainability action in product engineering (see also Chapter 5).

In addition, two clusters of suggestions could be identified with a focus on the implementation of sustainability action in product engineering:

Integrated Sustainability action should be integrated into product engineering (instead of being additional), and therefore address current decision makers (Faludi et al., 2020; Missimer and Mesquita, 2022). This requires the involvement of engineering management (Liu et al., 2021; Orlando, Ballestra, Scuotto, Pironti, and Del Giudice, 2022; Mesquita and Missimer, 2021), as indicated above in the discussion of the characteristics *strategic* and *consistent*, but also requires technical decision making (Cillo and Verona, 2022). This anticipates the need for an integrated implementation, which is discussed in more detail in Chapter 7.

Transformational Lastly, integrating new practices in product engineering also implicates a transformational character of the implementation of sustainability action. According to Diaz et al. (2022), this implementation of sustainability strategies can be considered a bottleneck to sustainability action. Watz and Hallstedt (2020a) state that, similar to operationalization, top-down and bottom-up approaches should be combined for successful implementation. As this can mean fundamental changes, e.g., in the value chain, products, and business models (Daniyan, Mpofu, Ramatsetse, and Gupta, 2021), conscious implementation is necessary (Glönkler et al., 2022). However, establishing sustainability practices in product engineering is a challenge opposed by a multitude of barriers, such as lack of e.g., resources, initiatives, methods, models, support tools, but also the current organizational structure or strategy (Xavier et al., 2020). This transformational character extends the evolving character of understanding (see Chapter 5.2) from understanding sustainability to operationalizing and implementing action on it in product engineering.

In summary, the first part of the analysis of suggestions in the literature offers a first characterization of sustainability action in product engineering. Previous analyses (see Chapter 5) kept the sustainability action in product engineering as a black box, while this analysis initially explored it, especially addressing the interfaces to understanding and implementation of sustainability action. The identified characteristics of sustainability action detail how it is suggested to be operationalized in product engineering, shedding more light on the demands that action-orientation raises towards an understanding of sustainability. The identified clusters, although they introduce different terms, support the generalizable aspects of understanding sustainability action in product engineering discussed in Chapter 5: *context-specific* (context-specific, stakeholder-oriented), *consistent* (consistent), *long-term oriented* (strategic), *evolving* (proactive). However, no dedicated clusters related to the success criteria *reasoned* and *explicit* could be found. Moreover, the statements found illustrate the implications for action when they are met (suggestions) or not (barriers). With respect to the operationalization itself, this analysis indicates that the confirmed generalizable aspects of understanding sustainability action are also relevant to its operationalization and indicate the challenges of this operationalization. In addition, these findings also introduce initial implications on the implementation of sustainability action, introducing the characteristics *integrated* and *transformational*, which are discussed in more detail in Chapter 7.

6.1.2 Fields of Action

Further exploring sustainability action in product engineering, 12 additional clusters of suggestions could be identified in the literature that describe sustainability action in product engineering and, therefore, can be summarized as potential fields of action (see also Figure 6.1).

Capabilities Capabilities are a first cluster that represents one potential field of action for sustainability action, where building company and individual capabilities can be differentiated. Hallstedt et al. (2020) name a variety of company capabilities needed for sustainability action, such as dynamic, strategic, and network-related capabilities. A more generic need for "sustainability" capabilities was also expressed in multiple publications (Schulte and Knuts, 2022, p. 738; Hallstedt et al., 2020, p. 15; Obal et al., 2020, p. 54; Schulte et al., 2020, p. 8). In addition to these sustainability-related capabilities, innovation and implementation capabilities are also needed for sustainability action, according to Christmann (2000). Individual capabilities that need to be built address engineers' and decision makers' skills equally. Examples for capabilities to be built among engineers are impact analysis capabilities (Aguiar et al., 2021), but also systems knowledge with multiple perspectives, life cycle thinking, and communication (Kattwinkel and Bender, 2020), and decision makers' competencies (Watz and Hallstedt, 2022). Moreover, Kumar and Prabir (2022), among others, suggest the introduction of environmental experts to support sustainability action in product engineering, which can also be seen as a form of acquisition of individual capabilities. This individual capability building also ties into the evolving character of understanding and plays a pivotal role in implementation (see also Chapters 5 and 7), which requires education and training opportunities for employees such as engineers (Jackson, Schuler, and Jiang, 2014; Mesa, Esparragoza, and Maury, 2020; Obal et al., 2020; Hallstedt et al., 2020; Evrard et al., 2021; Kumar and Prabir, 2022).

Objectives Sustainability objectives are a key element of sustainability action in product engineering (Schulte et al., 2020). In product engineering, a clear set of project objectives is needed for action (Soltész and Berényi, 2021), e.g., by setting requirements in response to sustainability risks (Schulte et al., 2020). A challenge in setting clear objectives is trade-offs and prioritization between sustainability objectives, which might conflict with other objectives and with each other (Kwok et al., 2020; Missimer and Mesquita, 2022; see also *consistent* and Chapter 5). At the company level with respect to the broader picture, for example, company challenges or competitive performance can conflict with social or environmental goals (e.g., Evrard et al., 2021; Ali et al., 2020), at the product level, for example, financial barriers can conflict with the strategic value of circular products (Diaz et al., 2022).

Missimer and Mesquita (2022) suggest clearly defined science-based goals at the company level. To provide guidance for proactive strategic action within the organization (see *proactive*), Schulte and Knuts (2022) and Hallstedt et al. (2020) suggest that these objectives are long-term and strategic (see also Chapter 5). Lack of strategy or vision poses a barrier to sustainability action, according to Xavier et al. (2020). Moreover, Markopoulos, Gann, Kirane, and Vanharanta (2020) raise that corporate sustainability is a prerequisite for environmental sustainability. This again suggests a strong integration of sustainability objectives and action in product engineering with a company's strategy (Christmann, 2000; Gallego-García et al., 2022; Boorsma, Peck, Bakker, Bakker, and Balkenende, 2022; Watz and Hallstedt, 2022; Xavier et al., 2020).

Leadership The leadership cluster comprises leadership by managers, e.g., on environmental issues (see, e.g., Skoglund and Bohm, 2020) but also the two sub-clusters of decision making and governance. According to Watz and Hallstedt (2022), corporate decision making should include sustainability decision making, which should be a transparent process (Delesposte, Rangel, Meiriño, Narcizo, and Alencar Junior, 2021). Multiple authors suggest including sustainability decision making in innovation management, also up to the firm level and with top-management involvement (Cillo and Verona, 2022). Moreover, Watz and Hallstedt (2022) suggest including sustainability criteria in decision making that are "necessary, sufficient, general, non-overlapping, and concrete" (p. 2). However, Feng et al. (2022) raise that handling the uncertainty and hesitation of decision makers remains a challenge. According to Mesquita and Missimer (2021), decision making should allow for top-down and bottom-up flows across levels. While Schulte et al. (2020) advocate for a top-down approach for sustainability risk management for appropriate decision making, Xavier et al. (2020) and Chatty and Faludi (2020) propose empowerment, delegation, decentralization, and employee involvement. However, top management involvement could reduce the time and resources needed for sustainability action, according to Suppipat and Hu (2022).

Motivation Another researched topic and cluster is the motivation of employees. On the one hand, Obal et al. (2020) suggest an encouraging culture, and Glönkler et al. (2022), among others, suggest top- and middle-management support to motivate for sustainability action. On the other hand, Aguiar et al. (2021), Xavier et al. (2020) find that a company's culture can also be a barrier to such action. To support sustainability action, incentives and deterrents are discussed in the literature, for example, linking sustainability action with compensation (Obal et al., 2020; Glönkler et al., 2022).

Organization A company's organization is predominantly stated as a barrier to sustainability action (e.g., Missimer and Mesquita, 2022; Xavier et al., 2020; Benabdellah et al., 2021). Thus, action requires aligning the organization with the task nature (Mafimisebi, Obembe, and Aluko, 2020), which may shift due to sustainability objectives (D'Angelo and Magnusson, 2021; Obal et al., 2020).

Processes As processes are a common conception of product engineering (see Chapter 2.1), multiple authors have researched the implications of sustainability action on product engineering processes. Hallstedt and Isaksson (2017) suggests an integration of sustainability action in the product engineering process and places great emphasis on strategic product planning (see also Diaz et al., 2021). Also Aguiar et al. (2021) and Kumar and Prabir (2022) propose the integration in the early stage, while Nunhes et al. (2021) suggest realizing this integration through sustainability criteria. Barriers to integrating sustainability action in these processes are the low understanding of what these changes are in detail (Hallstedt et al., 2020), which adds to the already present challenges of cumbersome development processes and long development cycles (Liu et al., 2021).

Collaboration Moreover, sustainability action requires an increased level of collaboration, in many terms: Mesquita and Missimer (2021) demand "coordination and communication across departments" (p. 17). Schulte et al. (2020), and Miller, Thomas, and Roeller (2020), state that cross-functional collaboration is needed across levels of the organization. Multiple authors stress the need for collaboration along the value chain (e.g., S. Wang and Su, 2022), for example, with suppliers (Yu and Lee, 2020; Dabić, Obradović, Vlačić, Sahasranamam, and Paul, 2022; D'Angelo and Magnusson, 2021). This also implicates a close integration of sustainability action with supply chain management (Uemura Reche, Canciglieri, Estorilio, and Rudek, 2021). However, such collaboration is hindered by unclear interfaces between engineers and stakeholders (Delaney et al., 2022). The increased need for collaboration with actors outside the company is further addressed by authors who suggest partnerships, e.g., with non-governmental organizations (NGOs; Schweitzer and Meng, 2022) or universities (Nunhes et al., 2021). In product engineering, cross-disciplinary collaboration and skills are suggested by Kumar and Prabir (2022), Hazen, Russo, Confente, and Pellathy (2021), and Perpignan, Baouch, Robin, and Eynard (2020).

Technology Technology orientation can play a pivotal role in sustainability action in a positive way (Pan, Oh, and Wang, 2021), e.g., as digital technologies might enable circular disruptions (M. Rusch, Schöggl, and Baumgartner, 2022), or opportunities for competitive advantages might arise from early adoption of environmental technologies (Christmann, 2000). At the same time, technology can also be a barrier to sustainability action according to Aguiar et al. (2021) and Benabdellah et al. (2021). Moreover, Feng et al. (2022) state the need to balance technology and sustainability.

Tools Hallstedt et al. (2020) state the need for tools enabling sustainable product development, while Diaz et al. (2022) more specifically require tools for circular product development, and Kumar and Prabir (2022) for data exchange to enable sustainability action.

Human Resources Social sustainability aspects such as employee safety, rights, and health (Nunhes et al., 2021), can be influenced within product engineering, for example, through a people focus of project managers (Soltész and Berényi, 2021) but also through Human Resources. But also more broadly, according to Jackson et al. (2014), human resource management systems can support sustainability action, through rewards or bonuses (see *motivation*), by recruiting, e.g., for sustainability value match or sustainability knowledge, or through introducing policies and collaboration.

Financing Financing and budgets are a predominantly negatively connoted cluster, which is often framed as a barrier to sustainability action in the literature, and not as an enabler (see, e.g., Benabdellah et al., 2021; Diaz et al., 2022).

Information Information, which can be, for example, required to measure the sustainability of products (Nunhes et al., 2021), is framed as an informational barrier to sustainability action in the reviewed literature (Benabdellah et al., 2021), for example, due to lack of access to the life cycle information of products (Diaz et al., 2021).

The second part of this literature review covered suggestions for sustainability action in product engineering clustered to potentially relevant fields of action. These clusters are interdependent as more than one third of the suggestions found also referred to a dependency of the stated barriers and practice needs to another cluster. For example, Ceptureanu, Ceptureanu, Popescu, and Orzan (2020) describe that investments are needed to build capabilities, while overcoming established organizational structures can be a prerequisite for collaboration (Missimer and Mesquita, 2022), and stakeholder orientation might lead to transparency in decision making (Delesposte et al., 2021). However, beyond a broad variety of interdependencies that illustrate the complexity of sustainability action in product engineering, a cohesive overall picture could not be derived.

In summary, this literature review initially characterizes (Chapter 6.1.1) and describes (Chapter 6.1.2) sustainability action in product engineering (see also Figure 6.1). However, it could not yet be derived how targeted sustainability action can be operationalized from the perspective of decision makers in product engineering. Yet, these literature-based findings on general sustainability action in product engineering laid a foundation for conducting an interview study that aims to address this perspective. Thus, in the second part of the interview guideline, the operationalization is revisited in order to create an overall picture with helpful connections between possible fields of action to understand how targeted sustainability action can be operationalized in product engineering (see next Chapter 6.2).

6.2 Operationalization Derived from Interview Study

Developed from the findings in Chapter 6.1, the second part of the interview guideline addresses the operationalization of targeted sustainability action in product engineering and thus the second research question. Details on the overall structure of the interview guideline can be found in Chapter 4.2.2 and the interview guideline in Appendix A.2. The second part of the interview guideline described here covers three topics, starting with barriers to sustainability action, then the characterization of targeted sustainability action, and last, how these characteristics can be induced.
The barriers, which were first openly asked for, where then detailed by asking for specific levels of such barriers (strategic, tactical, and operational), while challenging questions covered the reasons for and implications of these barriers.
To identify the characteristics, interviewees were asked to characterize a way of working that contributes to a potentially context-specific understanding of sustainability relevant to their work (see the first part of the interview guideline in Chapter 5). They were challenged by asking why these characteristics make a difference; examples based on the literature could be named if the interviewees asked.
Moving on how these characteristics can be induced, the open question asked for practices that constitute a way of working that induces these characteristics and asked for their conditions. Practices as a concept were explained if requested by the interviewees (see Chapter 2.1). The challenging questions covered how the interviewees would shape and use the suggestions identified as fields of action in the literature review (e.g., capabilities or tools). Lastly, the interviewees were asked for relevant dependencies between practices that they would highlight, as well as the reasons for this.

Similarly to the previous chapter, the interview results were analyzed according to the Gioia Methodology (Gioia et al., 2013; see Chapter 4.2.2 for details) and with respect to the second research question. The coding took into account all statements with implications for operationalization, and not only the answers to the questions stated above (see Table 4.2 in Chapter 4.2.2 for an overview of the interviews with identifiers), resulting in a data structure, which is shown in Figure 6.2, and the practices in Figure 6.3.

6.2.1 Characteristics

The identified characteristics are summarized in the data structure in Figure 6.2, with challenges and success criteria as aggregate dimensions providing the structure for the discussion below.

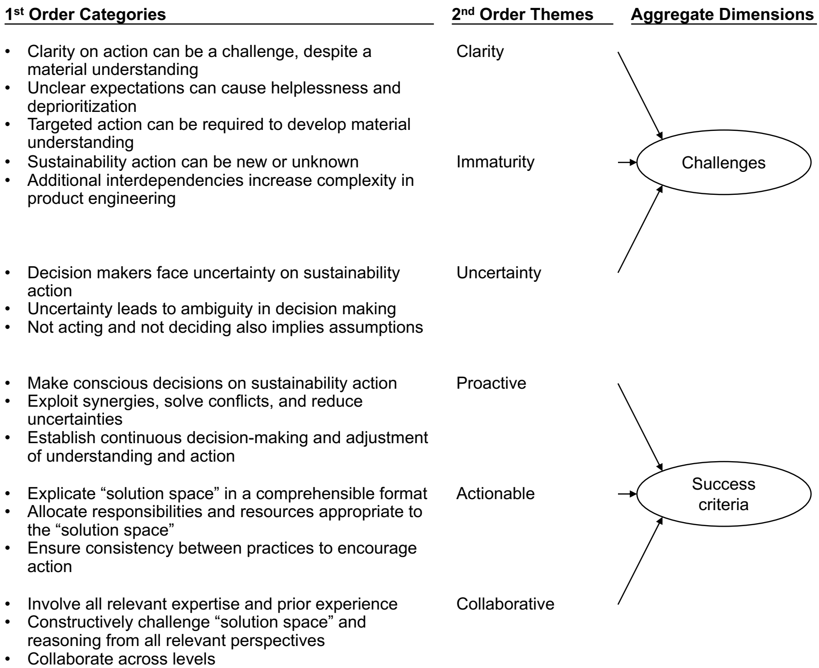

Figure 6.2: Data Structure Derived from the Interviews with Problem- (Challenges) and Solution-oriented (Success Criteria) Findings with Respect to the Second Research Question: Operationalizing Targeted Sustainability Action

The **challenge** in operationalizing targeted sustainability action, which emerged from a problem-oriented perspective as an aggregate dimension from the interview data, is to create *clarity* despite *immaturity* and *uncertainty*.

Clarity As described in Chapter 5.2, the lack of materiality in understanding sustainability action can be an obstacle to overcome for targeted action. Although a more material understanding of sustainability might lead to more clarity on action (DM32), it does not guarantee it: How to change a way of working (see Chapter 7) and therefore clarifying what to do can remain a challenge (C7). This translation of a material understanding into targeted sustainability action, and thus operationalizing it, can bring about "considerable difficulties" (C4, trans.) and uncertainties (C7). As one consultant put it, companies struggle "with getting this into their product engineering" (C3). And more specifically, for example, to propagate the understanding down to products and teams (C6), to translate it into product requirements (C6) or supplier selection criteria (DM12) and to derive measures for further action (DM14). This becomes evident in unclear product requirements (DM13), uncertainty about what can be done (DM12), and divergent action (C1). In essence, if not resolved, the challenge of creating the clarity required for targeted action is just passed on within the organization (DM43). Doing so can also lead to inaction, as it can cause helplessness among employees (DM32) and deprioritization of sustainability objectives in the organization (C2). Moreover, targeted sustainability action might be required in the absence of a material understanding of sustainability, especially to develop this material understanding, or to address changes over time (C6; DM21; see Chapter 5.2, *evolving*). Therefore, establishing clarity on action is a key challenge to tackle when operationalizing sustainability action.

Immaturity Sustainability demands can be broad and conceptually complex (see Chapter 5.2, *complexity*). This can make it difficult to determine how to act on them (C3), how to operationalize objectives (C4), and how to measure the achievement of sustainability objectives (C3). Even how to collect relevant data for decisions on action can be new to a company and an unclear challenge (C3; C4; DM16; DM21). Moreover, sustainability demands can involve previously unconsidered issues, e.g., carbon dioxide emissions (C3; C6), or biodiversity (C3; C6) that might require specific and new action. For example, the required accounting at the product level or along the supply chain (C3) can be entirely new for companies. Therefore, establishing a foundation for conscious decision-making on potential actions can be challenging itself (C7; DM16). Moreover, new measures with potentially increasing complexity might need to be continuously explored, e.g., when progressing toward climate neutrality (DM21). This immaturity of sustainability action becomes especially evident in circumstances where less experience is available, e.g., for new products or when entering new markets

(DM22; DM24). This can coincide with opportunities of sustainability action, e.g., in the case of electric mobility (DM11; DM26). In general, successful product engineering can pose a challenge to companies that requires action under uncertainties (see also Chapter 2.1) and on conflicting demands for which solutions are yet to be developed (DM21). Introducing additional (sustainability) objectives to product engineering therefore increases the complexity through additional interdependencies even if they are clear (C5). Sustainability action in product engineering therefore depends on various interdependent conditions that determine its operationalization, such as the product substance (DM42), its materials and production processes (DM23), or suppliers (DM42).

Uncertainty This complexity and the related immaturity of sustainability action is strongly connected to uncertainty among decision makers who face a “general kind of worry about how to achieve the targets that they have or set themselves” and meet identified demands (C7; see also *clarity*). Due to this uncertainty, which adds to the uncertainty in understanding sustainability (see Chapter 5.2), decisions under uncertainty and based on assumptions (DM16; DM31) can be required for targeted sustainability action (C3). This ambiguity can pose a challenge to decision makers, as the implications of decisions and actions may remain unclear (C1; C3). However, not deciding might lead to unspecific action (DM31; DM32), and not acting due to this uncertainty is “just as strong an assumption as well,” as one consultant stated (C3), which might also imply risks (DM22).

With respect to the main challenge of this thesis, which is developing support that is actionable and context-specific, while maintaining a broad perspective (see Chapter 3.1), the challenges of action orientation amid uncertainty can be summarized as follows: Creating materiality despite complexity in understanding targeted sustainability action, which can now be expanded to creating clarity despite immaturity in operationalizing targeted sustainability action.

As part of a solution-oriented perspective on the interview results related to the operationalization of sustainability action in product engineering, three **success criteria** could be identified that describe how clarity on action can be established.

Proactive Initiating targeted action requires clarity (see *clarity*) and therefore an explicit decision on what to do. Making this decision can be easy when a material understanding of sustainability or very specific demands are prevalent (C1; DM13). A consultant illustrates such a situation with specific demands in the machinery industry as: “Legislator says – you make a feature, put a price tag on it – wonderful.” (C1, trans.). But it can also be difficult (C3), especially when facing immaturity and/or uncertainty on sustainability action (see above). In such circumstances, clarity on action can and must be created to enable targeted action (DM13; DM21; DM31). To do so, conscious decision making based on an understanding of sustainability action or associated uncertainties is needed: "Acting now doesn't mean I act on everything right now. It just means I consciously act on things that make sense to act on. And to get there, you need that detailed understanding." (C7). Depending on the context, this also includes the conscious decision to not act or to react to certain conditions, e.g., when a short-term focus is required or necessary efficiency gains from upcoming industry standards are expected (C7; DM16; see also Chapter 5, *context-specific*, *long-term oriented*). In this sense, proactive operationalization of sustainability action is not defined by the result of decision making on action, e.g., the radicality of resulting action or the degree of implementation, but by conscious decision making itself (DM31).

Targeted sustainability action amid immaturity and uncertainty can require exploiting synergies (e.g., between raw material dependency and circularity, C6, or carbon dioxide emissions and cost reduction, C3) but also solving conflicts (e.g., between a more integrated product and circularity demands, DM22, or between different sustainability demands, C3), and/or reducing the uncertainties (e.g., on potential technical solutions DM32, supplier capabilities, DM12, or customer demands, C6). This requires synergies, conflicts and uncertainties to be surfaced, otherwise they cannot be acted on (see Understanding 5, *consistent*, *long-term oriented*, *explicit*). Through this action, the objectives of a material understanding of sustainability can be achieved, or the understanding itself can be created and changed allowing for further decision making and action (C6; DM23).

Since targeted sustainability action requires clarity, and a material understanding of sustainability requires action, continuous decision making and ongoing adjustment of both can be required (DM23; DM31; DM43; see also Chapter 5, *evolving*). Thereby, uncertainties can be reduced (C6) and additional opportunities surfaced (DM23). One Head of Engineering summarized the iterative nature of decision making and operationalization of sustainability action as: "You have to agree on something binding, otherwise you will never finish, because something always comes up again in the course of a project and somewhere you have to agree on a deadline and then you work through it. Then … we look in the next round to see what is now state-of-the-art. … Otherwise we won't make any progress." (DM42, trans.).

Actionable To initiate targeted action in the organization and provide guidance on this action, the results of decisions must be explained in a comprehensible format (DM13; DM14; DM16; DM22). This format depends on the intended action and the respective expectations (C3; DM31; DM41). Clear expectations can be expressed, for example, through broken down objectives at product level (DM16; DM43) and clear

criteria at process level (C4; DM16; DM31). Such guidance can create clarity and certainty on actions for employees, even though it might be the result of a decision amid uncertainty, e.g., taking a risk facing uncertain customer demands or regulations (DM13; DM14; DM31). Moreover, for early further decision making and focus of resources, clear priorities and focus need to be provided (C1; DM25; DM31; DM32). However, in the case of immaturity of sustainability action, it might be difficult to express these expectations as specifically as desired (DM32). In such cases a broader "solution space" needs to be communicated (DM32, trans.), for example, through company target pictures or higher-level roadmaps (DM21). The resulting sustainability action might differ substantially and requires narrowing over time to derive more specific action (C1, see *proactive*).
No action will follow the guidance if no responsibilities are appointed or resources are allocated (C4; DM11; DM21; DM43). Depending on the guidance (narrow or broader), appropriate resources must be deployed to ensure that they are capable of exploiting synergies, solving conflicts, and reducing uncertainties through the intended sustainability action (C1; C2). Clear guidance under uncertainty might be wrong, and therefore needs to allow for change (DM31; see also *proactive*). Reasoning and implications need to be communicated to enable addressing the solution space itself (DM31; see also Chapter 5, *reasoning*). If no clear guidance is provided by the appropriate level, uncertainty is passed on to people who might not be able to make the required decisions (C1; DM31), and sustainability action might depend on their personal motivation to engage (DM16). In addition, consistency between practices is needed (see also Chapter 5, *consistent*), especially between guidance for and evaluation of action (C3; DM22; DM43), as well as potential incentives (C1; C6). As one Engineering Project Lead summarizes measuring without guidance: "It is pointless just to fill out a checklist. … It also has to be taken into account up front in the requirements for each project." (DM43, trans.). And a consultant explains the effect on employees of guidance that lacks consistency with evaluations: "People want to [act] … but … they struggle … to make the right decisions because they feel they are still measured on cost, efficiency, safety, … but … [the measurement] does not capture the right decisions. So, … some, of course, get a bit disillusioned from this." (C3).

Collaborative Conscious decisions on sustainability action rely on a multitude of inputs like competition, regulation, standards, references, etc. (DM31), especially in the case of a broad "solution space", where a variety of options to act might exist (DM25; see also Chapter 5, *context-specific*). Therefore, all relevant experience and expertise should be involved in sustainability action and its operationalization. Involving expertise in sustainability action, but also on its conditions, enables an assessment of the status quo and the potential implications of sustainability action in product engineering (DM43), which is required to achieve objectives (DM25). Involving gained experience in sustainability action allows learning and building capabilities for further action (DM31; DM32).

Depending on the organization, not everything can and needs to be solved in product engineering or by engineers (C6), which is why a collaboration in the company is needed, especially for a broader "solution space". Stemming from the company perspective (see Chapter 5, *consistent*), strategy, and thus decision makers involved in shaping a company's strategy, can take a lead in understanding sustainability (C1). Although product engineering might be only one element within the company perspective (DM31), it can play a strong role in surfacing opportunities for sustainability action (C3; C4; DM33). Moreover, together with strategy, it can support breaking down objectives into clear guidance across levels (C1), ensuring a close alignment of sustainability action in product engineering and strategy (DM33; see Chapter 5, *consistent*). However, this operationalization and sustainability action itself should not only involve product engineering but also depending on the organization span across all relevant functions and business units (DM21; DM25), to include all relevant perspectives (DM32), to assess potential implications (DM22) and shape sustainability action (DM21). Examples can be sales or product management if not part of engineering to establish market intelligence (C6), to offer alternatives to customers, or to create certainty on demand (DM14; DM21; DM25; DM42). The involvement of industrial engineering, production, and procurement (DM14; DM24; DM32) can be required to identify potential opportunities and actions, as well as to assess their implications. This collaboration is not fundamentally different from best-practice engineering (C2; DM43), but it might not be current practice and therefore require additional transparency (DM25) and bringing people together (DM31). Moreover, collaboration on sustainability action might also be necessary beyond a company as not all conditions limiting a potential "solution space" can be directly influenced (C1; DM12; DM23), even to achieve one's own ambitions (DM23; DM33). For example, a change in purchased materials might involve suppliers, while the in-house production processes can be changed more independently (DM13). Therefore, the expertise and capabilities of the suppliers can be necessary for sustainability action (DM16; DM23), e.g., to identify potential options for action (DM25), although they could also limit access (DM43), or complex trade-offs might require alignment throughout the value chain (DM32). Although generic collaborations at industry level may not be value-adding (DM12), partnerships can avoid high investments needed for sustainability action (DM33) and implications might become assessable (C6). Beyond collaboration on the conditions of sustainability action, demands and their drivers can also be addressed directly. For example, in dialogue with drivers of demands, uncertainties can be reduced (DM32). Through collaboration, conflicts can be solved; for example, collaboration with regulators to create early transparency on upcoming regulation can be an alternative to more flexible processes in product engineering (C2). Proactive collaboration (DM23) beyond a company requires more open communication (DM42), which is why it should be done consciously and with caution regarding shared intellectual property (DM33).

Solving conflicts and reducing uncertainties requires a dialogue on potential solutions (DM31), especially when guidance provides a “solution space” due to uncertainty or dynamic demands (DM33). Compromises and trade-offs might be necessary, for which constructive discussions that challenge their reasoning are required (DM31; DM41; DM43). As one Head of Engineering reflects: “Product development is always a compromise somewhere … . And sustainability is another compromise in many things.” (DM42, trans.). For example finance can be a constructive resistor to avoid overdoing, which ensures a good reasoning for sustainability action (DM21; DM31; see also Chapter 5). Moreover, diverse teams ensure that more and potentially relevant perspectives are covered, which can foster such a dialogue (DM31; DM32). This challenging ensures conscious decisions (see *proactive*), and can calibrate ambitions (DM31), and create conviction among the people involved (DM22).

The prerequisite to such a dialogue is collaboration across levels within the organization, since expertise sits in many cases on the operational level (DM43), where conflicts can be identified and resolved (DM41). At the same time, depending on implications, a decision needs to be made on the appropriate level (C5; DM25). Therefore, top-down decisions (DM33), with a bottom-up exchange to consult expertise (DM42; DM43) and a joint dialogue to detail action (DM13) are required. For example, operational engineers can identify and suggest an opportunity, but the decision to enter a new market may need to be made at board level (C1; DM14). Or, for an identified conflict, a joint trade-off needs to be made with the product manager, as no technical solution could be found (DM41). Therefore, escalation paths, e.g., meeting cadences (DM22) which might already exist (DM25; DM43) across all levels are needed (DM21; DM31). Such collaboration requires a healthy error culture (DM31), as the evolution of sustainability action and understanding takes time (DM24; DM31).

Operationalizing sustainability action in product engineering means creating clarity on action under uncertainty and despite the immaturity of current action. Three success criteria could be identified that characterize an operationalization that addresses this challenge: Proactive, actionable, and collaborative. A summary of these success criteria can also be found in Appendix A.1 as part of the Guide for decision makers. How these success criteria can be met is discussed in the following Chapter 6.2.2, where the practices that constitute targeted sustainability action in product engineering are presented.

6.2.2 Practices

The practices that constitute targeted sustainability action were identified following the Gioia Methodology (Gioia et al., 2013, see Chapter 4.2.2). Their entirety can be seen methodologically as the third aggregate dimension to the second research question (together with the challenges and success criteria shown in Figure 6.2), while the practices themselves represent second-order themes (see Chapter 4.2.2). However, since their relationships are an essential part of this analysis and its results, their relation is illustrated in Figure 6.3 instead of a data structure.

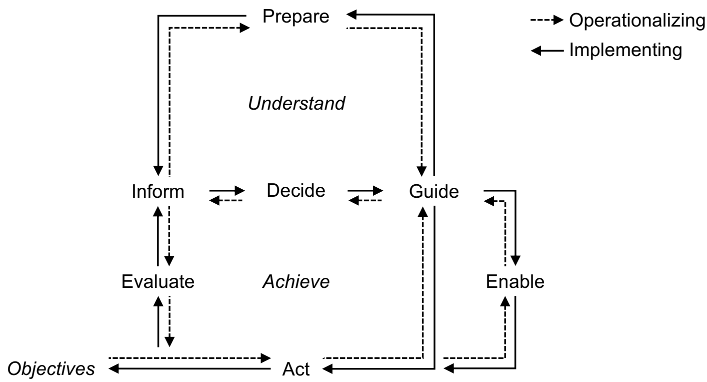

Figure 6.3: Practices of Targeted Sustainability Action Derived from the Interviews and their Interrelations (see also Jäckle et al., 2025)

Seven interrelated practices that constitute targeted sustainability action could be identified (see Figure 6.3). The three overarching success criteria allow the determination of their dynamic relationship, which is characterized by iterative cycles of practices. These cycles build continuous routines of targeted sustainability action with conscious decision-making at the core (see *proactive*). Collecting all relevant information to make these conscious decisions and explicating it in guidance initiates consistent action forming the two cycles (see *actionable*).

The first (upper) cycle sets a focus on action to better understand sustainability action, primarily contributing to a more material understanding. The second (lower) cycle focuses on action that is derived from such an understanding and primarily aims at achieving sustainability objectives determined by this understanding. Although this distinction in intention supports a more specific configuration of the practices, the two cycles can converge towards each other over time (see *prepare* and also Chapter 7). Representing a company perspective, these iterative cycles can span the organization, including product engineering, reflecting the *collaborative* nature, which can again be found in detailed descriptions of practices.

Two perspectives can be taken on the interrelation of these practices. An operationalization perspective and an implementation perspective (see also Chapter 7). The operationalization perspective starts from an initial understanding and its objectives. To achieve the objectives, it is required to *act* on them. This action must be enabled by capabilities (*enable*) and initiated by guidance (*guide*). The guidance must be defined by decision making (*decide*) which is informed by a fact base (*inform*). The fact base is built through preparations (*prepare*) and augmented by evaluations (*evaluate*). From an implementation perspective, preparations (*prepare*) build a fact base to *inform* decision making. Decision making (*decide*) defines guidance (*guide*) that initiates action (*act*, also *prepare* and *enable*). Action (*act*), that is enabled by capabilities (*enable*), achieves the objectives. Evaluations (*evaluate*) again *inform* further decision making (*decide*). For operationalizing targeted sustainability action, the operationalization perspective is more purposeful as it starts with the end in mind, helping to avoid non-value-adding practices, e.g., to avoid enabling without acting. Therefore, this perspective is used here to explain the practices. Further explanations can also be found as part of the Guide for decision makers in Appendix A.1.

Based on the interview results, these practices are detailed in the following with examples of who should execute them, when, and how. In addition, references to practices in other contexts are highlighted. A tabular overview summarizing each of these practices can be found in Appendix A.1, Tables A.23 to A.29, as part of the Guide for decision makers.

Act To achieve sustainability objectives, they must be acted upon collaboratively (DM23; see *collaborative*). This sustainability action consists of exploiting synergies, resolving conflicts, and reducing uncertainties (see *proactive*). This can be done through, on the one hand, collaborating on sustainability demands with their drivers (see *collaborative*) and, on the other hand, changing product engineering, specifically, the product substance (C2; DM11; DM13; DM14; DM21; DM26; DM43), product properties (C2; DM31), technologies (DM14; DM23; DM32) and/or their production processes (C1; DM13). The options for such action can vary broadly (C1). These actions can be alternatives to each other, for example, changing the properties of a product such as the materials used (DM25) and related changes in the production process (DM14; DM26). And they might depend on each other on varying levels, as changes in the production process might affect an entire product group (DM24). Also a change in product properties might mean a change in product substance for a supplier, as the example of electric drive trains in the automotive industry shows (DM13). A Head of Sustainability illustrates this variety of potential adjustments in their product engineering: "What can future sustainable products be? … Do I always call them sustainable products? Or are they simply new products with different properties? And what are these properties?" (DM31, trans.). These actions need to be performed by the appropriate level and functions to be able to resolve relevant conflicts with relevant expertise and experience (see *collaborative*). Sustainability action should be consciously introduced depending on the conditions (see *proactive*), such as lead times (C3; C5) or supplier contracts (DM25). It should be efficiently sequenced along new programs, technology, and investment fade-outs (DM24; DM33). Moreover, prioritizations should be made based on impact/feasibility (DM24) (see also Chapter 7, *efficient*). This action should be pragmatic and integrated, starting with exploiting synergies (see also Chapter 7, *pragmatic*, *integrated*). A reference for how to shape such action can be automatization of banking risk management from dedicated specialists to tools calculating risks at the front desk (C3).

Enable Employees must be enabled to act on sustainability objectives (C1; C7; DM16). Therefore, individual and collective capabilities must be built throughout the organization (C5; C6; C7), and respective tools or integrations in existing tools must be provided (C7; DM22). Required capabilities depend on the intended action but might, for example, include the decision makers' ability to make tradeoffs (C1; C6), or an engineer's ability to evaluate implications of decisions (C5; C7). It might also include the company's ability to measure, calculate, or track sustainability (C3; C5; DM23; DM32) or to understand the value chain (C7). Although the way of working in product engineering can remain similar (C7; DM33; see also *evaluate*), engineers need to acquire new know-how given the changing conditions (DM22; DM33). The development of these capabilities can be supported and led by a Center of Competence (CoC; C5; C6; C7; DM23; DM26) that develops standards (DM23), establishes tools (C1; C3) and provides training (DM21) and education (C1; DM33). Moreover, suppliers might need to be developed to have the required capabilities (DM26). Therefore, it is critical to ensure engineering competencies in such a CoC (C6) and a focus on relevant, company-specific capabilities (DM43). As one Head of Logistics put it: "We are selling … [products] not sustainability programs" (DM16, trans.). In addition, knowledge can also be acquired through dialogue, collaboration, and recruitment (DM32). As sustainability action in many cases follows a learning curve (C4), especially when engineers are fully staffed on a single multi-year project, an early start of capability building and introduction of tools might be needed to gain experience (C1). As one consultant summarized this learning curve: "The first shot is usually not good, not professional. The second shot is then one cycle later." (C1, trans.). A reference can be cost engineering capabilities, which can have similarities to, for example, carbon dioxide accounting and have been established in many companies within the past years (C7). Although these similarities can be so close that too much transparency on carbon dioxide emissions can also pose economic risks (DM21), tools might still need adjustments (DM42). In addition, building capabilities to act on certain sustainability aspects can also be a reference for action on others (C7).

Guide Guidance is needed to initiate targeted sustainability action in the organization (see *actionable*). Therefore, the "solution space" for action on which a decision has been made needs to be explicated from a company perspective (see *consistent*, *actionable*). The targeted action is only initiated when responsibilities and resources appropriate to the "solution space" are allocated (see *actionable*). One Head of Advanced Engineering emphasizes the need for clear priorities to allocate resources: "We don't really care what we prioritize. We just have to make sure that we make the most of our time to get the best out of it for the company" (DM12, trans.). Depending on the company, examples for the explication of the "solution space" can be company target pictures (DM31), a system of objectives with priorities (C1; C3; C5; DM31), roadmaps (DM11; DM21; DM26; DM32) for products (C2; C3) or for sustainability action (C3; C7; DM24), as well as requirements (C6; DM22; DM26; DM31; DM41; DM42). For resource allocation, examples are initiatives (DM21) or projects (DM12; DM14; DM25) with budgets (DM21). The guidance in its company perspective should be provided along the established governance across management levels and should be appropriate to the uncertainties and conflicts to be solved (see *collaborative*). Initial guidance should be provided with the first decisions taken to initiate action, and then detailed over time (see *proactive* and *actionable*), e.g., target picture to objectives to roadmap (DM25) to requirements (DM32; see also above). One consultant summarizes this key part of operationalizing sustainability action as: "To break down target elements …, so that an actual engineering organization, a concrete … project, can really incorporate them into its target structure and control structure and thus handle them relatively easily, without the solution space being too large, unknown, and creative for all those involved in development." (C1, trans.).

Decide The core of targeted sustainability action is conscious decision making (see *proactive*, *actionable*), which is the foundation needed for clear guidance. Conscious decisions need to be made on whether to act on objectives, their uncertainties, conflicts, and synergies, or not (see *proactive*). Moreover, conscious decisions need to be made on the radicality of intended action (see *proactive*), which can be varied (C2), and the "solution space" to act on remaining uncertainties and conflicts (see *actionable*), which can be limited or expandable (DM33). Decisions must be made at an appropriate level and function explicitly within the regular organization (C5; DM31) and not in parallel (C6; C7; DM23; DM26). As one consultant summarizes it: “Either you integrate it into the core business, either you integrate this into existing governance and core governance or it doesn’t exist.” (C6). This means, for example, that substantial strategic decisions or fundamental decisions might need to be made where responsibility can be taken, which can mean at board level (C4; DM21) and in collaboration with functions or business units (DM22). At the same time, operational engineers can solve conflicts through technical solutions (C5), but might not have a lever on the product portfolio itself (C2; see also *collaborative*). In either case, top management commitment is required to be able to take conscious decisions (C6); otherwise, the field is too wide to act (DM16). Conscious decisions should be made as early as possible, then continuously, as not deciding also has implications (see *uncertainty*). Proactively making conscious decisions about sustainability action embraces the entrepreneurial nature of these decisions (DM31), as opportunities can emerge from uncertainties (C1; C7; DM21; DM23) and innovations can occur where conflicts are resolved (DM22). Moreover, the decisions made should be made transparent (DM32), to allow for action (see also *guide*).

Inform Conscious decisions require a fact base that informs these decisions (C3; C7; DM21). Therefore, an overview of relevant data should be obtained and provided to decision makers (C1; C3). Depending on the decisions to be made, this information can cover demands (DM32) with drivers (DM31) and reasoning (DM31), prior decisions (DM31), the company strategy (C5; C7), the status quo (C7; DM14) like process data or current emissions, previous investments (DM33), the value chain (C3; C7), options for action (DM21; DM24; DM42; DM43) and their implications (C1; C4; C7) as well as relevant conditions (C7; DM22; DM31; DM43), etc. One Head of Sustainability emphasizes the importance of knowledge “about how it can actually be implemented in the company” in addition to “theoretical knowledge” (DM11, trans.). Potential formats of this information used as basis for decisions can vary, from more strategic decisions that might use scenarios (C1; DM22) via business cases (C3; C7; DM24), to integrated data collection and compilation in enterprise resource planning systems (ERP systems) for recurring decision making (C7). Similarly to the preparations, this information can be collected and compiled by a CoC (C7), any individual, e.g., Head of Sustainability (DM21), or group within the company (DM32). As sustainability action and the understanding of it evolve, these practices should be started early (DM32) and iterated (DM21) to create a “living on” decision basis (C7). Information can be collected through preparations (see *prepare*) or evaluations (see *evaluate*).

Prepare Preparations as part of targeted sustainability action primarily aim to expand the fact base to enable conscious decision making. Therefore, all relevant experience and prior experience should be gathered to create knowledge on drivers of sustainability demands and potential sustainability action (DM21; see also *collaborative*). For example, market intelligence can reduce uncertainty about demands (C6; DM33), or testing can ensure the feasibility of planned process changes (DM14). In addition, these preparations can include establishing a network within and outside the company to reduce uncertainties (DM12; DM21) or to increase awareness and conviction (DM25). Moreover, preparations can involve thinking through sustainability action (C1; DM14) and conducting dry runs, e.g., introducing a shadow carbon price (C1) or indexing repairability for certain products (DM41). Pilot projects that are still primarily focused on gaining experience on sustainability action to inform decision making might at the same time already contribute to achieving objectives (DM23; DM32). Therefore, *prepare* practices can evolve into *act* practices. However, over-investment should be avoided (DM21), and a trade-off needs to be found between efficient preparations and an efficient roll-out in the organization later (see Chapter 7, *efficient*). Such preparations can be done by a CoC (C7) or any individual (e.g., Head of Sustainability) or group within the company (DM16). However, a detailed understanding of the organization and a broad network is helpful. Their timing is, if resources allow it, as early as possible (C1; DM23; DM32), in order to have the answers ready when needed (DM21; DM32).

Evaluate To inform further decision making on sustainability action and allow adjustment, sustainability action must be evaluated (C1; DM23). These evaluations should be based on Key Performance Indicators (KPIs; DM31; DM41) and can cover the status quo (C7; DM12; DM23), the implementation of measures (DM11), and the progress of action on objectives (C1; DM11; DM15). Moreover, evaluations can also be a demand themselves, for example, a carbon footprint of a product requested by customers (DM11; DM13; DM26) or reporting required by regulations (DM33). How to evaluate in these cases can depend on the demand and driver (DM42), which might require different action and does not necessarily reflect reality, for example, actual emissions of product in operations (DM43). Deviations then may need to be communicated transparently and argued (DM42). Therefore, the purpose of these evaluations needs to be differentiated, determining the approach taken (DM21). Evaluations are especially perceived as value-adding if they inform further decision making (DM33), e.g., if prioritization can be derived (DM32) or possibilities for action or synergies are uncovered (DM31; DM43). Evaluations can be made by any instance in the organization or with relevant access and expertise (DM11; DM26; DM41; DM42; DM43; see also *enable*), but decisions should be made along the existing escalation paths and not in addition (see *collaborative*). Evaluations can provide a starting point for sustainability action (status quo), but they can also provide ongoing feedback on action, for example, when integrated into decision gates in product engineering (DM43) where product and project performance can be evaluated (DM41), when comparing competing concepts under development (DM32), or when re-evaluating the value chain for improvement potentials (DM26). Ongoing evaluation can support on operational level when integrated in daily tools, for example, the carbon footprint calculation in CAD, where designers are provided with immediate feedback on design changes (C4), such evaluations can enable quick iterations and optimization (DM22; DM23). This does not necessarily mean that the way of working is completely changed, but new criteria are evaluated as part of it (DM22). The more operational and iterative these evaluations get, the more relevant becomes automation (DM43), which might require a trade-off between one-time effort, for example, to adjust ERP systems, and ongoing efforts, e.g., to evaluate carbon footprints manually (DM42; DM43). As outlined, these evaluations need to be consistent with Guidance provided (see *actionable*, *guide*). Although KPIs can make objectives measurable and, therefore, are needed to achieve them (DM14; DM15; DM43), they do not necessarily specify how to achieve them (DM22; DM31). This also means that jointly with guidance, KPIs and evaluations need to evolve (DM31) and prioritization needs to be reflected in weights of KPIs (DM22). Controlling can be a reference for such evaluations (C3) and might also be the function that performs them (C2).

In summary, the solution-oriented findings based on the interview study allowed the identification of generalizable aspects which characterize and constitute the operationalization of targeted sustainability action in product engineering. The operationalization of targeted sustainability action in product engineering should be *proactive*, *actionable*, and *collaborative*.
A proactive operationalization puts conscious decision making at the core, allowing companies to exploit synergies, resolve conflicts, and reduce uncertainties in a targeted manner. Proactivity in targeted sustainability action was found to be related to conscious decision making itself and not the result of this decision, as described in the existing literature (see Chapter 6.1), which is in line with the understanding introduced in Chapter 5. Thus, ongoing conscious decision making ensures that the *context-specific*, *consistent*, *long-term oriented*, *evolving*, *reasoned* and *explicit* understanding of targeted sustainability action is converted into clear action.
Action orientation and actionable operationalization mean that these conscious decisions result in the initiation of targeted action. It was found that clarity on action requires guidance that explicates a “solution space” for action, allocates responsibilities and resources, and supports consistency between practices and their conditions. In addition, collaboration was found to be essential in many practices of targeted

sustainability action. This collaboration, on the one hand, means involving all relevant expertise and experience but, on the other hand, also to constructively challenge demands and intended action from all relevant perspectives and therefore collaborate across levels on operationalization of sustainability action itself. In addition to the existing literature that already suggests collaboration to achieve sustainability objectives (see Chapter 6.1), the interview results emphasize and detail the collaboration required on the operationalization itself. This involves assigning responsibilities appropriate to the "solution space" of intended action (e.g., operational engineers for technical solutions or senior management for strategic decisions) in the process of operationalizing sustainability action.

The identified practices surpass the existing literature in three aspects. First, they take a new perspective on sustainability action. Instead of applying an external framework to sustainability action in product engineering that limits the scope in product engineering or implies interdependencies between the practices (see Chapter 2.3.3), the practices are inductively derived from the interview data with an action-oriented company perspective, which is in line with the understanding of targeted sustainability action (see Chapter 5). Thereby, second, the interdependencies of these practices enabled the description of routines of continuous action and reflection forming targeted sustainability action, which provides a reference to its operationalization. The description of these routines, third, adds to existing literature by an action-oriented reframing of suggestions (see *proactive*, *collaborative*, and Chapter 6.1), which also introduced a new focus for operationalizing sustainability action, away from merely acting on (externally) given objectives and evaluating target achievement, to conscious decision making and initiating action in the organization (see *actionable*, Chapter 6.1).

6.3 Interim Conclusions

Operationalizing targeted sustainability action in product engineering addresses the second research question of this thesis: *How can targeted sustainability action be operationalized in product engineering?*

As described, operationalizing targeted sustainability action should be proactive, actionable, and collaborative. Therefore, targeted sustainability action is operationalized by defining practices to prepare, inform, decide, guide, enable, act, and evaluate, constituting continuous routines derived from and/or contributing to a context-specific understanding of targeted sustainability action in a way that they meet the success criteria above. Through these routines, decision makers can expand or reduce the time frame taken into account for conscious decision making, enabling companies to take advantage of opportunities emerging from sustainability demands and related uncertainties.

These generalizable aspects describe how targeted sustainability action can be operationalized by characterizing the operationalization itself and providing practices and routines to be established to form targeted sustainability action, which addresses the second research question and the second part of the first research need (see Chapter 3). How these practices and routines can be implemented is discussed in the following Chapter 7. In addition, these generalizable aspects provide the second step towards solving the main challenge of the thesis by describing the intended outcome to be achieved in utilizing the support: Practices forming targeted sustainability action in product engineering, which are derived and/or contributing to a context-specific understanding. The development of this support is discussed in Chapter 8, while the Guide, which also summarizes the main findings of Chapter 6, can be found in Appendix A.1.

7 Implementing Targeted Sustainability Action in Product Engineering

To realize targeted sustainability action in product engineering, the practices defined during its operationalization (see Chapter 6) must be implemented, and respective routines must be established. Therefore, in this chapter, generalizable aspects of implementing sustainability action in product engineering are identified.
Thus, this chapter aims to answer the third research question: *How can targeted sustainability action be implemented in product engineering?*

Based on the literature analysis in Chapter 6.1, the findings on the implementation of sustainability action in product engineering are briefly summarized below, while in Chapter 7.1 the results of the interview study are discussed, and in Chapter 7.2 interim conclusions are derived to answer the third research question, above.

A summary of the key findings of this chapter can also be found in the Guide for decision makers in Appendix A.1, as the results in this chapter were incorporated into this support. Specific references are provided throughout this Chapter, while the development of the Guide is described in Chapter 8. An overview of the Guide and the key concepts behind it have previously been published in Jäckle et al. (2025).

The **suggestions** found in the literature recommend an *integrated* character of sustainability action and therefore practices that align with current product engineering practices and current decision making (see Chapter 6.1, *integrated*, for the discussion of these suggestions). Establishing these integrated practices has a *transformational* character, and a conscious implementation was suggested (see Chapter 6.1, *transformational*). In addition, for individual fields of action, implications for the implementation of practices were indicated through barriers or suggestions (see Chapter 6.1). For example, the timeline and the resources required for implementation depend on the capabilities to be built and the involvement of top management (see Chapter 6.1 *capabilities*, *leadership*). The suggestions and barriers found indicate the critical role of implementing sustainability action, but provide only limited information on individual aspects. With respect to targeted sustainability action and the main challenge of this thesis, no clear suggestion on how to implement the targeted sustainability action could be derived from the existing literature. Therefore, the implementation of sustainability action was addressed in the interview study.

7.1 Implementation Derived from Interview Study

The third part of the interview guideline focuses on the third research question and was developed based on the findings in Chapter 6.1 that relate to the implementation of sustainability action (see *integrated* and *transformational*). It was split into two open questions. The first question asks how the interviewees would establish relevant practices (in their company), which could be challenged by asking for differences to other topics (like digitization). The second question asks for priorities in establishing practices as well as the reasoning for these priorities, and if uncertain, how they would identify such priorities. Details on the overall structure of the interview guideline can be found in Chapter 4.2.2, and the interview guideline in Appendix A.2.

Similarly to understanding and operationalizing, the interview results were analyzed using the Gioia Methodology (Gioia et al., 2013; see Chapter 4.2.2 for details), with respect to the third research question. The analysis also took into account all statements related to the implementation, and not only the answers to the dedicated questions (see Table 4.2 in Chapter 4.2.2 for an overview of the interviews with identifiers). The challenges and success criteria as are summarized as aggregate dimensions in the data structure shown in Figure 7.1 and are discussed below.

As part of a problem-oriented perspective that emerged from the interview data, the **challenges** decision makers face in implementing targeted sustainability action in product engineering under *uncertainty* could be identified and can be summarized as being *pragmatic* rather than *comprehensive*.

Pragmatism As described in Chapter 6.2, creating clarity on what needs to be done is required for targeted sustainability action. However, even if this clarity has been created, it does not mean that everything can be done immediately (see also Chapter 6.2, *proactive*). On the one hand, maintaining the manageability of targeted sustainability action can pose a challenge to decision makers (C1), but on the other hand, interdependencies between practices and context-specific conditions can be obstacles to their implementation (C1). Therefore, to initiate targeted sustainability action, an individual pragmatic approach to implementing targeted sustainability action in product engineering must be developed that recognizes context-specific circumstances (DM31; DM41; see also Chapter 6.2, *context-specific*). Due to these obstacles, being systematically pragmatic in implementation can be conceptually more difficult than being theoretically comprehensive (C1; DM24), for example, when making accurate but simplifying assumptions (DM43) or translating a future state into actions that can already be taken today (C3). However, immediate implementation of “full-blown” external solutions are also likely to fail, as coping with context-specific

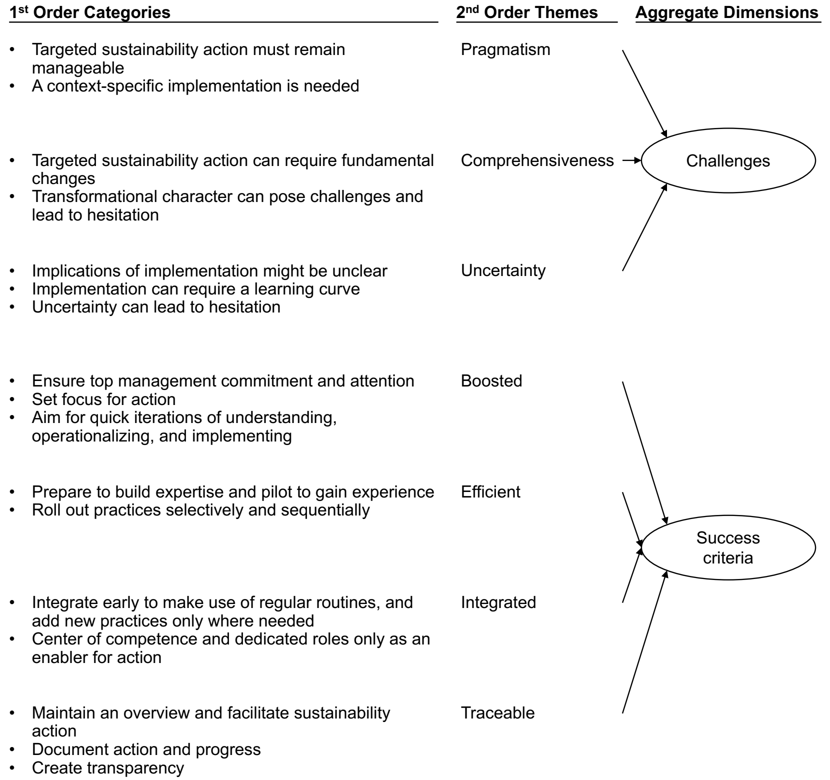

Figure 7.1: Data Structure Derived from the Interviews with Problem- (Challenges) and Solution-oriented (Success criteria) Findings with Respect to the Third Research Question: Implementing Targeted Sustainability Action

company realities becomes critical to successfully initiating and executing targeted sustainability action (see 5.2, *evolving*).

Comprehensiveness At the same time, targeted sustainability action beyond pilot projects can require fundamental changes in current product engineering (C6; C7) that introduce a transformational character to its implementation (C7; DM23). Such a transformation poses a challenge to companies (C7; DM24), which can be existential, especially in smaller companies, as it requires the ability to change the way of working

(DM26) and can lead to anxiety and hesitation among employees (DM33; see also *uncertainty*). Examples for these fundamental changes to be implemented can be “to essentially upgrade all your processes” (C7) or actually bring cross-functional collaboration to life (C3).

Uncertainty However, which practices lead to the intended effects, and whether objectives are achievable (DM21) can be unknown (see also Chapters 5.2 and 6.2, *uncertainty*), making it difficult to consciously decide when and where to implement such comprehensive changes (C3; DM23; DM43). In addition, the implementation of targeted sustainability action itself can be uncertain, as it could require a learning curve for the individuals and the company itself (C1; C3; C4). In addition, such a transformation of product engineering requires time (DM11; DM23; DM31) during which the conditions could change again (DM31), especially in the case of long development cycles (C2; C3; DM21). These uncertainties and the potential comprehensiveness of targeted sustainability action can lead to hesitation across levels (C3; DM21; DM22; DM31), which poses an additional challenge to initiating targeted action (DM31; DM43).

Therefore, implementing targeted sustainability action in product engineering requires well-placed pragmatism that maintains manageability under context-specific conditions and at the same time ensures the required fundamental changes.
This extends the main challenge of this thesis beyond creating a material understanding and clarity on action to executing a pragmatic implementation in order to develop broad, yet context-specific and actionable support.

As part of the solution-oriented perspective that emerged from the interview data on the implementation of targeted sustainability action, four **success criteria** could be identified that allow for a pragmatic implementation: An implementation should be *boosted*, *efficient*, *integrated*, and *traceable*.

Boosted Realizing fundamental changes, but also conscious pragmatism, requires top management commitment (DM31) for multiple reasons. First, since targeted sustainability action starts with an understanding from a company perspective (DM15; see also Chapter 5), the implementation of targeted sustainability action starts with setting objectives at the top management level (C6; DM15). Based on these objectives, dialogue can be started with business units (DM22), to set it as a management topic, and derive action (DM26). Such a dialogue and participation can create conviction (DM15; DM22), while the clarity of top management commitment can avoid destructive discussions (DM43; see also Chapter 6, *collaboration*). And through role modeling in this dialogue (DM22; DM31), a mindset shift can be triggered across levels (C7). In addition, customers might demand an explanation of the top management perspective on sustainability before awarding long-term contracts (DM26). Second, to allocate resources (DM43) and invest (DM15) a top management decision might be required (see Chapter 6.2, *guide*). For example, top management can appoint a facilitator of targeted sustainability action (DM26; DM32), who, for example, fosters critical reflection (DM31), which in itself can create attention. This dedicated facilitator, therefore, can provide start-up help (DM23) that accelerates a transformation (DM31). And third, under uncertainty, in case of divergent perspectives or when taking risks (DM21), conscious decision-making requires strong leadership (C6; see also Chapter 6.2, *decide*). One consultant summarizes this necessity for top-management commitment: "If there is no buy-in from the top to do things differently, you will never have the budget, never have the legitimacy, and never have the acceptance in the company to change things." (C4, trans.).

To initiate action, clarity on action must be created, which can be done through priorities (see Chapter 6.2). This also holds true for the implementation, where a systematic prioritization of practices (DM24) and a joint discussion of this prioritization (DM12) based on impact and feasibility (DM24) are required. Early prioritization accelerates the creation of clarity (DM31; DM32; see also Chapter 6.2, *guide*) and, therefore, allows action in a targeted manner (DM32). Moreover, a clear focus on where in the organization to implement these practices is required for targeted action (DM25). This focus can be guided by preparations (DM32; see also Chapter 6.2, *prepare*), or by status-quo evaluations (C1; DM16; DM25; see also Chapter 6.2, *evaluate*), which can lead to context-specific results even with a comparable evaluation logic (DM23). Priorities and focus can be provided through guidance (DM21; DM32; see also Chapter 6.2, *guide*), which allows decision makers to allocate time (DM12) and resources (DM11), e.g., by breaking down long-term objectives into short-term projects (DM23). This can again guide efforts, which enables pragmatic action (DM11) but also to drive fundamental changes in product engineering (DM21) and thereby accelerate sustainability action (DM31). Moreover, this focus is important to steer collaboration to contribute to targeted action (see Chapter 6.2, *collaboration*).

Starting from a reasoned focus (see also Chapter 5.2, *reasoned*), targeted sustainability action should be implemented pragmatically (see *pragmatic*), and continuous improvement should be started to establish the required routines (C7; see also Chapter 6.2, *proactive*). Quick iterations allow one to gain experience across all levels to account for the learning curve (C4; see *uncertainty*) and create more and more clarity on operationalization (C7), building the foundation for conscious decision making and, therefore, targeted sustainability action (DM21). One consultant illustrated establishing these iterations and collaboration across levels as a "frozen pie that you are heating. You can get the actions from the top management. Then you get the actions, … ambitions and ideas from … a couple of steps down in the company, and then you have the frozen middle" (C3).

Efficient Targeted sustainability action also means efficient implementation, which requires preparations (see also Chapter 6.2, *proactive*). Preparations enable this efficiency (DM21; see also Chapter 6.2, *prepare*), as they allow one to plan ahead (DM21; DM26) and think through the upcoming product generations (DM42), which also allows one to determine focus (see above) and prepare fundamental changes (DM23). As described in Chapter 6.2 (*prepare*), these preparations can at some point evolve into action. For example, developing multiple products in parallel is expensive (DM32), thus overinvesting should be avoided (DM21; see also Chapter 6.2, *prepare*). Therefore, pilot projects play a special role in implementing sustainability action, which can start from dry runs (DM14), serve as proof-of-concept (C4) or initial steps (C7) to gain experience (DM23) in smaller areas before scaling up (C7; DM25). Therefore, they mark the transition from preparation to action and changing the way of working (DM23; DM24; see Chapter 6.2, *prepare*). Although the point in time for broader implementation might be uncertain (DM23), it can be critical to act quickly once clear (DM21). This also means involvement of a broader group of people within the organization, where a trade-off between efficient preparations and an efficient roll-out of action needs to be made (DM32). This involvement in preparations creates awareness and builds a consistent understanding among the people involved (DM14; DM16). The involvement can be voluntary (DM41) and start with open-minded people (DM15) to create success stories (DM25) that can lead to conviction, further engagement (DM24; DM25), and a critical mass before a broader roll-out (DM15).
Rolling out sustainability action, for example new technologies (DM33), beyond pilot projects based on gained experience, is again context-specific (DM43), for example, depending on the economic situation (C4), customer willingness (DM25), but also the current project status of the product portfolio (C1). However, efficiency in this rollout can be gained, through starting with synergies, e.g., with cost implications (C3; C7; DM13; DM24) or between sustainability aspects (C1), and where experience is extensive, for example, with long-running products with process steps that can be omitted as they proved to be not necessary (DM24). Also, in cases where customer value can be created (C1; DM43), product engineering naturally tends towards sustainability action (C1; DM42). Moreover, if prepared, this rollout should be done selectively and sequenced (see *pragmatic* and Chapter 6.2, *proactive*). Sequencing allows efficient integration of sustainability action with upcoming changes in product engineering, like new investments (DM26; DM33), and makes use fade-outs of products or technologies (DM33). Thus, obsolete investments are avoided (DM33) and the context-specific situation is acknowledged, including existing contracts with suppliers (DM25) and the current product portfolio (DM14). A prepared sequencing

does not necessarily mean delaying action, but might also lead to earlier action due to even longer lead times (DM21; DM31) depending on the understanding of targeted sustainability action (DM31).

Integrated Implementing targeted sustainability action means to “integrate it into the core business … and core governance or it doesn’t … exist” (C6). This also means making use of existing routines and adding new practices only where needed to avoid wasting resources (DM11) and frustration among employees (DM33). This integration leads to a transformational character of targeted sustainability action (see *comprehensiveness*). Thus, an integration of sustainability action with the company strategy and the communication thereof is required (DM11; DM22; DM26; see also Chapter 5.2, *consistent* and Chapter 6.2, *collaborative*). Sustainability action should also be integrated with strategic programs (DM21). Consequently, it should be integrated into daily decision making (DM31) along current escalation paths (DM25) and processes (DM11) within business units and functions (DM42; see also Chapter 6.2, *collaborative*) changing the way of working (C6; DM43; see also Chapter 6.2, *enable* and *evaluate*). At the operational level, this might mean integration into requirements (DM32), checklists (DM14), workflows (DM14), processes (DM23; DM43), decision gates (DM22), business cases (C7), rules and forms (DM23), ERP systems (DM42; DM43), and tools (C4).
Although integration into core business is crucial to drive change (C6), a dedicated facilitator role or CoC can support sustainability action. When decoupled from the organization (C6; C7), such a CoC lacks decision-making power (C5) and cannot achieve sustainability objectives by itself (C6), often resulting in mere report writing (C6). However, a CoC can act as an enabler for targeted sustainability action (C5; C7) that bundles required competencies such as understanding the regulatory environment (C6), provides information (DM13) and works on foundational topics such as methods, tools, and guidelines (DM23; DM32; DM41) in close collaboration with decision makers (DM23) to increase the efficiency of implementation (DM43). These activities require engineering profiles (C6), similar to cost engineering (C5). A dedicated facilitator role, even in addition to other responsibilities (DM21), can already support decision makers with know-how (DM25; DM41), experience and expertise (DM42), or establish a network among relevant decision makers within the organization (DM25; DM31; DM32) who can collaboratively take the lead (DM31) to support the integration of sustainability practices.

Traceable Creating a “single point of entry” (DM21) can ensure that understanding and action reflect a consistent company perspective (DM15; DM31; DM32; see also Chapter 5.2, *consistent*) and avoids double work (DM41), contributing to an efficient implementation. This responsibility can be taken by a facilitator (DM31), a committee

(DM41), or a team (DM41) that reports to top management, e.g., board (DM21). Moreover, they can steer the foundational work in a CoC (see *integrated*). As integrated implementation can require collaboration (see also Chapter 6.2, *collaborative*) across the organization, it might need to be facilitated beyond avoiding double work. Therefore, a facilitator should have an overview of the people involved (DM41; DM42), and coordinate their collaboration (DM15; DM21; DM25; DM42) within the company across levels and functions (DM25; DM31), and externally (DM31).
Traceability of sustainability action is essential to sustain the progress achieved and build on it (DM23). Therefore, sustainability should be documented from the reasoned understanding used for initial decision making (see Chapter 5.2, *reasoned*) to the knowledge and experience gained to build capabilities (DM43; see also Chapter 6.2, *collaborative*). Moreover, documented initial decisions can already serve as guidance (DM31; see also Chapter 6.2, *guide*), and documented evaluations enable further decision making (see Chapter 6.2, *evaluate*). This fosters operationalization (DM43) and implementation (DM41) of sustainability action.
An explicit understanding of targeted sustainability action is needed to make required decisions and initiate targeted action (DM14; see also Chapter 5.2, *explicit* and Chapter 6.2, *guide*). Therefore, transparency on targeted sustainability action must be created as a starting point for collaboration and involvement (DM12; DM15; DM22; DM25; DM32). This transparency can ensure consistency in understanding (DM31) and action (DM43), shows commitment (DM22), and reduces uncertainty (DM25). It also enables fact-based discussions (DM22) that build conviction (DM15) and can break resistance (DM31). Therefore, communicating sustainability action to the broader company beyond directly involved people, e.g., integrated with strategy communications (DM11) can also make sense (DM14). External transparency can also be required, for example, to collaborate with value chain partners (DM23), but also to enable value creation for customers (DM42; DM43). However, this external transparency should be created consciously where needed (DM24), as risks might be involved, e.g., with respect to intellectual property (DM33) or competitive disadvantages (DM11; DM21).

In summary, a new action-oriented perspective on the implementation of targeted sustainability action could be described that supports well-placed pragmatism but also fundamental changes. It was found that the implementation of this action can be driven through quick iterations of focused action with top management commitment (*boosted*). In addition to focused action, a pragmatic implementation can be achieved through efficient preparations and a selective and sequenced roll-out of practices (*efficient*). The findings further emphasize the need for the integration of sustainability action into product engineering and confirm the transformational character of such an implementation (*integrated*). Therefore, active facilitation is also required to maintain

the overview, ensure documentation, and create transparency (*traceable*).
This perspective adds to the existing literature (see also Chapter 6.1, and the introduction to Chapter 7) not only by detailing the need for integration and the implications of the transformational character of sustainability action, but also by incorporating action-oriented pragmatism into targeted sustainability action. Furthermore, clear limitations of dedicated sustainability roles could be identified, namely that they can support targeted sustainability action by facilitating or enabling but cannot drive change in the organization or execute this action on their own.

7.2 Interim Conclusions

Implementing targeted sustainability action in product engineering addresses the third research question of this thesis: *How can targeted sustainability action be implemented in product engineering?*
As described, the implementation of targeted sustainability action should be *boosted*, *efficient*, *integrated* and *traceable*. Therefore, targeted sustainability action is implemented by establishing practices that form targeted sustainability action and facilitating them in a way that meets these success criteria. This allows companies to initiate targeted action on opportunities emerging from sustainability demands and related uncertainties.

In answering the third research question, these generalizable aspects complement the efforts made as part of this thesis to address the first research need (see Chapter 3). The respective conclusions are drawn in Chapter 9. With respect to the second research need and, therefore, the support to be developed, these findings detail what the support is intended to help decision makers with: The initiation of targeted sustainability action in product engineering. The development of this support is discussed in Chapter 8, while the Guide, which also summarizes the main findings of Chapter 7, can be found in Appendix A.1.

8 Supporting Targeted Sustainability Action in Product Engineering

The second research need to be met in this thesis is to address the uncertainty of decision makers and support them in initiating targeted sustainability action in product engineering (see also Chapter 3).
In this chapter, the fourth research question is answered: *How can decision makers be supported in addressing their uncertainty about targeted sustainability action and initiating targeted sustainability action in product engineering?*
Therefore, building on the findings in Chapters 5 to 7 the main challenge of this thesis is tackled: Developing broad, yet context-specific and actionable support for decision makers.

First, the intended support is described (Chapter 8.1) through a system of objectives for this support and the operationalization of these objectives. Based on this intended support, the actual support is developed. To ensure relevance and applicability, the support is iteratively developed in three consecutive studies, with an increasing maturity of the support. Within each study, a new version of the support is developed and evaluated in an iterative way (see Blessing and Chakrabarti, 2009). This allowed for early evaluation of core concepts and integration of decision makers' feedback in the subsequent versions. Thus, these versions can be termed "engineering generations" as per Albers et al. (2020). The structure of the remainder of Chapter 8 follows this approach.
In Chapter 8.2 the initial version of the support is presented in the form of a workshop concept and document, which was applied and evaluated in workshops in a case company. Chapter 8.3 describes the second version of the support in the form of an explanatory presentation that was reviewed in expert discussions involving experienced consultants. In Chapter 8.4 the third version of the support is presented, which was developed in parallel to the application in a project setting in a case company, and was accompanied by a master's thesis (Herrmann, 2025)[6] that was co-supervised by the author.
This latest version of the support is a Guide for decision makers in a document format, which can be found in its entirety in Appendix A.1. An overview of the Guide and the key concepts behind it have previously been published in Jäckle et al. (2025). Therefore, in this chapter, the versions of this support are described with a focus

[6] Co-supervised master's thesis (unpublished)

on its development and the differences between the versions. References to the Guide for decision makers in Appendix A.1 and the generalizable aspects of targeted sustainability action in Chapters 5 to 7, on which the support is based, are included where relevant.
The three studies, and therefore the first version of the support, were preceded by two workshops on the topic based on initial literature-based findings and facilitated by the researcher with a kitchen appliance manufacturer and a university institute. Although no explicit integration of these results into the support for decision makers was done, the protocols, notes, and the author's own reflection certainly equipped him with experience in such discussions.
Overall, the research approach to develop and evaluate this support (see Figure 8.1) parallelizes the Prescriptive Study (PS) and Descriptive Study II (DS II) stages of the DRM in an iterative way (see Blessing and Chakrabarti, 2009). Following Marxen (2014), the iDSDM activity of design support development, "Embodiment of design support", is alternated with experimental, transfer, and implementation studies, as illustrated in Figure 8.1.

8.1 Intended Support

The support is intended to reduce the uncertainty of decision makers about targeted sustainability action and thus support them in initiating it. Consequently, the support aims to fill the research gap identified in Chapter 2.3.3: Broad, yet context-specific, and actionable support. Although such support itself currently represents a gap in the existing literature, several authors state **suggestions** for the development of support for sustainability action.

Diaz et al. (2021) for example share suggestions for decision-making support: "a) to be adaptable to different company contexts (terminology); b) to be intuitive, accessible to non-experts, educational; c) to require in-person interactions and exchanges; d) to be simple, easy to use; e) to provide granular results, and disaggregated information" (p. 1042). Although identified in the context of circular economy, these suggestions can be relevant to decision-making support in a more general way. Faludi et al. (2020, p. 8) also find the need for easy implementation and company-specificity of Sustainable Design Methods and Tools. In addition, they state that such support should "better balance incentives" and result in "clear actionable recommendations" (Faludi et al., 2020). Missimer and Mesquita (2022) suggest, among other things, a larger and more strategic focus of research, instead of developing "theoretically correct and detailed support" in order to implement, in this case, social sustainability (p. 4).

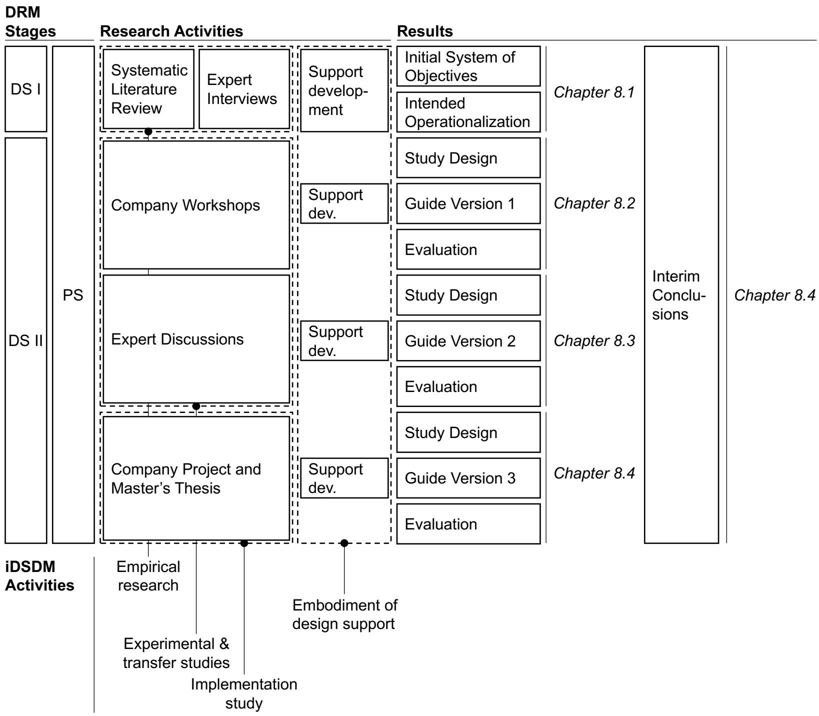

Figure 8.1: Research Approach with a Focus on the Development of a Support for Decision Makers Resulting in the Structure of Chapter 8

In addition to these initial literature suggestions, the interview study conducted as part of this research (see Chapter 4.2.2) examined the **support needs** of decision makers. Therefore, the fourth part of the interview guideline asked about support needs seen by the respective interviewee at the case company overall, and about their individual support needs in order to contribute to sustainability, as well as whether this support already exists or why they think it does not exist. If requested, the examples named were, guidance, approaches, methods, or tools. Details on the overall structure of the interview guideline can be found in Chapter 4.2.2, and the interview guideline in Appendix A.2.

Similarly to the previous chapters, the interview results were analyzed using the Gioia Methodology (Gioia et al., 2013; see Chapter 4.2.2 for details), with respect to the second research question. This analysis took into account all statements related to support needs, not only the answers to the dedicated questions (see Table 4.2 in Chapter 4.2.2 for an overview of the interviews with identifiers).

The interview data shows that the support need for targeted sustainability action in product engineering can be manifold and strongly depends on the maturity of sustainability action in a company (C5). It can range from strategic perspectives (C5), e.g., reducing uncertainty on future developments (DM25), or defining processes (C4), creating transparency on specific data (C5; C7), finding new unknown suppliers (C5; DM32), providing tool integration (C3; C7; DM41), to supporting technology implementation (DM14). Also, in building capabilities and expertise, support can be required (C4; DM15) that then needs to be in-depth and not just awareness-raising (C7; DM22), which might start in university, as it has proven to be successful in other topics (DM22). Potentially, support is needed on all challenges of targeted sustainability action (C6; see Chapters 5 to 7). The nature of support can also vary from external help, for example, to accelerate preparations (DM11) or industry collaboration (DM32; DM43), to guidance on creating clarity and extending the planning horizon of context-specific sustainability action (DM31; DM33).
However, while the need for support was found in many cases, the demand for support on targeted sustainability action was found to be low (C2), which can be for multiple reasons. Under uncertainty, decision makers had difficulties expressing their support need (DM12; DM13) or deciding which support to use (DM31; DM32). Some decision makers felt comfortable dealing with currently known demands (DM26; DM32; DM43), however, one also stated that this could suddenly change in the case of changing demands (DM26). In addition, consulting external support on targeted sustainability action is also an entrepreneurial decision (DM14) that requires an initial conviction to not deprioritize such an investment (C6). Moreover, many of the stated needs can also be addressed by dedicated roles within the company (see Chapter 7), while external support can be perceived as theoretical, not feasible, or not pragmatic enough (DM11; see also Chapters 5.2, *evolving*, and 7.1, *pragmatic*).

In summary, the findings derived from the interview study focus on support needs, as well as the barriers to and value of such support, with the underlying reasons, while suggestions from the literature focus on the characteristics of support.

8.1.1 Initial System of Objectives

Based on these findings from the literature and the interview study, as well as the results of previous chapters, a system of objectives can be compiled for the support to be developed. The main objective of the support is derived from the research need and its two core aspects, which have been stated above: Reduce the uncertainty of decision makers about targeted sustainability action and support them in initiating it. To achieve this objective, the main challenge of this thesis needs to be overcome, which requires the development of broad, but context-specific, actionable support. This challenge is addressed in two ways.

First, the support to be developed should guide decision makers throughout the entire journey from initial understanding, via its operationalization, to the implementation of targeted sustainability action, leveraging the generalizable aspects identified in Chapters 5 to 7. In this way, all key decisions that could be identified based on the generalizable aspects can be explicitly addressed, together with identified challenges and potential uncertainties. Fulfilling the success criteria in this process ensures broad, yet context-specific and actionable results: Targeted sustainability action.

Second, the support itself and its design should also nurture these success criteria and not compromise overcoming the main challenge. Therefore, to enable context-specific use of the support, it should minimize potential presuppositions, or make them explicit and allow one to incorporate the current status quo of sustainability action. Moreover, the application of the support should remain manageable without oversimplification, acknowledging the breadth and complexity of the topic, while being easy to implement and providing clear actionable recommendations. In addition, the support should provide relevant information accessible to non-experts in an educational way.

The resulting four objectives are listed in Table 8.1, together with their intended operationalization, which is discussed in the following Chapter 8.1.2.

8.1.2 Intended Operationalization

To provide a starting point and develop the initial version of the support, the objectives are operationalized, which can be seen as “intended support” as per Blessing and Chakrabarti (2009, p. 34). In total, four different objectives are specified, as an initial system of objectives, based on Chapter 8.1.1, and operationalization measures that represent the intended support are derived (see Table 8.1). This initial system of objectives and its operationalization represent the intended support prior to the development of the first version of the actual support. The wording has been updated for consistent traceability throughout the studies.

Table 8.1: Initial System of Objectives for the Support for Decision Makers with Its Intended Operationalization

Objective	**Intended Operationalization**
Reduce the uncertainty of decision makers about targeted sustainability action and support them in initiating it in product engineering	A Guide with key decisions in understanding, operationalizing and implementing targeted sustainability action
	Provide problem descriptions with common *challenges and uncertainties*
	Provide *success criteria* for targeted sustainability action with descriptions and interpretations relevant to key decisions
Minimal and explicit presuppositions	Formulate key decisions as open-ended *guiding questions*
	Include purpose of support
	Allow incorporation status quo
Balanced complexity and manageability	Follow a top-down structure with success criteria and guiding questions at its core, *application concept* and non-exhaustive details as reference (focused on initial steps)
	Provide templates
	Reason and explain structure and process
Educational and accessible information	Provide details as references for each decision (conditions, implications and interdependencies) and explain their relevance and use

The intended operationalization of the system of objectives (see Table 8.1) describes a Guide for decision makers with five key concepts to understand, operationalize, and implement targeted sustainability action. First, the *challenges and uncertainties* relevant to these steps, which can be found in problem-oriented perspectives described in Chapters 5 to 7. Based on the solution-oriented perspective as part of the generalizable aspects in these chapters, in which, second, the *success criteria* for these steps can be found, third, the key decisions and thus the *guiding questions* can be derived. Further insights from these chapters can be summarized for decision makers and provided as, fourth, the *application concept* of the Guide, and, fifth, *supporting materials* comprising details, templates, etc.

Based on this intended support, the actual support – the Guide – was developed in three successive versions in which the key concepts were realized with increasing maturity. These versions were applied and evaluated as part of three studies, enabling early iteration with decision makers, allowing their feedback to be incorporated into subsequent versions. The following chapters are therefore structured along the studies conducted and cover the study design, a description of the developed version of the Guide, and the results of the study. The latest version of the Guide for decision makers is described in Chapter 8.4 and attached in Appendix A.1.

8.2 Company Workshops

The first study during the development of the support comprises two workshops with a company interested in targeted sustainability action in product engineering. A workshop-based setting was chosen because it allowed discussion of the core concepts of the support under development, while allowing enough flexibility to adjust to the status quo and the participants' needs, as the maturity of the support was relatively low shortly after the evaluation of the results of the interview study. In addition, in a workshop, potential obstacles could be identified immediately and feedback could be collected early from multiple perspectives, as the support is provided as part of the interaction. The design of the study is described in Chapter 8.2.1, the Guide Version 1 in Chapter 8.2.2 and the results in Chapter 8.2.3.

A short summary of the workshops and selected results of the post-workshop survey have previously been published in Jäckle et al. (2025).

8.2.1 Study Design

For the workshops, a company was chosen that had not participated in the previous interview study (see also Chapter 4.2.2) and had expressed uncertainty about sustainability action in product engineering. The manufacturing company in the field of precision motion control with 1,000-5,000 employees is headquartered in Germany with multiple engineering hubs across three continents.

The workshops were conducted in preparation of a joint project on sustainability action in product engineering (see Chapter 8.4). Together with a senior product engineering decision maker, the participants for the workshops were identified and invited (similar to the interview study described in Chapter 4.2.2). The six invited participants covered all perspectives that were considered relevant for an initial discussion of the topic, including sustainability management, functional leaders, project managers, and development operations. The workshops were facilitated by the author and were supported by a research assistant.

The two workshops were conducted in September and October 2024 with a duration of three hours each. The workshops were planned and conducted in person, but one participant in the first workshop and two participants in the second workshop needed to attend virtually, leading to a hybrid setting. The workshop agenda and concept are described in Chapter 8.2.2 as they are part of this first version of the Guide in a workshop format.

To understand in more detail the context in which the workshops were conducted, the participants completed a survey at the beginning of the first workshop. It captured their understanding of sustainability, their perception of uncertainties, and the status quo of sustainability action in product engineering in their company, as well as their expectations (the data collection form for the pre-workshop survey can be found in Appendix A.3, and the results in Chapter 8.2.3). Between the two workshops, a follow-up discussion was conducted with the company coordinator to reflect on the first workshop and collect qualitative feedback. After the second workshop, participants completed a survey to evaluate the workshops (actual support) with respect to key aspects of the intended support (objectives) and provide feedback (the data collection form for the post-workshop survey can be found in Appendix A.3, and the results in Chapter 8.2.3). This survey focused on the main objective and covered individual aspects of the other objectives with respect to the decision-maker perspective and the workshop setting. In addition, the workshops were documented by a research assistant.

8.2.2 Guide Version 1

The first version of the actual support consisted of the Guide in the form of a workshop concept and presentation. Therefore, parts of the Guide were presented by the researcher and parts were applied and used by the participants. The flow and use of the Guide in this format are described below and summarized in Figure 8.2. Having in mind the three steps, 1, “Understanding”, 2, “Operationalization”, and 3, “Implementation” of the intended support, a focus was set on the first step as it is the most fundamental one in an initial discussion to reduce the uncertainty of decision makers.

The first workshop consisted of three parts. In the first part, the pre-workshop survey was filled by the participating decision makers to evaluate the conditions under which the workshops took place, and therefore under which the results are to be interpreted. Then the motivation and context for the workshops were presented by the author who facilitated the workshop, and the participants were given time to present their

perspective on current sustainability efforts at the company.
In the second part, which covered most of the workshop, the Guide was applied: First, the structure of the Guide was explained, with its steps and their challenges, success criteria, guiding questions, and interdependencies (see also the Guide for decision makers in Appendix A.1). An introduction was given to the elements of Step 1, "Understanding" (see also Chapter 5 and the Guide for decision makers in Appendix A.1), and the first guiding question was raised: "Why is targeted sustainability action relevant to the company?", which was then answered by the participants in two groups. For this exercise, the participants received templates (see also Table A.7 in the Guide) to document their results, and supporting materials for reference (see also the Guide in Appendix A.1). Both groups shared their results in the plenary for discussion.
The third and last part of the workshop contained an open discussion of the results and led to the invitation for a second workshop to continue with the second guiding question based on the results of this first workshop. One week after this workshop, a follow-up discussion was conducted with the coordinator on the company side to reflect on the workshop outcomes.

The second workshop was conducted three weeks later. At the beginning, time was given to the groups to review and refine their answers to the first research question as a recap. Then using the refined results, the author facilitated a plenary discussion to answer the second research question: "What could be achieved through targeted sustainability action at the company?" Opportunities and risks were discussed, and potential objectives were identified. These objectives were split and taken into two groups for detailing, for which again templates were provided (see also Table A.13 in the Guide). The detailed objectives were again presented and discussed in the plenary, where next steps were agreed. The end of the second workshop marked the post-workshop survey (see Appendix A.3) for evaluation of the provided guidance by the participating decision makers. The results are discussed in Chapter 8.2.3. An overview of this first version of the Guide in workshop format is given in Figure 8.2.

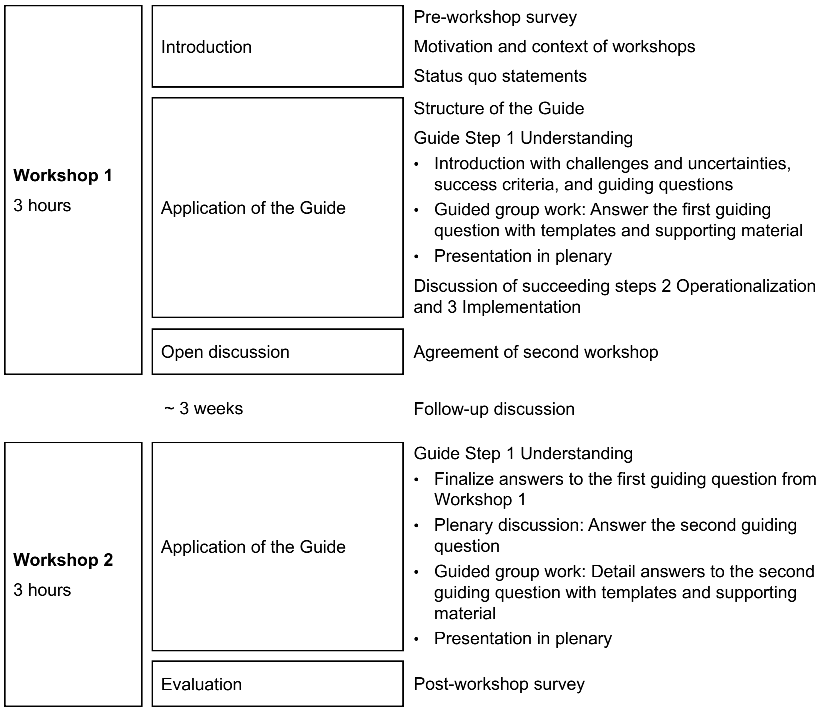

Figure 8.2: Guide Version 1: Workshop Concept to Reduce the Uncertainty of Decision Makers with Focus on an Action-oriented Understanding of Sustainability in Product Engineering

8.2.3 Evaluation Results

The *pre-workshop survey* covered five questions that captured the setting in which the workshops were held (see Appendix A.3). The answers to these questions are summarized below. Direct quotations from the decision makers' statements are indicated by quotation marks, while direct attribution of these statements to the individual decision makers (n=6) is avoided in order to ensure their anonymity. The personal understanding of sustainability ranged from a broad understanding of "long-term strategy" to conceptions such as "ESG", "three pillars", and "resource preservation". With respect to companies' understanding of and uncertainties about sustainability in

product engineering, multiple points were raised. On the one hand, it was stated that a sustainability understanding is “not existing” as a respective strategy is currently under development. On the other hand, participants perceived an “only environmental” focus or “recycling” as the current understanding. Uncertainties were raised regarding the understanding “What does sustainability include?”, and its operationalization/implementation. “Everybody knows it, everybody wants it, nobody knows how.” More specific uncertainties entailed missing methods, objectives, and poor data quality. Previous sustainability action in the company focused on “CE documentation” and “sustainability management was introduced but not yet implemented.” Thus, the workshops were perceived as “first steps”. Regarding the workshops, the participants expected and “introduction to the topic” with “indications for methods and an approach” as well as a “common understanding and starting point.” In addition, a “gap analysis for next steps at the end” and initial ideas on “implementation of sustainability in product engineering” were hoped for.
Overall, the pre-workshop survey indicated a suitable setting to test guidance that is intended to reduce decision makers’ uncertainties on targeted sustainability action in product engineering due to multiple reasons. First, uncertainties about all three steps were openly raised by the decision makers who attended the workshop. Second, understandings and perceptions of the understanding and previous efforts varied, while an interest in a common understanding was indicated. Third, previous efforts were in the initial stages, and relevant decision makers involved could inject the status quo into the workshops. The setting will be considered when discussing the results of the post-workshop survey and qualitative feedback in the following.

Follow-up discussions with the company’s coordinator revealed that examples would be helpful as inspiration to answer the guiding questions and that a prioritization of “low-hanging fruits” should be explicitly possible between steps. Moreover, the coordinator indicated that prioritization needs to happen based on the scope of action and opportunistically based on current initiatives in the company. This is in line with the success criteria (see Chapter 6, *actionable* and Chapter 7, *efficient*). Challenges were seen in potential conflicts between “what we want and what we can.” For the second workshop, the coordinator suggested a thorough preparation based on the results of Workshop 1 to directly address the identified critical points, which was done. The other suggestions were considered in the development of the subsequent versions of the Guide.

The *post-workshop survey* was filled by the participants (n=6) at the end of the second workshop. It was derived from the system of objectives (see Chapter 8.1), and differentiated the success criteria for each of Steps 1, “Understanding”, 2, “Operationalization” and 3, “Implementation”. However, in this evaluation, the objective of

providing information for decisions in an educational way was omitted, as the form of communication of the information changes, when moving from a workshop in Version 1 to a guide format in Versions 2 and 3. Answers were possible on a five-step Likert scale (strongly disagree, disagree, neutral, agree, strongly agree). Due to the early stage and the limited exposure during the workshops, the participants were given the option to leave out any questions they did not feel prepared to answer. In addition, the possibility of qualitative feedback was provided. This post-workshop survey can be found in Appendix A.3, while the results are discussed below and shown in Figure 8.3.
For an indication in the sense of a "success evaluation" (Blessing and Chakrabarti, 2009, p. 37) the outward looking question was asked whether participants expect the application of the Guide to enable targeted sustainability action in product engineering. Four of six participants agreed, while two were neutral at that stage. The other questions of the survey focused on the set objectives and can therefore be seen as a "application evaluation" as per Blessing and Chakrabarti (2009, p. 37). Regarding the overarching objective "reducing uncertainties of decision makers," four participants agreed, while two were neutral after the two workshops. The participants agreed that moral judgments were excluded (0/1/5)[7] and the status quo was incorporated by the Guide (0/0/6). In addition, most of the participants confirmed that the Guide focused on key decisions and balanced complexity and manageability (1/2/4).
The majority of the participants perceived the success criteria of Step 1, "Understanding", as fulfilled (esp. context-specificity[8] could be confirmed 0/0/5). Regarding the success criteria of Steps 2, "Operationalization", and 3, "Implementation", which were only presented during the workshops, the responses were more neutral. However, with respect to Step 2, "Operationalization", two participants each saw the success criteria fulfilled. In Step 3, "Implementation", one participant doubted that the application of the Guide would boost the implementation of sustainability action, while three participants agreed that the application would support the integration and traceability of sustainability action.

Given the early stage of the support development and the limited exposure time of the participants during the workshops, the evaluation overall showed that the Guide development takes a promising direction to fulfill the objectives set as part of the intended support. However, during further development, attention should be paid to balancing manageability and complexity, focusing on key decisions, and boosting the implementation, as disagreement was indicated by one participant each.

[7] (Strongly) disagree / neutral / (strongly) agree

[8] At the time of the survey, the success criterion was called "context-dependency" and "long-term oriented" was called "long-term", which have been updated here and in Figure 8.3 to enhance traceability. The questionnaire used can be found in Appendix A.3.

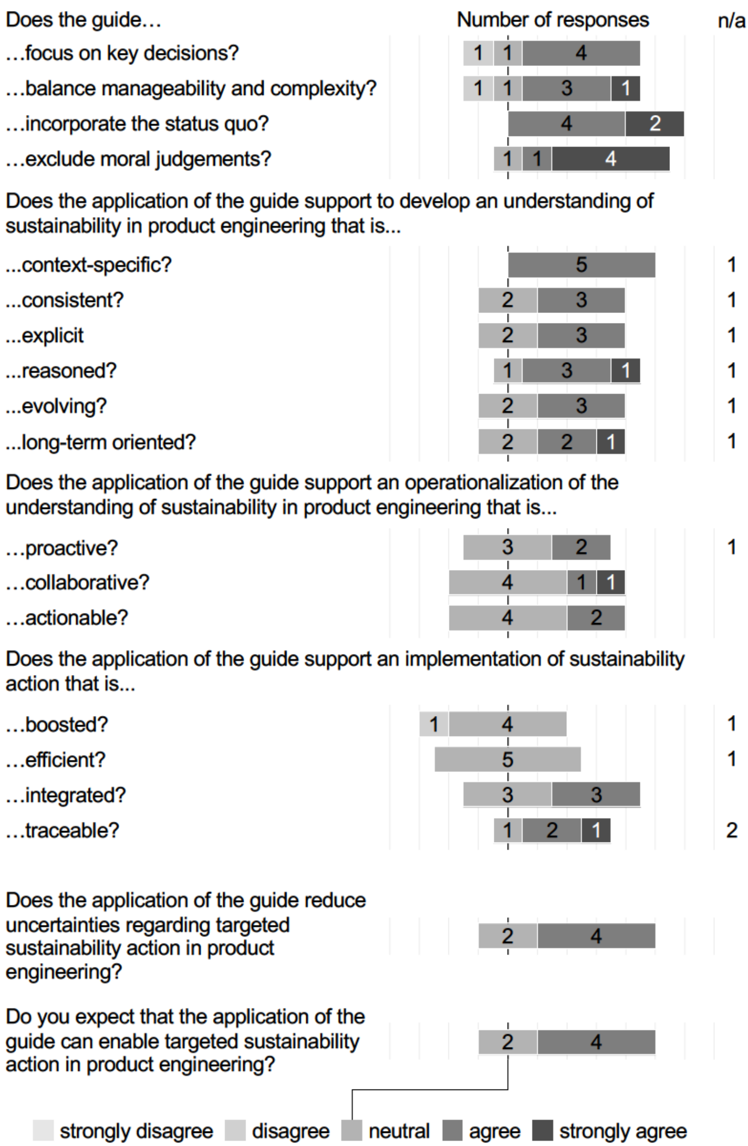

Figure 8.3: Results of Post-workshop Survey Filled by the Participating Decision Makers (n=6)

The qualitative feedback in the survey addressed these points; for example, one decision maker stated that the discussion can easily get lost in details without guidance and that more time would be needed for in-depth application of the Guide. Furthermore, a participant suggested an early alignment with the strategy and asked for a relative classification of the application of the Guide to existing efforts such as the double materiality assessment according to CSRD (see also Chapter 2.2), which was performed in the company and presented as part of the status quo. Explicit use cases for the support could address this demand.

Overall, although detailed guidance during the application was needed at that initial stage, the survey showed that the support development was headed in a promising direction and is in line with the objectives set. The following versions should ensure focused discussions on key decisions with appropriate complexity supported by comprehensive guidance. Explicit aspects to add were a delimitation of existing efforts, prioritization of “low-hanging fruits”, and examples of filled templates.

8.3 Expert Discussions

The second study conducted involved expert discussions for which the Guide was further developed from a workshop concept (Version 1) to an explanatory Guide in presentation format (Version 2), which decision makers can use as a reference to initiate targeted sustainability action in product engineering. As the first study (workshop) was conducted with decision makers in a company, these expert discussions were intended to cover a view across companies. Therefore, the second version of the Guide was reviewed and discussed with experienced consultants representing a second potential user group of the Guide. The study design can be found in Chapter 8.3.1. The description of the second version of the Guide can be found in Chapter 8.3.2 and the results of the study in Chapter 8.3.3.

8.3.1 Study Design

The second version of the Guide in a presentation format (see Chapter 8.3.2) was shared with three consultants with more than seven years of experience in the field of product engineering and/or sustainability. Two experts (Experts 1 and 2) represent deep content expertise on product engineering and therefore are potential users of the Guide. They were not part of the previous interview study. One expert representing deep content expertise on sustainability action (Expert 3) was part of the previous interview study (see Chapter also 4.2.2). Reviewing the Guide with these experts aimed to offer an external perspective and additional feedback compared to the previous workshop study. The author engaged with each expert individually. All experts received the Guide for an offline review, and in addition a discussion with each expert was conducted. In the case of Expert 1, the Guide was introduced, discussed, and then shared for an offline review. Experts 2 and 3 received the Guide beforehand for review and were then invited for a discussion. The discussions with Experts 2 and 3 followed the same semi-structured flow, where the expert was given time to share observations from the review and then was asked for their perspective on four topics. Looking for a broader evaluation of the actual support, the following four questions were derived based on the system of objectives (Chapter 8.1), which, however, also cover elements of support and application evaluation as per Blessing and Chakrabarti (2009) (see also Chapter 8.2):

- Relevance: Is the Guide and topic relevant to the companies you are working with?
- Comprehensibility: Are the Guide and its content comprehensible?
- Applicability of the Guide and its supporting materials: Is the proposed approach feasible?
- Support provided by the Guide: Is the support that you consider necessary being provided?

The expert discussions were conducted in November and December 2024, ranged from 30 to 45 minutes in duration, and were documented through note-taking by the author.

8.3.2 Guide Version 2

The second version of the support can be described as an explanatory Guide that exceeds the first version by addressing the objective of providing educational and accessible information (detailed below). It was realized in a presentation format that enabled a maturity of the Guide suitable for its development stage (guidance explained in bullets, not yet continuous text). Moreover, the format was known to the experts and, therefore, easy to review.

The second version contained an executive summary, an introductory overview section, and separate sections for all three steps: 1, “Understanding”, 2, “Operationalization”, and 3, “Implementation”.
The overview section motivated targeted sustainability action in product engineering. Additional aspects of the intended support (see Chapter 8.1) were added, such as the three steps, their relation, the purpose of the Guide, its support when conducting

the three steps, and its detailed structure. In addition, an overview of the main concepts, namely success criteria and guiding questions (see Chapter 8.1), was given throughout the three steps (see Tables A.2 and A.3 in the Guide).
A standardized structure for the three steps was introduced that comprised a summary and five sections along the questions, “Why?”, “What?”, and “How?”, inspired by the findings in Chapter 2.3.2 (see Table A.1 in the Guide). “Why?” was addressed by challenges and uncertainties to the step. “What?” by success criteria and guiding questions. “How?” by a section explaining the application of the step and supporting materials. The order was chosen to increase the level of detail of the Guide incrementally in line with the intended support (see Chapter 8.1), so it could be used as a high-level orientation but also operationally (see Table A.3 in the Guide).
To explain the Guide and provide information in an educational way, written explanations were added to the sections and supporting materials. This included information that was covered verbally during the workshops or was found relevant based on the experience and evaluations during the workshops. Thus, the key changes between Guide Versions 1 and 2 can be summarized as the change in format from the workshop concept to a presentation, with additional details and explanations based on the generalizable aspects of targeted sustainability action in line with the intended support and the experiences in the workshop.

8.3.3 Evaluation Results

The results of the *expert discussions* are summarized by the four areas of interest: Relevance, Comprehensibility, Applicability, and Support (see Chapter 8.3.1). However, the expert discussions were semi-structured, leading to varying focus areas between the experts.

All experts considered targeted sustainability action in product engineering and the Guide to be relevant. Expert 3 stated that companies are “falling behind their objectives” and need to revise their operations with “deep integration,” otherwise sustainability action might become “very costly.” In addition, Expert 3 confirmed that the storyline of the Guide captures the companies’ perspective well. Expert 2 saw an even more drastic situation than described in the Guide and stated that companies focus on “functional topics” resulting from sustainability regulation (e.g., CBAM, see also Chapter 2.2), and currently do not have the capacity for “generic discussions on sustainability,” indicating the need for more targeted action.
Experts 1 and 2 stated that the structure and storyline of the Guide are “logical and comprehensible.” Expert 3 said that “case examples” would make it easier to understand the breadth and depth of the concepts. Moreover, Expert 3 saw potential to

emphasize the need for clear priorities with trade-offs and the “evolving aspect” of the Guide.

Expert 1 perceived the Guide as directly applicable as is; however, Expert 1 suggested that a split depending on the addressees could be helpful, so that parts of the Guide could be used for different discussions. Expert 3 suggested describing “explicit use cases” in which potential users “can find themselves.” Moreover, Expert 3 felt that a “minimum conviction and alignment” need to happen at a company to commit to a proper application of the Guide.

In terms of support that is provided for decision makers aiming for targeted sustainability action in product engineering, Expert 3 stated that references to other solutions and helpful tools in the field like life cycle assessments etc. could be helpful. In line with the interview study, Expert 3 indicated that “data always becomes an issue at one point in time.”

The expert discussions confirmed the relevance of the Guide and further emphasized the context-based perspective the Guide takes on targeted sustainability action in product engineering. Although the overall structure was comprehensible, individual aspects (“evolving aspect”, prioritization) could be made more explicit in future versions, and tailoring to addressees could be introduced. To enhance the comprehension and application of the Guide, additional context (esp. explicitly defined use cases, enabling delimitation from existing efforts) would be helpful. According to the experts’ suggestions, also including required preconditions (esp. conviction), case examples, and references to other approaches would help to do so. Through these suggestions, the experts provided valuable and actionable feedback to further develop the Guide in Version 3, which is described as part of the third study presented in the next Chapter.

8.4 Company Project

The third study conducted as part of this thesis is a complete application of the Guide through facilitators in a company, which was accompanied by a co-supervised master’s thesis (Herrmann, 2025)[9]. The six-month company project was started in December 2024 at the same company where the workshops were conducted during the first study (see Chapter 8.2). The study is characterized by a parallel development of the third version of the support during the company project, which also incorporates the findings of the previous studies. The study design is described

9 Co-supervised master’s thesis (unpublished)

in Chapter 8.4.1, the third version of the Guide in Chapter 8.4.2, and the results of the study in Chapter 8.4.3.

8.4.1 Study Design

The company project was established in conjunction with two product engineering decision makers at the company. The senior decision maker (who invited the workshops, see Chapter 8.2) took a sponsor role, while a junior decision maker was appointed project lead. Together with a master's student, who applied the Guide operationally and on site, they took a facilitator role, collaborating with relevant decision makers in the company to initiate targeted sustainability action (see the Guide in Appendix A.1). None of the facilitators had prior experience in sustainability action beyond their participation in the workshops (see Chapter 8.2). However, they could build on documented results (Herrmann, 2025)[10]. The decision makers were part of a central department, which, due to its existing interface function, had excellent prerequisites to collaborate closely with the relevant decision makers in the organization (Herrmann, 2025)[11]. The project was set up for six months as part of the regular project landscape and department operations (Herrmann, 2025)[12]. The project was documented through the respective master's thesis of Herrmann (2025)[13], which was co-supervised by the author of this thesis and served as an interface to research.

Two phases can be distinguished, building on different versions of the Guide (see Figure 8.4). At the beginning of the company project and in parallel with the expert discussions (see Chapter 8.3), the second version of the Guide was provided to the facilitators. It was the basis for initial planning and the first weeks of the company project. The resulting feedback was collected from the facilitators by the researcher during weekly exchanges (Herrmann, 2025)[14]. Together with the findings of previous studies, this feedback was the basis for a major update of the Guide that resulted in Guide Version 3 (see Chapter 8.4.2). The development of this version of the Guide was started in December 2024. It was first shared in January 2025, starting the second phase of the company project and the continuous collaboration and integrated refinement of Guide Version 3 with the execution of the company project, which resulted in further updates (see Chapter 8.4.2).

[10] Co-supervised master's thesis (unpublished)
[11] Co-supervised master's thesis (unpublished)
[12] Co-supervised master's thesis (unpublished)
[13] Co-supervised master's thesis (unpublished)
[14] Co-supervised master's thesis (unpublished)

The planning and execution of the company project was carried out by the facilitators based on the Guide. In weekly exchanges they had the possibility to consult the author in case of questions and provided feedback to the author to improve the guide. The facilitators also collaborated with each other in weekly exchanges to align the next steps and coordinate collaboration with decision makers. Since the facilitators could build on the workshops conducted earlier, they omitted additional workshops during Step 1, ”Understanding”, and augmented the initial understanding with individual follow-up interviews with workshop participants and other decision makers that were identified as relevant at this point in time. The subsequent steps were performed according to the Guide (see Chapter 8.4.3 and Appendix A.1). (Herrmann, 2025)[15]

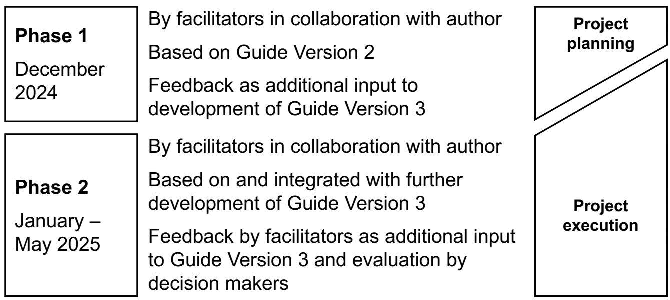

Figure 8.4: Overview of the Application of Guide Version 3 During the Company Project

As described above, feedback on the Guide from the facilitators was collected throughout the company project during weekly exchanges. In addition a summarizing reflection of the operational facilitator (as part of the master’s thesis) and independently a reflection of the project lead was documented after the completion of the project. The summarizing reflection was done along the four questions shared by the author, which were already used for the expert discussions (see Chapter 8.3.1). The first question was slightly altered to fit the company project setting and facilitators’ perspective and augmented by the open question for additional feedback: “Relevance of the topic and the Guide: Why is the Guide relevant to the company and your work?” Thus, this

15 Co-supervised master’s thesis (unpublished)

feedback can be categorized as support and application evaluation (see Blessing and Chakrabarti, 2009) in the context of this company project.

The evaluation of the Guide's application also captured the perspective of the decision makers involved. For this purpose, the final results of the application of the Guide covering understanding, operationalization, and implementation of targeted sustainability action developed in the course of the project were presented to the decision makers (see also Chapter 8.4.3 for a summary). After this recapitulation, the decision makers were asked to complete a survey capturing their perspective on the project results (post-project survey; see Appendix A.3, adapted from Herrmann, 2025[16]). Four questions related to their overarching perception. Two questions directly addressed two artifacts (a checklist for project management and a work instruction for project execution) developed during the project. And two questions asked for further feedback and support needs. The responses to the overarching questions can be found in Chapter 8.4.3. They address the main objective (to reduce uncertainties and initiate targeted sustainability action) as well as the success criteria of the three steps. (Herrmann, 2025)[17]
Thus, this evaluation uses the project results as a proxy to evaluate the effects of the Guide's application, which is why the questions are slightly altered compared to the evaluation after the workshops (see Chapter 8.2.3).

8.4.2 Guide Version 3

The third version of the Guide for decision makers is the final version of this thesis. It can be found in its entirety in Appendix A.1.

It has a document format with continuous text passages to include more detailed instructions and explanations again based on the generalizable aspects of targeted sustainability action and the intended support (see Chapter 8.1). In addition to the changes in the format and the more in-depth explanations compared to Guide Version 2, feedback and findings from previous studies (workshops with Guide Version 1 and expert discussions with Guide Version 2) were incorporated. Moreover, this version also includes the findings from the refinement parallel to the company project (see Chapter 8.4.1). The major changes are described below, while a detailed overview of the feedback incorporated and the resulting adjustments can be found in Table 8.2.

[16] Co-supervised master's thesis (unpublished)
[17] Co-supervised master's thesis (unpublished)

The major changes in the Introduction include use cases for the Guide, delimitations of other efforts, preconditions for the application of the Guide and context on addressees, potential roles, and an explanation of the modular character of the Guide (see also Figure A.3 in the Guide). Additionally, a Step 0, “Preparations”, was added to create the preconditions required for application. Steps 1 to 3 now include explanations for the usage of the supporting materials and examples of the filled templates. Moreover, a stronger differentiation between practices that are done only once (one-offs) and lasting routines was introduced. Moreover, the transition from Guide application to continuous improvement cycles was emphasized in the Introduction and Step 3, “Implement”. In Phase 2 of the company project, guidance was introduced on a potential parallelization of Steps 2 and 3 with a split by objectives. In addition to these major updates, many improvements have been made to the Guide based on the experience gained during both phases of the company project, e.g., more precise wordings, corrections, or refinements of illustrations.

8.4.3 Evaluation Results

During the project, a refined understanding of targeted sustainability action specific to the company could be developed (Step 1) that included 18 objectives, which could be consolidated to eight major objectives with their interdependencies considering uncertainties, conflicts, and synergies. Three closely interlinked major objectives were prioritized in further steps: Compliance with regulations, meeting customer requirements, and reducing raw material usage in product engineering. Although the facilitators operationalized all eight objectives in collaboration with the author (Step 2), special emphasis was placed on the collaborative involvement of relevant decision makers in the three prioritized objectives. For implementation (Step 3), two of the three objectives were again prioritized, where targeted action could already be initiated within the project. Thus, after planning the implementation and initial decision making, a work instruction was developed for project executions to achieve regulatory compliance and a product management checklist to support capturing customer needs. For both objectives, practices for further decision making and action were defined that describe continuous iterations of targeted sustainability action. The understanding, as well as the proposed operationalization and planned implementation for all objectives, was documented for further decision-making and presented to the decision-makers together with the artifacts developed as part of targeted action. (Herrmann, 2025)[18]

[18] Co-supervised master’s thesis (unpublished)

Table 8.2: Adjustments in Guide Version 3 Compared to Versions 1 and 2

Section	Operationalization	Feedback	Study – Source
Introduction	Use cases for the Guide	Explicate use cases in the context of "classic" sustainability and functional topics	Expert discussions – Experts 2,3
		Delimit application of Guide from existing efforts	Company workshops – Post-workshop survey, Expert discussions – Experts 2,3
	Preconditions for application	Address required conviction explicitly	Expert discussions – Experts 2,3
	Addressees and roles, modularity explained	Clear facilitator perspective, explain who does what during application	Company project – Facilitator feedback Phase 1
		Make modularity by addressee and steps explicit	Expert discussions – Expert 1
Steps	Preparation phase at beginning of steps	Include organizational check-in at beginning of each step	Company project – Facilitator feedback Phase 1
		Allow for prioritization of low-hanging fruits	Company workshops – Follow-up discussion
		Limited resources require prioritization	Company project – Facilitator feedback Phase 2
	Explanations for usage of supporting materials	Explain in more detail how to use supporting material	Company project – Facilitator feedback Phase 1
	Filled templates with examples	Examples would help to fill templates	Company workshops – Follow-up discussion, Company project – Facilitator feedback Phase 1
		Examples allow to show breadth and levels of potential results	Expert discussions – Experts 1,2, Company project – Facilitator feedback Phase 1
Overarching	Stronger differentiation between one-off practices and lasting routines	Evolving results, and deep integration more explicit	Expert discussions – Expert 3
	Potential parallelization and split by objectives in Step 2 and 3 described	Choosing objectives more explicit	Expert discussions – Expert 3
		Deviating duration of operationalization and implementation	Company project – Facilitator feedback Phase 2
	Transition to continuity explained in Introduction and Step 3	Explicit end of application and transition from Guide application into continuity	Company project – Facilitator feedback Phase 1

The feedback of the operational user of the Guide (master's student) saw the core value of the Guide compared to theory-based approaches found in the literature in the "structured derivation of objectives" and the "assistance in deriving concrete practices" (Herrmann, 2025, p. 69, trans.)[19]. The Guide was found to be "comprehensible and logical" (Herrmann, 2025, p. 69, trans.)[20], while more detailed examples to clarify terms, and a visualized delimitation of the templates for operationalization and implementation due to the strong interdependencies, as well as a German translation were suggested to increase "certainty in application" (Herrmann, 2025, p. 69, trans.)[21]. Early prioritization was identified as key to focus resources and coordinate the time-intensive collaboration with decision makers. In addition, decision makers introduced associatively developed objectives during the course of the project, which created new uncertainties about how to handle them, suggesting their explicit incorporation into the Guide. With respect to the support provided, the value of guiding questions, success criteria, and check sheets was highlighted. The student suggested developing accompanying tools, e.g., Excel sheets to document the objectives that could further support the application of the Guide and, if optional, without compromise on flexibility. In addition, continuous collaboration with the author was considered helpful for the application of the Guide. (Herrmann, 2025)[22]

The project lead's perspective differs from that of the operational user as it evaluates the Guide based on the collaboration with the operational user, not directly. The project lead described the "high relevance" of the topic of sustainability for the company and argued the motivation for the application of the Guide with the "great need to approach the issue of sustainability in product engineering in a systematic and methodological manner." The project lead highlighted the examples introduced in the third version as helpful, but could not further elaborate on the comprehensibility of the Guide due to the indirect exposure. With regard to applicability, two aspects were highlighted. First, the transition from Guide application to continuity was raised during the joint discussions and implemented in the third version of the Guide. Second, the templates for Step 1, "Understanding", were evaluated as "self-explaining" and "simple to apply," while the templates for the other steps were regarded as helpful but required additional context, which was provided through the Guide (or by the author during development). Overall, the support provided through the application of the Guide "has helped to systematically and methodologically approach the topic

19 Co-supervised master's thesis (unpublished)
20 Co-supervised master's thesis (unpublished)
21 Co-supervised master's thesis (unpublished)
22 Co-supervised master's thesis (unpublished)

of sustainability in product engineering, define goals, and establish concrete measures for implementation.” Additional feedback from the project lead addressed the dependency of this perspective on the operational use of the Guide mentioned at the beginning, suggesting studies with users of varying experience in sustainability action or the application of similar guides.

Eleven decision makers participated in the presentation of the project results. Of these, nine filled the post-project survey, of which four had management positions and five had expertise-focused roles in several functions involved in product engineering. The responses evaluating the results of the company project included the project lead (junior decision maker) and the sponsor (senior decision maker). The understanding was positively evaluated, with no disagreement that the success criteria are met by the objectives that were developed based on company-specific opportunities and risks. A similar picture is shown in the responses regarding the proposed action derived from this understanding. The results also reduced the uncertainties of seven of the nine decision makers regarding targeted sustainability action. Moreover, the results were found to contribute to targeted sustainability action by eight out of nine decision makers. The responses regarding success criteria[23] and the objectives of the Guide are visualized in Figure 8.5. The two artifacts (checklist and work instruction) were found to be comprehensible, intuitive, and contributing to the respective objective. The decision makers stated that further support is needed in involving “all relevant groups in execution” (trans.), in establishing a “mindset on the topic sustainability” (trans.) and in developing a “comprehensive definition of the term sustainability” (trans.) for the company. (Herrmann, 2025)[24]

The first phase of the company project with a planning focus was already found valuable as it exposed multiple aspects to be detailed to allow the application of the Guide (see Table 8.2). In the second phase, adjustments could be directly applied in the project and at the same time incorporated into the Guide, as feedback was continuously collected and discussed. Two conceptual aspects stood out (see also Table 8.2) in this regard. Prioritization, which was anticipated to be relevant based on previous studies, remained a point of discussion due to the limited resources in the project. Furthermore, since the efforts were driven through the high level of collaboration with decision makers, this prioritization also required a parallelization of

[23] At the time of the survey, the success criterion “context-specific” was called “context-dependent”, and “long-term oriented” was called “long-term”, which have been updated in Figure 8.5 to enhance traceability. The questionnaire used also included addressee-specific additions to “collaborative” and “integrated” and can be found in Appendix A.3.

[24] Co-supervised master’s thesis (unpublished)

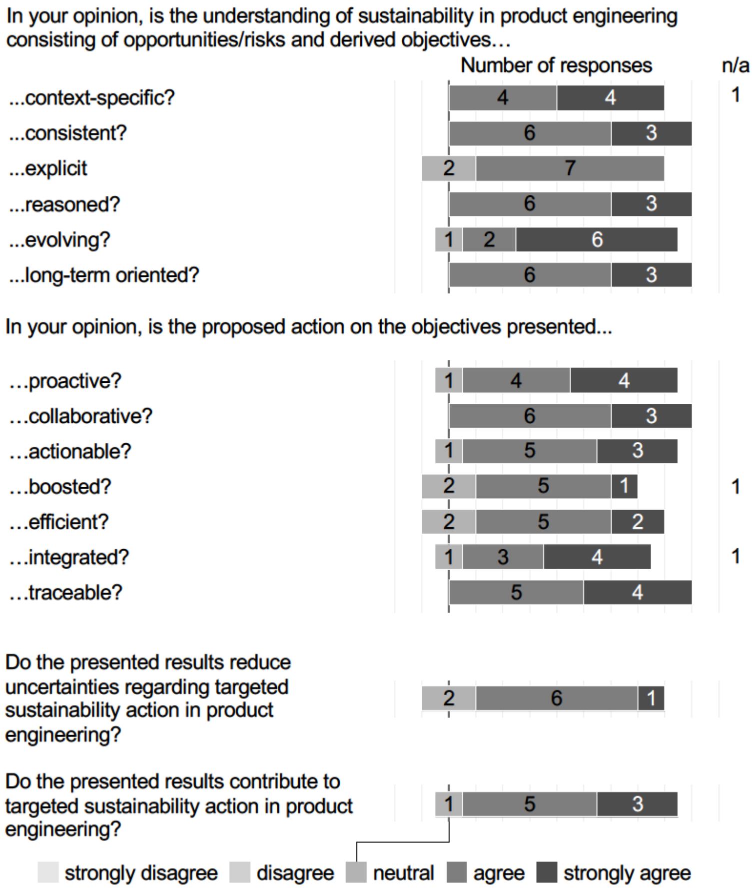

Figure 8.5: Results of the Post-project Survey Filled by the Involved Decision Makers (n=9)

Steps 2 and 3 to accelerate the initiation of action, which introduced a more explicit split among the addressed objectives in these steps of the Guide.

Overall, the evaluation as part of the company project showed that the project results met the success criteria and that the objectives of reducing the uncertainty of decision makers and supporting them in initiating targeted sustainability action could be achieved. At the same time, with regard to the company, it was found that broader ongoing efforts are needed to drive transformational changes throughout the organization, again suggesting the strong interdependency between the project setting and the solution space for targeted sustainability action (see also Chapter 8.2.3). Moreover, it allowed for comprehensive improvements to the Guide and indicated additional opportunities for potential future versions, including more detailed template examples, translations, and accompanying tools.

8.5 Interim Conclusions

Supporting targeted sustainability action in product engineering addresses the second research need and the fourth research question of this thesis: *How can decision makers be supported in addressing their uncertainty about targeted sustainability action and initiating targeted sustainability action in product engineering?*
To answer this research question, the findings on targeted sustainability action in product engineering from the previous chapters were synthesized, resulting in a Guide for decision makers. This Guide addresses the main challenge of this thesis on two levels. First, it provides guidance through all key decisions in understanding, operationalizing, and implementing targeted sustainability action with challenges, success criteria, guiding questions, and further details to address uncertainties about targeted sustainability action and initiate it. Second, the design of the Guide aims for minimal and explicit presuppositions, a balance between complexity and manageability, and the provision of educational and accessible information to not compromise on the success criteria and overcome the main challenge of this thesis when applied.
The Guide was developed in three studies, each with a distinctive focus based on their individual setting, the third resulting in its current version which can be found in its entirety in Appendix A.1. The first study (see Chapter 8.2) in the form of company workshops allowed a live joint application of the first version of the synthesized support. The surveys and follow-up discussions confirmed the general direction of the Guide's development and provided early practical feedback enabling further detailing of the support into an actual Guide. The second study included expert discussions based on a second version of the support that provided valuable feedback from an company-external perspective on the relevance, comprehensibility, and applicability

of the Guide, which could be incorporated into the third version of the Guide in document format. The third study, a company project, is characterized by an integration of support development and application, which enabled detailed feedback on applicability that could be directly discussed and incorporated into the Guide. The results developed during the company project for each of the steps were evaluated by the decision makers involved, who confirmed that they reduced uncertainties regarding targeted sustainability action and contributed to the initiation of targeted sustainability action.

Overall, the evaluations showed that a comprehensible support could be developed to address the uncertainty of decision makers, which if applied can lead to a reduction of uncertainties regarding targeted sustainability action and contribute to its initiation. However, the development of the Guide and these initial applications all involved a close collaboration with the author, while executing a project solely based on a written document can be expected to be more challenging, especially for facilitators with little experience. This thesis might introduce more details that can potentially equip inexperienced facilitators with additional background for a standalone application of the Guide. Hence, standalone applications should be explored in further studies with facilitators with varying experience in sustainability action and/or comparable endeavors to identify potential challenges. In these studies, the feedback on balancing manageability and complexity, especially suggesting more detailed guidance (e.g., through more detailed templates, examples, tools, and references) should also be explored further. Even with explicit presuppositions, an uncritical adoption of such detailed support can be tempting, leading to a trade-off with promoting a critical discourse, which should be investigated. “In addition, further studies might … include comparative studies between decision makers who use and do not use the guide” (Jäckle et al., 2025, p. 9) to understand its impact in more detail.

9 Conclusions and Outlook

9.1 Summary

Starting from the practical challenge of decision makers facing uncertainty about targeted sustainability action in product engineering, leaving them exposed to potentially untouched risks and opportunities emerging from sustainability demands, a problem-centered research project has been conducted to address this uncertainty, which is presented in this thesis.

As a basis for analyzing conceptions of sustainability in product engineering, common conceptions of product engineering and sustainability were discussed. No consensus on or convergence of the conceptions of sustainability in product engineering could be identified. Therefore, the underlying understanding of publications in the field was analyzed. Although no implicitly shared understanding could be identified, the results of this analysis suggested a broad conception of sustainability with a consistent and context-specific narrowing of action. Against this background, existing support was categorized and discussed, resulting in the research gap, which can be summarized as the main challenge addressed by this thesis, namely, developing broad, yet context-specific and actionable support for decision makers to address their uncertainties and initiate targeted sustainability action. Overcoming this challenge would bridge the research gap and enable decision makers to address their uncertainty and initiate targeted sustainability action.

Tackling this challenge involved addressing two research needs. First, the identification of generalizable aspects – in terms of transferability to other contexts – of targeted sustainability action that do not compromise on overcoming the challenge, and second, the development of a support that addresses the uncertainties of decision makers and supports them in initiating targeted sustainability action. The two research needs were further broken down into four research questions based on the knowledge gained in the initial analyses, splitting the first need into generalizable aspects of understanding, operationalizing and implementing targeted sustainability action, while covering the development of the support by a fourth research question.

Due to the intention to support decision makers on targeted sustainability action in product engineering, the research project itself was organized along the DRM (Blessing and Chakrabarti, 2009) and the iDSDM (Marxen, 2014). To answer the research questions in a way that overcomes the challenge required a research approach that allowed a clear action orientation (actionable) and the consideration of context-specific circumstances (context-specific), but introduced few presuppositions (broad). Therefore, as the main source of data for the DS I, an interview study with 25 interviews was conducted covering multiple decision-maker perspectives in four case companies, as well as the perspectives of experienced consultants. The analysis of the interview data followed a grounded theory approach based on the Gioia Methodology (Gioia et al., 2013), while literature reviews with a focus on understanding and operationalizing sustainability action were used to prepare the semi-structured interviews, leading to a predominantly inductive approach. The support was developed and applied in early iterations of PS and DS II through workshops, expert discussions, and a company project that resulted in the third and final version of the Guide for decision makers, attached in Appendix A.1.

Understanding targeted sustainability action in product engineering was found to pose a challenge for decision makers in coping with missing materiality amid complexity and uncertainty. This materiality can be achieved through an understanding of targeted sustainability action that is context-specific, consistent, long-term oriented, evolving, reasoned, and explicit. Therefore, targeted sustainability action was defined as conscious action or inaction that contributes to such an understanding or is derived from it. Moreover, it implied that the support should guide decision makers in developing their own context-specific understanding instead of merely acting based on a given understanding.

Operationalizing targeted sustainability action requires decision makers to create clarity on action despite immaturity and uncertainty in this action. This clarity can be achieved through a proactive, actionable, and collaborative operationalization. Targeted sustainability action consists of practices that constitute continuous routines derived from or contributing to a context-specific understanding of targeted sustainability action. These practices and routines are the intended outcome of the support application and allow decision makers to expand or reduce the time frame taken into account for conscious decision making.

Implementing targeted sustainability action poses the challenge for decision makers to be pragmatic rather than comprehensive when faced with uncertainty. This pragmatism can be achieved through a boosted, efficient, integrated, and traceable implementation. Targeted sustainability action is initiated by establishing practices and the facilitation thereof, which details what the support should help decision makers with.

Supporting targeted sustainability action addresses the second research need and builds on the generalizable aspects identified in the pursuit of addressing the first research need. Therefore, the main challenge of this thesis (broad, yet context-specific, and actionable support) was addressed in two ways: First, by developing support for decision makers on understanding, operationalizing, and implementing targeted sustainability action. And second, by designing the actual support in a way that does not compromise this intended support. This actual support was embodied in a Guide that supports decision makers, with success criteria, guiding questions, and complementary details throughout the three steps to address their uncertainty and initiate targeted action. The initial application of the Guide in the workshops and the company project, as well as the expert discussions, allowed for early refinement based on decision makers' feedback. The evaluations in workshops and the company project showed that the application of the Guide and its results met the success criteria in all three steps, reduced the uncertainties of the decision makers involved, and was expected to contribute to targeted sustainability action in the company. Building on these findings and to further develop the Guide, future studies should explore standalone applications, comparative studies, and review its level of detail under varying conditions, such as level of facilitator experience.

9.2 Conclusions

With the Guide, this thesis addresses the main challenge to bridge the gap in the literature of broad, yet context-specific and actionable support. With the inductively developed generalizable aspects – in terms of transferability to other contexts – of targeted sustainability action, this thesis not only addresses the first research need in order to develop this Guide, but thereby also introduces a consistently action-oriented perspective on sustainability in product engineering to the academic literature.

The problem-centered approach used in this thesis led to novel insights into sustainability action in product engineering across understanding, operationalization, and implementation that add to the existing literature. Understanding targeted sustainability action introduces a new context-specific company perspective on sustainability in product engineering, as well as a new leeway in coping with sustainability demands, instead of fostering the adoption of a pre-fixed understanding of sustainability action. Operationalizing targeted sustainability action introduces continuous routines that put the practices of sustainability action into a new action-oriented relation, with conscious decision making at the core. Implementing targeted sustainability action introduces a new pragmatism in sustainability action instead of aiming for theoretical comprehensiveness and contributes to existing literature by detailing the initiation and facilitation of such action.

Overall, targeted sustainability action with all its new aspects also sheds a new light on conceptualizing the maturity of sustainability action. Instead of measuring the maturity of sustainability action based on the extent to which a pre-fixed conception of sustainability is fulfilled, the maturity of targeted sustainability action is measured by a convincing rationale grounded in company-specific needs. This also means that the maturity of targeted sustainability action is not measured by the radicality of decisions, but by how consciously these decisions are made. Thus, it is also not measured by the degree to which an objective is achieved but by whether targeted action is initiated to achieve it.

For decision makers, the identified generalizable aspects of targeted sustainability action open up a new approach to sustainability in product engineering because they represent an explicitly action-oriented company perspective, which has several implications.
First, it acknowledges the variety of dynamic and not necessarily consistent demands for sustainability action, which allows decision makers to navigate these demands and associated perspectives. Thus, the identified aspects of targeted sustainability action also emphasize the entrepreneurial character of sustainability action.
Second, it acknowledges that an academic perspective is also incomplete and that proposed approaches based on pre-fixed sustainability conceptions are bound to presuppositions and sometimes even implicit moral judgments as part of preconceived ambitions. Targeted sustainability action also helps decision makers in leveraging these academic approaches and the support they offer, as it enables them to compare the presuppositions of academic approaches to their context-specific conditions, allowing for an informed and targeted application of academic approaches rather than an uncritical adoption.
Third, this explicit company perspective also emphasizes critical reflection and conscious decision making at appropriate levels and functions, where responsibility for these decisions and related action can be taken, rather than deferring these decisions within the organization. Thereby, clarity on action can be created under uncertainty. This is also closely associated with the collaborative character of targeted sustainability action, as the ability to resolve a conflict differs among decision makers within an organization. For example, an operational engineer should only be expected to resolve a conflict if a technical solution can be expected.
Fourth, this perspective also emphasizes the challenge of conceptual complexity in targeted sustainability action. This complexity is tackled through a material understanding and clarity in operationalization, which in turn enables a pragmatic implementation of targeted sustainability action. Oversimplification in understanding and operationalization, e.g., through a pre-fixed conception of sustainability or generic approaches, may seem to yield quick results but can lead to persistent complexity in the implementation of targeted sustainability action, and thus hinder it.
In summary, the generalizable aspects and the Guide support decision makers in understanding sustainability demands for what they are and addressing them in a targeted manner by initiating targeted sustainability action in product engineering. This enables decision makers to account for the entrepreneurial character of sustainability action. Thus, this thesis surpasses existing literature by conveying how to act on actual sustainability demands, instead of just presenting another conception of sustainability that may or may not be adopted. Hence, it addresses the uncertainty of decision makers in a new way, enabling them to exploit opportunities and mitigate risks emerging from sustainability demands in a targeted manner.

9.3 Limitations and Outlook

Due to its focus on product engineering within established manufacturing companies in Europe and the author's background, this research only illuminates a limited number of perspectives and does not resolve decision makers' uncertainties on targeted sustainability action in its entirety or in a universal way. Numerous additional studies could be considered to detail or broaden this picture.

To detail targeted sustainability action in product engineering, additional studies could further explore the generalizable aspects identified – in terms of transferability to other contexts – and improve or adjust the support developed as appropriate, as described in Chapter 9.1. Moreover, the collected interview data could be analyzed with specific foci, e.g., comparing perspectives across case companies, the cases with each other, or possibly examining individual aspects of sustainability action and/or product engineering to derive additional insights on these aspects. To broaden the understanding of targeted sustainability action, additional studies could be conducted in other regions or industries, but also with the inclusion of additional functions and perspectives.

Furthermore, that the research was conducted between 2022 and 2025 can have a significant influence on the transferability of the results presented in this thesis, as sustainability demands and action in companies and their product engineering are evolving rapidly. Thus, the uncertainties and priorities of decision makers also change over time. Therefore, additional studies could also examine whether the findings can be transferred to potentially new types of demands and action in product engineering beyond sustainability.

In addition, future studies might also explore the implications of this thesis on product engineering research. In this thesis, product engineering was defined in line with the KaSPro – Karlsruhe School of Product Engineering and described through a practice-theoretical lens that allowed the application of grounded-theory-inspired approaches to openly explore sustainability action. Thus, the results are compatible with both perspectives, enabling the examination of theoretical implications of this research in engineering and organization sciences, but also the exploration of the synergies emerging from combining these perspectives.

From an engineering perspective, for example, a systematic exploration of innovation related to targeted sustainability action could further empower decision makers to take advantage of opportunities and resolve conflicting demands. Furthermore, aspects of targeted sustainability action could be examined from the perspective of related research fields in product engineering, such as foresight, product design, or validation, in order to explore additional implications of targeted sustainability action in product engineering, considering the rich existing research in these fields. Similarly, from an organizational perspective, the interdependence of strategy praxis and product engineering praxis could be examined. Such research, especially in conjunction, could support a better understanding of product engineering as a part of organizations. In particular, the evolution of product engineering over time and its transformation represent a promising field of research to understand product engineering beyond processes. Thus, in the context of the KaSPro, the iPeM – integrated Product engineering Model and the interdependencies between its layers could be investigated further, especially with respect to the strategy layer. Building on the conception of product engineering employed in this thesis, the system of resources as part of the operation system and the interface to the system of objectives could be detailed across layers from an action-oriented perspective to further explore modeling the relationship between product engineering, the broader organization, and its context. Moreover, the use of the model of SGE – System Generation Engineering could be examined to describe the evolution of product engineering and its operation system over time, potentially in generations.

However, more important than broadening and detailing the findings of this thesis could be taking a step back and reflecting on the implications that the research carried out could possibly have on further advancing research on sustainability action in product engineering. When demands or ambitions are (implicitly) presupposed in publications, they should be made explicit, no matter what perspective they reflect. And, the reasons for reflecting a perspective should be explained so that decision makers can compare it with their own intentions. Otherwise, and especially under uncertainty, there is a risk that the support provided by a publication will be misunderstood as demand or vice versa. This could lead to a further divergence between academic research and product engineering practice especially with respect to sustainability action. To counteract this divergence, a healthy error culture is also necessary in academia, just as it is in targeted sustainability action itself.

The author hopes that this thesis will be challenged on the basis of its reasoning, so that the concept of targeted sustainability action can be further refined and evolved to better support decision makers. Moreover, he hopes that this thesis inspires others to recognize uncertainty as a key topic in sustainability research, to think about the presuppositions of support being developed with respect to varying decision makers' intentions, and to conduct pragmatic problem-centered research to further understand product engineering practice and support decision makers on its challenges (see also Jäckle et al., 2025).

Bibliography

Aguiar, M. F., Jugend, D. (2022). Circular product design maturity matrix: A guideline to evaluate new product development in light of the circular economy transition. *Journal of Cleaner Production*, *365*, Article 132732. https://doi.org/10.1016/j.jclepro.2022.132732

Aguiar, M. F., Mesa, J. A., Jugend, D., Pinheiro, M., Fiorini, P. D. C. (2021). Circular product design: strategies, challenges and relationships with new product development. *Management of Environmental Quality: An International Journal*, *33*(2), 300–329. https://doi.org/10.1108/MEQ-06-2021-0125

Ahmadi-Gh, Z., Bello-Pintado, A. (2021). The Effect of Sustainability on New Product Development in Manufacturing—Internal and External practices. *Administrative Sciences*, *11*(4), Article 115. https://doi.org/10.3390/admsci11040115

Albers, A. (2010, April 12–16). Five Hypotheses about Engineering Processes and their Consequences. In I. Horváth, F. Mandorli, Z. Rusák (Eds.), *Proceedings of TMCE 2010 Symposium* (pp. 343–356). Ancona, Italy. https://tmce.io.tudelft.nl/pages/proceedings/2010.pdf

Albers, A., Burkardt, N., Meboldt, M., Saak, M. (2005, August 15–18). Spalten problem solving methodology in the product development. In A. Samuel W. Lewis (Eds.), *Proceedings ICED 05, the 15th International Conference on Engineering Design.* Melbourne, Australia. https://doi.org/10.5445/IR/1000007075

Albers, A., Bursac, N., Wintergerst, E. (2015, March 15–17). Product Generation Development - Importance and Challenges from a Design Research Perspective. In N. Mastorakis C. W. S. To (Eds.), *New Developments in Mechanics and Mechanical Engineering* (pp. 16–21). Vienna, Austria. https://www.inase.org/library/2015/vienna/MECH.pdf

Albers, A., Fahl, J., Hirschter, T., Endl, M., Ewert, R., Rapp, S. (2020). Model of PGE – Product Generation Engineering by the Example of Autonomous Driving. *Procedia CIRP*, *91*, 665–677. https://doi.org/10.1016/j.procir.2020.03.113

Albers, A., Gausemeier, J. (2012). Von der fachdisziplinorientierten Produktentwicklung zur Vorausschauenden und Systemorientierten Produktentstehung (Institute of Product Engineering, Trans.). In R. Anderl, M. Eigner, U. Sendler, R. Stark (Eds.), *Smart Engineering* (pp. 17–29). Springer. https://doi.org/10.1007/978-3-642-29372-6_3

Albers, A., Lohmeyer, Q., Ebel, B. (2011, August 15–19). Dimensions of objectives in interdisciplinary product development projects. In S. J. Culley, B. J. Hicks, T. C. McAloone, T. J. Howard, J. Clarkson

(Eds.), *Proceedings of the 18th International Conference on Engineering Design (ICED 11)* (Vol. 2, pp. 256–265). Lyngby/Copenhagen, Denmark. https://www.designsociety.org/download-publication/30476/dimensions_of_objectives_in_interdisciplinary_product_development_projects

Albers, A., Rapp, S. (2022). Model of SGE: System Generation Engineering as Basis for Structured Planning and Management of Development. In D. Krause E. Heyden (Eds.), *Design Methodology for Future Products* (pp. 27–46). Springer. https://doi.org/10.1007/978-3-030-78368-6_2

Albers, A., Reiss, N., Bursac, N., Richter, T. (2016). iPeM – Integrated Product Engineering Model in Context of Product Generation Engineering. *Procedia CIRP*, *50*, 100–105. https://doi.org/10.1016/j.procir.2016.04.168

Albers, A., Tusch, L., Jäckle, M., Seidler, M., Kempf, C. (2024). Circularity in product engineering – towards a forward-looking approach across product generations. *Proceedings of the Design Society*, *4*, 1–12. https://doi.org/10.1017/pds.2024.3

Ali, S., Poulova, P., Yasmin, F., Danish, M., Akhtar, W., Javed, H. (2020). How Big Data Analytics Boosts Organizational Performance: The Mediating Role of the Sustainable Product Development. *Journal of Open Innovation: Technology, Market, and Complexity*, *6*(4), Article 190. https://doi.org/10.3390/joitmc6040190

Alquist, J. L., Baumeister, R. F. (2024). Dealing with uncertain situations. *The Journal of Positive Psychology*, *19*(6), 923–946. https://doi.org/10.1080/17439760.2023.2282781

Arslan, M., Bursac, N., Killer, B., Albers, A. (2018, June 30–July 4). Developing R&D-Strategies for Future Innovations: Activities in the Context of Technological Transformation and PGE - Product Generation Engineering. In *R&D Management Conference 2018.* Milan, Italy. https://www.researchgate.net/publication/326156514_Developing_RD-Strategies_for_Future_Innovations_Activities_in_the_Context_of_Technological_Transformation_and_PGE_-_Product_Generation_Engineering

Arslan, M., Haug, F., Heitger, N., Kraemer, L., Albers, A. (2016, July 3–6). Don't get stuck in complexity: Coping with strategic complexity in the context of Product Generation Engineering. In *R&D Management Conference 2016.* Cambridge, United Kingdom. https://publikationen.bibliothek.kit.edu/1000068305

ATLAS.ti. (2024). *ATLAS.ti.* (Version 24.1.1) [Software]. ATLAS.ti Scientific Software Development GmbH. https://atlasti.com/

Balikci, A., Borgianni, Y., Maccioni, L., Nezzi, C. (2021). A Framework of Unsustainable Behaviors to Support Product Eco-Design. *Sustainability*, *13*(20), Article 11394. https://doi.org/10.3390/su132011394

Benabdellah, A. C., Benghabrit, A., Bouhaddou, I., Benghabrit, O. (2020). Design for relevance concurrent engineering approach: integration of IATF 16949 requirements and design for X techniques. *Research in Engineering Design*, *31*(3), 323–351. https://doi.org/10.1007/s00163-020-00339-4

Benabdellah, A. C., Zekhnini, K., Cherrafi, A., Garza-Reyes, J. A., Kumar, A. (2021). Design for the environment: An ontology-based knowledge management model for green product development. *Business Strategy and the Environment*, *30*(8), 4037–4053. https://doi.org/10.1002/bse.2855

Bierwisch, A., Huter, L., Pattermann, J., Som, O. (2021). Taking Eco-Innovation to the Road-A Design-Based Workshop Concept for the Development of Eco-Innovative Business Models. *Sustainability*, *13*(16), Article 8811. https://doi.org/10.3390/su13168811

Billing, F., Windhagen, E., Petersen, G. (2021). *Germany 2030: Creative Renewal.* McKinsey & Company. https://www.mckinsey.de/publikationen/deutschland2030-kreative-erneuerung

Bland, R., Corb, L., Granskog, A., Nauclér, T., Siccardo, G. (2023). *Scaling green businesses: Next moves for leaders.* McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/scaling-green-businesses-next-moves-for-leaders

Blessing, L. T., Chakrabarti, A. (2009). *DRM, a Design Research Methodology*. Springer. https://doi.org/10.1007/978-1-84882-587-1

Bohnsack, R., Kolk, A., Pinkse, J., Bidmon, C. M. (2020). Driving the electric bandwagon: The dynamics of incumbents' sustainable innovation. *Business Strategy and the Environment*, *29*(2), 727–743. https://doi.org/10.1002/bse.2430

Boorsma, N., Peck, D., Bakker, T., Bakker, C., Balkenende, R. (2022). The strategic value of design for remanufacturing: a case study of professional imaging equipment. *Journal of Remanufacturing*, *12*(2), 187–212. https://doi.org/10.1007/s13243-021-00107-0

Broman, G. I., Robèrt, K.-H. (2017). A framework for strategic sustainable development. *Journal of Cleaner Production*, *140*, 17–31. https://doi.org/10.1016/j.jclepro.2015.10.121

Brones, F., Zancul, E., Carvalho, M. M. (2021). Insider action research towards companywide sustainable product innovation: ecodesign transition framework. *International Journal of Managing Projects in Business*, *14*(1), 150–178. https://doi.org/10.1108/IJMPB-02-2020-0043

Capomaccio, A.-L., Reyes Carrillo, T., Richet, S. (2023). LAYING THE FOUNDATIONS FOR A METHODOLOGY TO INTEGRATE AND MANAGE THE CORPORATE SOCIAL RESPONSIBILITY ISSUES OF A COMPANY IN THE

PRODUCT DEVELOPMENT PROCESS. *Proceedings of the Design Society*, *3*, 2415–2424. https://doi.org/10.1017/pds.2023.242

Cavaciuti-Wishart, E., Heading, S., Kohler, K., Zahidi, S. (2024). *The Global Risks Report 2024* (No. 19). World Economic Forum. https://www.weforum.org/publications/global-risks-report-2024

Ceptureanu, S. I., Ceptureanu, E. G., Popescu, D., Orzan, O. A. (2020). Eco-innovation Capability and Sustainability Driven Innovation Practices in Romanian SMEs. *Sustainability*, *12*(17), Article 7106. https://doi.org/10.3390/su12177106

Ceschin, F., Gaziulusoy, I. (2016). Evolution of design for sustainability: From product design to design for system innovations and transitions. *Design Studies*, *47*, 118–163. https://doi.org/10.1016/j.destud.2016.09.002

Chang, T.-W., Yeh, Y.-L., Li, H.-X. (2020). How to Shape an Organization's Sustainable Green Management Performance: The Mediation Effect of Environmental Corporate Social Responsibility. *Sustainability*, *12*(21), Article 9198. https://doi.org/10.3390/su12219198

Charter, M., Tischner, U. (Eds.). (2001). *Sustainable Solutions: Developing Products and Services for the Future*. Routledge. https://doi.org/10.4324/9781351282482

Chatty, T., Faludi, J. (2020). PERCEPTION of SUSTAINABLE DESIGN INTEGRATION BENEFITS AMONG INDUSTRY PRODUCT DEVELOPMENT TEAMS: A CASE STUDY. *Proceedings of the Design Society: DESIGN Conference*, *1*, 2475–2483. https://doi.org/10.1017/dsd.2020.54

Chatty, T., Harrison, W., Ba-Sabaa, H. H., Faludi, J., Murnane, E. L. (2022). Co-Creating a Framework to Integrate Sustainable Design into Product Development Practice: Case Study at an Engineering Consultancy Firm. *Sustainability*, *14*(15), Article 9740. https://doi.org/10.3390/su14159740

Christmann, P. (2000). Effects of "Best Practices" of Environmental Management on Cost Advantage: The Role of Complementary Assets. *The Academy of Management Journal*, *43*(4), 663–680. https://www.jstor.org/stable/1556360

Cillo, P., Verona, G. (2022). The strategic organization of innovation: State of the art and emerging challenges. *Strategic Organization*, *20*(4), 743–756. https://doi.org/10.1177/14761270221119113

Corb, L., Granskog, A., Nauclér, T., Pacthod, D. (2023). *Full throttle on net zero: Creating value in the face of uncertainty.* McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/full-throttle-on-net-zero-creating-value-in-the-face-of-uncertainty

Costa, J., Freire, P., Reis, J. (2021). Open Innovation and User-Community as Enhancers of Sustainable Innovation Ecosystems. In A. M. Tavares, R. G. Thomé, L. F. Barbastefano, J. C. Scavarda, M. Gonçalves dos Reis, P. C. Amorim (Eds.), *Industrial Engineering and Operations Management* (pp. 65–77). Springer. https://doi.org/10.1007/978-3-030-78570-3_5

Crispeels, P., Inia, D., Legge, H., Nauclér, T., Radtke, P. (2023). *Decarbonize and create value: How incumbents can tackle the steep challenge.* McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/decarbonize-and-create-value-how-incumbents-can-tackle-the-steep-challenge

Dabić, M., Obradović, T., Vlačić, B., Sahasranamam, S., Paul, J. (2022). Frugal innovations: A multidisciplinary review & agenda for future research. *Journal of Business Research*, *142*, 914–929. https://doi.org/10.1016/j.jbusres.2022.01.032

D'Angelo, V., Magnusson, M. (2021). A Bibliometric Map of Intellectual Communities in Frugal Innovation Literature. *IEEE Transactions on Engineering Management*, *68*(3), 653–666. https://doi.org/10.1109/TEM.2020.2994043

Daniyan, I., Mpofu, K., Ramatsetse, B., Gupta, M. (2021). Review of life cycle models for enhancing machine tools sustainability: lessons, trends and future directions. *Heliyon*, *7*(4), Article e06790. https://doi.org/10.1016/j.heliyon.2021.e06790

Delaney, E., Liu, W., Zhu, Z., Xu, Y., Dai, J. S. (2022). The investigation of environmental sustainability within product design: a critical review. *Design Science*, *8*, Article e15. https://doi.org/10.1017/dsj.2022.11

Delesposte, J. E., Rangel, L. A. D., Meiriño, M. J., Narcizo, R. B., Alencar Junior, A. A. M. (2021). Use of multicriteria decision aid methods in the context of sustainable innovations: bibliometrics, applications and trends. *Environment Systems & Decisions*, *41*(4), 501–522. https://doi.org/10.1007/s10669-021-09814-2

Department of Economic and Social Affairs. (2024). *The Sustainable Development Goals Report 2024.* United Nations. https://unstats.un.org/sdgs/report/2024/

Diaz, A., Reyes, T., Baumgartner, R. J. (2022). Implementing circular economy strategies during product development. *Resources, Conservation and Recycling*, *184*, Article 106344. https://doi.org/10.1016/j.resconrec.2022.106344

Diaz, A., Schöggl, J.-P., Reyes, T., Baumgartner, R. J. (2021). Sustainable product development in a circular economy: Implications for products, actors, decision-making support and lifecycle information management. *Sustainable Production and Consumption*, *26*, 1031–1045. https://doi.org/10.1016/j.spc.2020.12.044

Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. (n.d.). *Industrial alliances.* European Commission, European Union. Retrieved November 2, 2024, from https://single-market-economy.ec.europa.eu/industry/industrial-alliances_en

Doherty, R., Kampel, C., Koivuniemi, A., Pérez, L., Rehm, W. (2023). *The triple play: Growth, profit, and sustainability.* McKinsey & Company. https://www.mckinsey.com/capabilities/strategy-and-corporate-finance/our-insights/the-triple-play-growth-profit-and-sustainability

Dzebo, A., Janetschek, H., Brandi, C., Iacobuta, G. (2019). *Connections between the Paris Agreement and the 2030 Agenda: The case for policy coherence.* Stockholm Environment Institute. https://sdgs.un.org/sites/default/files/2023-01/connections-between-the-paris-agreement-and-the-2030-agenda.pdf

El Dehaibi, N., Herrera, A., Rattanakongkham, D., MacDonald, E. F. (2022). A Test for Product Design Features Perceived as Sustainable to Drive Online Purchasing Decisions. *Journal of Mechanical Design*, *144*(11), Article 111401. https://doi.org/10.1115/1.4054873

European Parliament and Council. (2022). *Amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting* (No. Directive (EU) 2022/2464). European Union. http://data.europa.eu/eli/dir/2022/2464/oj

Evrard, D., Rejeb, H. B., Zwolinski, P., Brissaud, D. (2021). Designing Immortal Products: A Lifecycle Scenario-Based Approach. *Sustainability*, *13*(6), Article 3574. https://doi.org/10.3390/su13063574

Faludi, J., Hoffenson, S., Kwok, S. Y., Saidani, M., Hallstedt, S. I., Telenko, C., Martinez, V. (2020). A Research Roadmap for Sustainable Design Methods and Tools. *Sustainability*, *12*(19), Article 8174. https://doi.org/10.3390/su12198174

Feldman, M., Orlikowski, W. J. (2011). Theorizing Practice and Practicing Theory. *Organization Science*, *22*(5), 1240–1253. https://doi.org/10.1287/orsc.1100.0612

Feldman, M., Pentland, B. T. (2003). Reconceptualizing Organizational Routines as a Source of Flexibility and Change. *Administrative Science Quarterly*, *48*(1), 94–118. https://doi.org/10.2307/3556620

Feldman, M., Worline, M. (2016). The Practicality of Practice Theory. *Academy of Management Learning & Education*, *15*(2), 304–324. https://doi.org/10.5465/amle.2014.0356

Feng, C., Huang, Y., Chen, X. (2022). Sustainable Design for Transforming Sustainability Requirements to Design Parameters Based on Multi-criteria Decision-Making Methodology. In Tan J. (Ed.), *Advances in Mechanical Design* (pp. 933–959). Springer. https://doi.org/10.1007/978-981-16-7381-8_59

Framework Convention on Climate Change. (2015). *Adoption of the Paris Agreement* (No. FCCC/CP/2015/L.9/Rev.1). United Nations. https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

Framework Convention on Climate Change. (2024). *Nationally determined contributions under the Paris Agreement* (No. FCCC/PA/CMA/2024/10). United Nations. https://docs.un.org/en/FCCC/PA/CMA/2024/10

Gallego-García, S., Ren, D., Gallego-García, D., Pérez-García, S., García-García, M. (2022). Dynamic Innovation Information System (DIIS) for a New Management Age. *Applied Sciences*, *12*(13), Article 6592. https://doi.org/10.3390/app12136592

Ganji, E. N., Shah, S., Coutroubis, A. (2020). Sustainable demand chain toward prosperity of NPD projects: a systematic review. *IET Collaborative Intelligent Manufacturing*, *2*(4), 151–163. https://doi.org/10.1049/IET-CIM.2019.0052

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

General Assembly. (2015). *Transforming our World: The 2030 Agenda for Sustainable Development* (No. A/RES/70/1). United Nations. https://documents.un.org/doc/undoc/gen/n15/291/89/pdf/n1529189.pdf

Gioia, D. A. (2021). A Systematic Methodology for Doing Qualitative Research. *The Journal of Applied Behavioral Science*, *57*(1), 20–29. https://doi.org/10.1177/0021886320982715

Gioia, D. A., Corley, K. G., Hamilton, A. L. (2013). Seeking Qualitative Rigor in Inductive Research: Notes on the Gioia Methodology. *Organizational Research Methods*, *16*(1), 15–31. https://doi.org/10.1177/1094428112452151

Global Reporting Initiative. (2021). *The GRI Standards: A Guide for Policy Makers.* https://www.globalreporting.org/media/nmmnwfsm/gri-policymakers-guide.pdf

Glönkler, V., Reick, B., Stetter, R., Till, M., Pfeil, M. (2022). A Contribution to Sustainable Product Development Using the Example of Battery Electric Vehicles. *Sustainability*, *14*(7), Article 3729. https://doi.org/10.3390/su14073729

Granskog, A., Ahlawat, H., Kalavar, S., Agarwal, V. (2024). *Reflections post COP29: The landscape has shifted—are you adapting fast enough?* McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/reflections-post-cop29-the-landscape-has-shifted-are-you-adapting-fast-enough#/

Grant, A., Haider, Z., Raufuss, A. (2023). *Black swans, gray rhinos, and silver linings: Anticipating geopolitical risks (and openings).* McKinsey & Company. https://www.mckinsey.com/capabilities/risk-and-resilience/our-insights/black-swans-gray-rhinos-and-silver-linings-anticipating-geopolitical-risks-and-openings

Hales, C., Gooch, S. (2004). *Managing Engineering Design* (2nd ed.). Springer. https://doi.org/10.1007/978-0-85729-394-7

Hallstedt, S. I. (2017). Sustainability criteria and sustainability compliance index for decision support in product development. *Journal of Cleaner Production*, *140*, 251–266. https://doi.org/10.1016/j.jclepro.2015.06.068

Hallstedt, S. I., Isaksson, O. (2017). Material criticality assessment in early phases of sustainable product development. *Journal of Cleaner Production*, *161*, 40–52. https://doi.org/10.1016/j.jclepro.2017.05.085

Hallstedt, S. I., Isaksson, O., Nylander, J. W., Andersson, P., Knuts, S. (2023). Sustainable product development in aeroengine manufacturing: challenges, opportunities and experiences from GKN Aerospace Engine System. *Design Science*, *9*, Article e22. https://doi.org/10.1017/dsj.2023.22

Hallstedt, S. I., Isaksson, O., Rönnbäck, A. Ö. (2020). The Need for New Product Development Capabilities from Digitalization, Sustainability, and Servitization Trends. *Sustainability*, *12*(23), Article 10222. https://doi.org/10.3390/su122310222

Hallstedt, S. I., Ny, H., Robèrt, K.-H., Broman, G. I. (2010). An approach to assessing sustainability integration in strategic decision systems for product development. *Journal of Cleaner Production*, *18*(8), 703–712. https://doi.org/10.1016/j.jclepro.2009.12.017

Hallstedt, S. I., Thompson, A. W., Lindahl, P. (2013). Key elements for implementing a strategic sustainability perspective in the product innovation process. *Journal of Cleaner Production*, *51*, 277–288. https://doi.org/10.1016/j.jclepro.2013.01.043

Hanski, J., Uusitalo, T., Rantala, T., Hemilä, J. (2024). Sustainability Assessment in Product Design—Perspectives from Finnish Manufacturing Companies. In S. G. Scholz, R. J. Howlett, R. Setchi (Eds.), *Sustainable Design and Manufacturing 2023* (pp. 21–32). Springer. https://doi.org/10.1007/978-981-99-8159-5_3

Hazen, B. T., Russo, I., Confente, I., Pellathy, D. (2021). Supply chain management for circular economy: conceptual framework and research agenda. *International Journal of Logistics Management*, *32*(2), 510–537. https://doi.org/10.1108/IJLM-12-2019-0332

Jäckle, M., Does, E., Tusch, L., Albers, A. (2025). Sustainability in product engineering - a guide to initiate targeted sustainability action. *Proceedings of the Design Society*, *5*, 2961–2970. https://doi.org/10.1017/pds.2025.10310

Jäckle, M., Seidler, M., Tusch, L., Rapp, S., Albers, A. (2023). Towards a Consistent Understanding of Sustainability in Product Engineering - A Systematic Literature Review and Explication Framework. *Procedia CIRP*, *119*, 770–775. https://doi.org/10.1016/j.procir.2023.03.123

Jackson, S. E., Schuler, R. S., Jiang, K. (2014). An Aspirational Framework for Strategic Human Resource Management. *Academy of Management Annals*, *8*(1), 1–56. https://doi.org/10.1080/19416520.2014.872335

Jarzabkowski, P., Kaplan, S., Seidl, D., Whittington, R. (2016). If you aren't talking about practices, don't call it a practice-based view: Rejoinder to Bromiley and Rau in Strategic Organization. *Strategic Organization*, *14*(3), 270–274. https://doi.org/10.1177/1476127016655998

Jarzabkowski, P., Spee, A. P. (2009). Strategy–as–practice: A review and future directions for the field. *International Journal of Management Reviews*, *11*(1), 69–95. https://doi.org/10.1111/j.1468-2370.2008.00250.x

Jarzabkowski, P., Whittington, R. (2008). Hard to disagree, mostly. *Strategic Organization*, *6*(1), 101–106. https://doi.org/10.1177/1476127007087155

Johansson, G., Sundin, E. (2014). Lean and green product development: two sides of the same coin? *Journal of Cleaner Production*, *85*, 104–121. https://doi.org/10.1016/j.jclepro.2014.04.005

Johl, S. K., Toha, M. A. (2021). The Nexus between Proactive Eco-Innovation and Firm Financial Performance: A Circular Economy Perspective. *Sustainability*, *13*(11), Article 6253. https://doi.org/10.3390/su13116253

Jugend, D., Fiorini, P. D. C., Pinheiro, M. A. P., Da Silva, H. M. R., Pais Seles, B. M. R. (2020). Building Circular Products in an Emerging Economy: An Initial Exploration Regarding Practices, Drivers and Barriers. *Johnson Matthey Technology Review*, *64*(1), 59–68. https://doi.org/10.1595/205651320x15706349546439

Kattwinkel, D., Bender, B. (2020). COMPETENCES FOR THE DEVELOPMENT of ECODESIGN PRODUCTS. *Proceedings of the Design Society: DESIGN Conference*, *1*, 1735–1744. https://doi.org/10.1017/dsd.2020.43

Kortus, L., Gutmann, T. (2023). How do firms build dynamic capabilities to develop sustainable products? A multiple case study in the manufacturing industry. *Journal of Cleaner Production*, *415*, Article 137887. https://doi.org/10.1016/j.jclepro.2023.137887

KPMG. (2024). *Addressing the Strategy Execution Gap in Sustainability Reporting: 2024 Sustainability Organization Survey.* https://kpmg.com/kpmg-us/content/dam/kpmg/pdf/2024/kpmg-2024-esg-organization-survey.pdf

Kravchenko, M., Pigosso, D. C. A., McAloone, T. C. (2021). A Trade-Off Navigation Framework as a Decision Support for Conflicting Sustainability Indicators within Circular Economy Implementation in the Manufacturing Industry. *Sustainability*, *13*(1), Article 314. https://doi.org/10.3390/su13010314

Kumar, S. P., Prabir, S. (2022). A DEMATEL Approach to Evaluate the Enablers for Effective Implementation of Ecodesign in Sustainable Product Development: A Case of MSMEs. In A. Sachdeva, P. Kumar, O. P. Yadav, M. Tyagi (Eds.), *Innovative Product Design and Intelligent Manufacturing Systems* (pp. 123–133). Springer. https://doi.org/10.1007/978-981-15-2696-1_12

Kwok, S. Y., Schulte, J., Hallstedt, S. I. (2020). APPROACH FOR SUSTAINABILITY CRITERIA AND PRODUCT LIFE-CYCLE DATA SIMULATION IN CONCEPT SELECTION. *Proceedings of the Design Society: DESIGN Conference*, *1*, 1979–1988. https://doi.org/10.1017/dsd.2020.297

Liu, H., Luo, Y., Geng, J., Yao, P. (2021). Research Hotspots and Frontiers of Product R&D Management under the Background of the Digital Intelligence Era—Bibliometrics Based on Citespace and Histcite. *Applied Sciences*, *11*(15), Article 6759. https://doi.org/10.3390/app11156759

Llanos, A. O., Raven, R., Bexell, M., Botchwey, B., Bornemann, B., Censoro, J., … Yunita, A. (2022). Implementation at Multiple Levels. In F. Biermann, T. Hickmann, C.-A. Sénit (Eds.), *The Political Impact of the Sustainable Development Goals* (pp. 59–91). Cambridge University Press. https://doi.org/10.1017/9781009082945.004

Lubis, M., Fathoni, M., Lubis, A. R. (2020, July 17–19). New Product Development Architectural Framework for Sustainability and Innovation within Telecommunication Industry. In *ICCCM '20: Proceedings of the 8th International Conference on Computer and Communications Management* (pp. 145–150). Singapore. https://doi.org/10.1145/3411174.3411197

Mafimisebi, O. P., Obembe, D., Aluko, O. (2020). Organization and product design pairings: A review of product innovation capabilities, conceptualization, and future directions. *Strategic Change*, *29*(1), 13–24. https://doi.org/10.1002/jsc.2306

Mallalieu, A., Hallstedt, S. I., Isaksson, O., Watz, M., Almefelt, L. (2024). Barriers and enablers for the adoption of sustainable design practices using new design methods – Accelerating the sustainability transformation in the manufacturing industry. *Sustainable Production and Consumption*, *51*, 137–158. https://doi.org/10.1016/j.spc.2024.08.023

Maon, F., Lindgreen, A., Swaen, V. (2021). Developing a sustainability strategic agenda. In S. Markovic, C. Sancha, A. Lindgreen (Eds.), *Handbook of Sustainability-Driven Business Strategies in Practice* (pp. 3–17). Edward Elgar Publishing. https://doi.org/10.4337/9781789908350.00011

Markopoulos, E., Gann, E. L., Kirane, I. S., Vanharanta, H. (2020). Green Capitalism: Democratizing Sustainable Innovation by Recycling Intellectual Capital Energy. In T. Ahram, R. Taiar, V. Gremeaux-Bader, K. Aminian (Eds.), *Human Interaction, Emerging Technologies and Future Applications II* (pp. 507–519). Springer. https://doi.org/10.1007/978-3-030-44267-5_77

Markovic, S., Tollin, K. (2021). Business model innovation for sustainability: the intersections among business models, innovation, and sustainability. In

S. Markovic, C. Sancha, A. Lindgreen (Eds.), *Handbook of Sustainability-Driven Business Strategies in Practice* (pp. 144–157). Edward Elgar Publishing. https://doi.org/10.4337/9781789908350.00021

Marxen, L. (2014). A Framework for Design Support Development based on the integrated Product Engineering Model iPeM. Dissertation. In A. Albers (Ed.), *Forschungsberichte des IPEK – Institut für Produktentwicklung. Systeme, Methoden, Prozesse* (Vol. 74). Karlsruhe Institute of Technology (KIT). https://doi.org/10.5445/IR/1000045823

Mesa, J. A., Esparragoza, I., Maury, H. (2020). Modular architecture principles–MAPs: a key factor in the development of sustainable open architecture products. *International Journal of Sustainable Engineering*, *13*(2), 108–122. https://doi.org/10.1080/19397038.2019.1634157

Mesquita, P. L., Missimer, M. (2021). Social Sustainability Work in Product Development Organizations: An Empirical Study of Three Sweden-Based Companies. *Sustainability*, *13*(4), Article 1986. https://doi.org/10.3390/su13041986

Miller, C., Thomas, B. C., Roeller, M. (2020). Innovation management processes and sustainable iterative circles: an applied integrative approach. *Journal of Work-Applied Management*, *12*(1), 69–90. https://doi.org/10.1108/JWAM-11-2019-0037

Missimer, M., Mesquita, P. L. (2022). Social Sustainability in Business Organizations: A Research Agenda. *Sustainability*, *14*(5), Article 2608. https://doi.org/10.3390/su14052608

Muschik, S. (2011). Development of Systems of Objectives in Early Product Engineering. Dissertation. In A. Albers (Ed.), *Forschungsberichte des IPEK – Institut für Produktentwicklung* (Vol. 50). Karlsruhe Institute of Technology (KIT). https://doi.org/10.5445/IR/1000023768

Nunhes, T. V., Garcia, E. V., Espuny, M., Santos, V. H. M., Isaksson, R., de Oliveira, O. J. (2021). Where to Go with Corporate Sustainability? Opening Paths for Sustainable Businesses through the Collaboration between Universities, Governments, and Organizations. *Sustainability*, *13*(3), Article 1429. https://doi.org/10.3390/su13031429

Obal, M., Morgan, T., Joseph, G. (2020). Integrating sustainability into new product development: The role of organizational leadership and culture. *Journal of Small Business Strategy*, *30*(1), 43–57. https://jsbs.scholasticahq.com/article/26357-integrating-sustainability-into-new-product-development-the-role-of-organizational-leadership-and-culture

Oliveira, A. S., Silva, B. C. S., Ferreira, C. V., Sampaio, R. R., Machado, B. A. S., Coelho, R. S. (2021). Adding technology sustainability evaluation to product development: A proposed methodology and an assessment model. *Sustainability*, *13*(4), Article 2097. https://doi.org/10.3390/su13042097

Orlando, B., Ballestra, L. V., Scuotto, V., Pironti, M., Del Giudice, M. (2022). The Impact of R&D Investments on Eco-Innovation: A Cross-Cultural Perspective of Green Technology Management. *IEEE Transactions on Engineering Management*, *69*(5), 2275–2284. https://doi.org/10.1109/TEM.2020.3005525

Östlin, J., Sundin, E., Björkman, M. (2009). Product life-cycle implications for remanufacturing strategies. *Journal of Cleaner Production*, *17*(11), 999–1009. https://doi.org/10.1016/j.jclepro.2009.02.021

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., … Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*, *372*, Article n71. https://doi.org/10.1136/bmj.n71

Pan, X., Oh, K.-S., Wang, M. (2021). Strategic Orientation, Digital Capabilities, and New Product Development in Emerging Market Firms: The Moderating Role of Corporate Social Responsibility. *Sustainability*, *13*(22), Article 12703. https://doi.org/10.3390/su132212703

Park, J. Y., Perumal, S. V., Sanyal, S., Ah Nguyen, B., Ray, S., Krishnan, R., … Thangam, D. (2022). Sustainable Marketing Strategies as an Essential Tool of Business. *American Journal of Economics and Sociology*, *81*(2), 359–379. https://doi.org/10.1111/ajes.12459

Perpignan, C., Baouch, Y., Robin, V., Eynard, B. (2020). Engineering education perspective for sustainable development: A maturity assessment of cross-disciplinary and advanced technical skills in eco-design. *Procedia CIRP*, *90*, 748–753. https://doi.org/10.1016/j.procir.2020.02.051

Petersen, M. (2021). How Corporate Sustainability Affects Product Developers' Approaches Toward Improving Product Sustainability. *IEEE Transactions on Engineering Management*, *68*(4), 955–969. https://doi.org/10.1109/TEM.2019.2914262

Pratono, A. H. (2022). Reinterpreting excellence for sustainable competitive advantage: the role of entrepreneurial culture under information technological turbulence. *Measuring Business Excellence*, *26*(2), 180–196. https://doi.org/10.1108/MBE-04-2021-0056

Purvis, B., Mao, Y., Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins. *Sustainability Science*, *14*(3), 681–695. https://doi.org/10.1007/s11625-018-0627-5

Ramus, T., Vaccaro, A., Berrone, P. (2021). Time Matters! How hybrid organizations use time to respond to divergent stakeholder demands. *Organization Studies*, *42*(10), 1529–1555. https://doi.org/10.1177/0170840619900341

Relich, M., Adamczyk, J., Dylewski, R., Kister, A. (2024). Case-Based Reasoning in Achieving Sustainability Targets of New Products. *Sustainability*, *16*(4), Article 1502. https://doi.org/10.3390/su16041502

Riesener, M., Kuhn, M., Tittel, J., Schuh, G. (2021, Dec 13–16). Concept for Enhancing the Contribution of Product Development to Organizational Resilience of Manufacturing Companies. In *2021 IEEE International Conference on Industrial Engineering and Engineering Management, IEEM 2021* (pp. 1303–1307). Singapore. https://doi.org/10.1109/IEEM50564.2021.9672979

Riesener, M., Kuhn, M., Tittel, J., Singh, P., Schuh, G. (2023, November 14–17). Design Elements Of Corporate Functions In The Trade-Off Between Efficient Goal Achievement And Prevention Of Disturbance Impacts. In Herberger D. Hubner M. (Eds.), *Proceedings of the Conference on Production Systems and Logistics: CPSL 2023 - 2* (pp. 56–65). Stellenbosch, South Africa. https://doi.org/10.15488/15307

Ropohl, G. (1999). *Allgemeine Technologie: Eine Systemtheorie der Technik* (2nd ed.). Hanser. https://doi.org/10.5445/KSP/1000011529

Rusch, F., Demke, N., Willems, W., Mantwill, F. (2024). Context-based Derivation of Holistic Sustainability Requirements in the Early Phase of Product Development. *Procedia CIRP*, *122*, 306–311. https://doi.org/10.1016/j.procir.2024.01.045

Rusch, M., Schöggl, J.-P., Baumgartner, R. J. (2022). Application of digital technologies for sustainable product management in a circular economy: A review. *Business Strategy and the Environment*, *32*(3), 1159–1174. https://doi.org/10.1002/bse.3099

Sachs, J. D., Lafortune, G., Fuller, G., Iablonovski, G. (2025). *Financing Sustainable Development to 2030 and Mid-Century: Sustainable Development Report 2025.* Sustainable Development Solutions Network, Dublin University Press. https://doi.org/10.25546/111909

Sakao, T., Sundin, E. (2019). How to Improve Remanufacturing? - A Systematic Analysis of Practices and Theories. *Journal of Manufacturing Science and Engineering*, *141*(2), Article 021004. https://doi.org/10.1115/1.4041746

Schulte, J., Hallstedt, S. I. (2018a). Company Risk Management in Light of the Sustainability Transition. *Sustainability*, *10*(11), Article 4137. https://doi.org/10.3390/su10114137

Schulte, J., Hallstedt, S. I. (2018b). Self-Assessment Method for Sustainability Implementation in Product Innovation. *Sustainability*, *10*(12), Article 4336. https://doi.org/10.3390/su10124336

Schulte, J., Knuts, S. (2022). Sustainability impact and effects analysis - A risk management tool for sustainable product development. *Sustainable Production and Consumption*, *30*, 737–751. https://doi.org/10.1016/j.spc.2022.01.004

Schulte, J., Villamil, C., Hallstedt, S. I. (2020). Strategic Sustainability Risk Management in Product Development Companies: Key Aspects and Conceptual Approach. *Sustainability*, *12*(24), Article 10531. https://doi.org/10.3390/su122410531

Schweitzer, F., Meng, Y. (2022). How Collaborating with NGOs Makes Green Innovations More Desirable. *Business & Society*, *62*(2), 363–400. https://doi.org/10.1177/00076503221084733

Schwoy, S., Dutzi, A. (2021). Materiality analysis as the basis for sustainability strategies and reporting - a systematic review of approaches and recommendations for practice. In S. Markovic, C. Sancha, A. Lindgreen (Eds.), *Handbook of Sustainability-Driven Business Strategies in Practice* (pp. 35–58). Edward Elgar Publishing. https://doi.org/10.4337/9781789908350.00013

Science Based Targets initiative. (2024). *SBTi Monitoring Report 2023: Looking back at 2023 and moving forward to 2024 and beyond.* https://sciencebasedtargets.org/resources/files/SBTiMonitoringReport2023.pdf

Shu, E. (2022). Paradoxical framing and coping process on sustainable new product development. *Technovation*, *111*, Article 102392. https://doi.org/10.1016/j.technovation.2021.102392

Skoglund, A., Bohm, S. (2020). Prefigurative Partaking: Employees' Environmental Activism in an Energy Utility. *Organization Studies*, *41*(9), 1257–1283. https://doi.org/10.1177/0170840619847716

Soltész, L., Berényi, L. (2021). Success factors in product development projects: expert opinions. *Journal of Physics: Conference Series*, *1935*(1), Article 012003. https://doi.org/10.1088/1742-6596/1935/1/012003

Spain and the European Commission. (2023). *The update of the nationally determined contribution of the European Union and its Member States.* European Union. https://unfccc.int/sites/default/files/NDC/2023-10/ES-2023-10-17%20EU%20submission%20NDC%20update.pdf

Stammnitz, F. (2025). Structural Change in the Automotive Industry: Guideline for the Strategy Process in medium-sized Companies with a Methodology for asset-based Business Unit Development. Dissertation. In A. Albers S. Matthiesen (Eds.), *Forschungsberichte des IPEK – Institut für Produktentwicklung. Systeme, Methoden, Prozesse* (Vol. 182). Karlsruhe Institute of Technology (KIT). https://doi.org/10.5445/IR/1000180518/V2

Suppipat, S., Hu, A. H. (2022). A scoping review of design for circularity in the electrical and electronics industry. *Resources, Conservation and Recycling Advances*, *13*, Article 200064. https://doi.org/10.1016/j.rcradv.2022.200064

Taticchi, P., Demartini, M. (2021). A Modern Definition of Corporate Sustainability. In P. Taticchi M. Demartini (Eds.), *Corporate Sustainability in Practice* (pp. 65–74). Springer. https://doi.org/10.1007/978-3-030-56344-8_4

Teece, D. J. (1986). Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. *Research Policy*, *15*(6), 285–305. https://doi.org/10.1016/0048-7333(86)90027-2

Teece, D. J., Pisano, G., Shuen, A. (1997). Dynamic Capabilities and Strategic Management. *Strategic Management Journal*, *18*(7), 509–533. http://www.jstor.org/stable/3088148

Trint. (2024). *Trint.* [Software]. Trint Limited. https://trint.com/

Tusch, L., Jäckle, M., Albers, A. (2024, August 12–14). Towards Design for Cross-Generational Remanufacturing: A Literature Review and Concept Proposal. In *Proceedings of NordDesign 2024* (pp. 206–215). Reykjavik, Iceland. https://doi.org/10.35199/NORDDESIGN2024.23

Uemura Reche, A. Y., Canciglieri, O., Estorilio, C. C. A., Rudek, M. (2021). Green Supply Chain Management and the Contribution to Product Development Process. In W. Leal Filho, P. R. Borges de Brito, F. Frankenberger (Eds.), *International Business, Trade and Institutional Sustainability* (pp. 781–793). Springer. https://doi.org/10.1007/978-3-030-26759-9_46

United Nations Development Programme. (2019). *Decade of Action.* United Nations. Retrieved November 2, 2024, from https://www.undp.org/stories/decade-action

Upadhyay, P., Kumar, A. (2020). A house of sustainability-based approach for green product design: Setting future research agenda. *Management of Environmental Quality: An International Journal*, *31*(4), 819–846. https://doi.org/10.1108/MEQ-03-2019-0057

Urbański, M., ul Haque, A. (2020). Are You Environmentally Conscious Enough to Differentiate between Greenwashed and Sustainable Items? A Global Consumers Perspective. *Sustainability*, *12*(5), Article 1786. https://doi.org/10.3390/su12051786

van Rooyen, M., van der Lingen, E. (2024). Reducing uncertainty associated with managing technology innovation. *Social Sciences and Humanities Open*, *9*, Article 100771. https://doi.org/10.1016/j.ssaho.2023.100771

Verein Deutscher Ingenieure. (2019). *Design of technical products and systems: Model of product design* (No. VDI 2221 Blatt 1). https://www.vdi.de/mitgliedschaft/vdi-richtlinien/details/vdi-2221-blatt-1-entwicklung-technischer-produkte-und-systeme-modell-der-produktentwicklung

Verein Deutscher Ingenieure. (2021). *Development of mechatronic and cyber-physical systems* (No. VDI/VDE 2206). https://www.vdi.de/richtlinien/details/vdivde-2206-entwicklung-mechatronischer-und-cyber-physischer-systeme

Villamil, C., Hallstedt, S. I. (2021). Sustainabilty integration in product portfolio for sustainable development: Findings from the industry. *Business Strategy and the Environment*, *30*(1), 388–403. https://doi.org/10.1002/bse.2627

Villamil, C., Schulte, J., Hallstedt, S. I. (2022). Sustainability risk and portfolio management—A strategic scenario method for sustainable product development. *Business Strategy and the Environment*, *31*(3), 1042–1057. https://doi.org/10.1002/bse.2934

Villamil, C., Schulte, J., Hallstedt, S. I. (2023). Implementing sustainability in product portfolio development through digitalization and a game-based approach. *Sustainable Production and Consumption*, *40*, 277–296. https://doi.org/10.1016/j.spc.2023.07.002

Vilochani, S., Borgianni, Y., McAloone, T. C., Pigosso, D. C. A. (2024). An investigation into the extent to which sustainable product development practices are implemented in manufacturing companies. *Sustainable Production and Consumption*, *50*, 155–167. https://doi.org/10.1016/j.spc.2024.07.022

Vilochani, S., McAloone, T. C., Pigosso, D. C. A. (2024). Consolidation of management practices for Sustainable Product Development: A systematic literature review. *Sustainable Production and Consumption*, *45*, 115–125. https://doi.org/10.1016/j.spc.2024.01.002

von Carlowitz, H. C. (1713). *Sylvicultura Oeconomica, Oder Haußwirthliche Nachricht und Naturmäßige Anweisung Zur Wilden Baum-Zucht*. Braun. http://digital.slub-dresden.de/id380451980

von der Gathen, A., Hagenbeek, O., Broby Eckert, N., Ibisevic, M. (2024). *Sustainability 2024: Navigating consumer behavior.* Simon-Kucher & Partners. https://www.simon-kucher.com/sites/default/files/perspectives-files/Brochure_2024_Sustainability_Study_compressed.pdf

Wang, S., Su, D. (2022). Sustainable Product Innovation and Consumer Communication. *Sustainability*, *14*(14), Article 8395. https://doi.org/10.3390/su14148395

Wang, T., Yang, L. (2023). Combining GRA with a Fuzzy QFD Model for the New Product Design and Development of Wickerwork Lamps. *Sustainability*, *15*(5), Article 4208. https://doi.org/10.3390/su15054208

Watz, M., Hallstedt, S. I. (2020a). GROUP MODEL BUILDING WITH CAUSAL LOOP DIAGRAMS TO FOSTER CAPABILITIES FOR SUSTAINABLE DESIGN AND PRODUCT DEVELOPMENT. *Proceedings of the Design Society: DESIGN Conference*, *1*, 2207–2216. https://doi.org/10.1017/dsd.2020.53

Watz, M., Hallstedt, S. I. (2020b). Profile model for management of sustainability integration in engineering design requirements. *Journal of Cleaner Production*, *247*, Article 119155. https://doi.org/10.1016/j.jclepro.2019.119155

Watz, M., Hallstedt, S. I. (2022). Towards sustainable product development – Insights from testing and evaluating a profile model for management of sustainability integration into design requirements. *Journal of Cleaner Production*, *346*, Article 131000. https://doi.org/10.1016/j.jclepro.2022.131000

Watz, M., Hoffenson, S., Hallstedt, S. I. (2021). EXPLORING SYSTEMIC FORCES THAT INFLUENCE SUSTAINABLE DESIGN TRANSITIONS. *Proceedings of the Design Society*, *1*, 1501–1510. https://doi.org/10.1017/pds.2021.411

Watz, M., Johansson, C., Bertoni, A., Hallstedt, S. I. (2022). Investigating effects of group model building on sustainable design decision-making. *Sustainable*

Production and Consumption, *33*, 846–862. https://doi.org/10.1016/j.spc.2022.08.005

Wernerfelt, B. (1984). A Resource-Based View of the Firm. *Strategic Management Journal*, *5*(2), 171–180. https://doi.org/10.1002/smj.4250050207

Wilmsen, M., Dühr, K., Albers, A. (2019). “A context-model for adapting design processes and methods”. *Procedia CIRP*, *84*, 428–433. https://doi.org/10.1016/j.procir.2019.04.243

Wolff, S., Bronner, M., Held, M., Lienkamp, M. (2020). Transforming automotive companies into sustainability leaders: A concept for managing current challenges. *Journal of Cleaner Production*, *276*, Article 124179. https://doi.org/10.1016/j.jclepro.2020.124179

World Commission on Environment and Development. (1987). *Our Common Future* (No. A/42/427). United Nations. https://docs.un.org/en/A/42/427

Wurster, S., Heß, P., Nauruschat, M., Jütting, M. (2020). Sustainable Circular Mobility: User-Integrated Innovation and Specifics of Electric Vehicle Owners. *Sustainability*, *12*(19), Article 7900. https://doi.org/10.3390/SU12197900

Wynn, D. C., Clarkson, P. J. (2024). *The Design and Development Process: Perspectives, Approaches and Models*. Springer. https://doi.org/10.1007/978-3-031-38168-3

Xavier, A., Reyes, T., Aoussat, A., Luiz, L., Souza, L. (2020). Eco-Innovation Maturity Model: A Framework to Support the Evolution of Eco-Innovation Integration in Companies. *Sustainability*, *12*(9), Article 3773. https://doi.org/10.3390/su12093773

Yu, G. J., Lee, J. (2020). The mediating effect of innovation on the relationship between supplier collaboration and environmental performance. *Uncertain Supply Chain Management*, *8*(4), 831–838. https://doi.org/10.5267/j.uscm.2020.6.003

Zipse, O., Hornegger, J., Becker, T., Beckmann, M., Bengsch, M., Feige, I., Schober, M. (2023). *Road to Net Zero: Strategic Pathways for Sustainability-Driven Business Transformation*. Springer. https://doi.org/10.1007/978-3-031-42224-9

Student theses co-supervised by the author in the context of this dissertation at IPEK – Institute of Product Engineering at Karlsruhe Institute of Technology (KIT):

Herrmann, S. (2025). *Sustainability in Product Engineering - Application and Evaluation of an Approach of Initiating Targeted Action Using the Example of a Technology Company.* Unpublished Master’s Thesis. Karlsruhe Institute of Technology (KIT).

A Appendix

A.1 Guide

A Guide for Decision Makers to Initiate Targeted Sustainability Action in Product Engineering

Executive Summary

To take advantage of opportunities and mitigate risks that emerge from sustainability demands, companies need to establish targeted sustainability action in product engineering.

The sustainability demands and conditions under which companies operate are diverse and dynamic, which requires a company-specific and entrepreneurial approach to act on them in a targeted manner. As the political and economic situation remains volatile and uncertainty increases in many markets, a short-term focus on decision making may be necessary. Thus, it becomes critical to consciously expand or reduce the time horizon considered for decision making. This is necessary to avoid being exposed to risks and to take advantage of opportunities emerging from sustainability demands, such as creating competitive advantages, growth, and even cost reductions. This can be done by targeted sustainability action.

Initiating practices and routines that form targeted sustainability action requires three steps:

1 Understand targeted sustainability action based on context-specific risks and opportunities to identify company-specific objectives

2 Operationalize targeted sustainability action in product engineering through practices with conscious decision making at the core to create clarity on action

3 Implement targeted sustainability action by pragmatically establishing and facilitating practices until they become fully integrated routines.

This Guide aims to support decision makers in these steps and is, therefore, structured along them. An Introduction provides context and an overview of the Guide covering why, what, and how it supports. Step 0 “Preparations” advises how to prepare for the application of the Guide, followed by the three steps to be executed: 1 “Understand”, 2 “Operationalize”, and 3 “Implement”. For each of the three steps, it highlights potential challenges with uncertainties and provides:

- Success criteria for targeted sustainability action
- Guiding questions addressing the key decisions during the steps
- Details on conditions, interdependencies and implications of these decisions

which can be used in a modular way by a facilitator to support decision makers in initiating targeted sustainability action.

Introduction

Why?

Targeted sustainability action in product engineering is becoming critical to stay ahead of competition

Sustainability has become a key strategic pillar for many companies. Sustainability alliances have been formed and public sustainability targets have been set at global, national, and company level.
In a volatile economic situation, short-term focus may be required in decision making, leading to divergent expectations and demands with respect to long-term sustainability action. These context-specific and potentially inconsistent perspectives, as well as the dynamic nature of sustainability demands, amplify the uncertainties under which companies and decision makers act.
Although this situation can leave companies exposed to risks, product engineering can play a pivotal role in mitigating them and in creating opportunities such as:

- Competitive advantages
- Technological advancement
- Growth
- Synergies between short-term and long-term objectives

if acting on sustainability demands in a targeted manner.

Conscious decision making under uncertainty is needed to navigate opportunities and risks

"To not decide is also a decision" – Unreflected inaction can result in a loss of scope of action, missing set targets, a greater talk-walk gap, and green washing. Uncoordinated action can result in unknown blind spots, negative impact, and overdoing it.

"Uncertainties create entrepreneurial opportunities" – Decision makers face a high degree of uncertainty as the implications and conditions of decisions on sustainability action are often unclear, resulting in hesitation, "sustainability firefighting", deferred decisions, and unclear guidance for engineers. These uncertainties need to be explicitly addressed to enable decision makers to consciously make entrepreneurial decisions, thus navigating opportunities and risks, and taking advantage of them.

What?

Initiate targeted sustainability action in product engineering in three steps resulting in continuous adjustment

To act on sustainability demands in a targeted manner, three consecutive and cyclic steps are required:

1. **Understand** targeted sustainability action based on company-specific risks and opportunities to identify potential objectives
2. **Operationalize** targeted sustainability action in product engineering through practices with conscious decision making at the core to create clarity on action
3. **Implement** targeted sustainability action by pragmatically establishing and facilitating practices until they become fully integrated routines

To enable continuous reflection and adjustment to changing demands and conditions, these steps must be performed in ongoing cycles. These cycles also allow decision makers to expand or reduce the time horizon taken into account for conscious decision making.

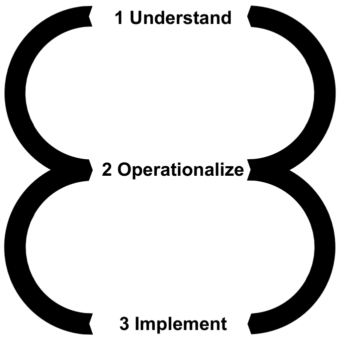

Figure A.1: Steps to Initiate Targeted Sustainability Action in Product Engineering

This Guide supports decision makers to initiate targeted sustainability action in product engineering

The Guide is intended to support decision makers in initiating targeted sustainability action in product engineering. To do so, it starts from a company perspective on sustainability demands, explicitly addressing uncertainties to enable action in a targeted manner. Therefore, it aims to support in three situations from which the use cases emerge:
First, in case of uncertainties about targeted sustainability action, the Guide can be applied to reduce the uncertainties of decision makers (as far as they can be reduced) and to initiate targeted sustainability action, independent of the companies'/the decision makers' current long- or short-term focus. One example of a use case would be reducing uncertainty during initial encounters with sustainability demands, e.g., due to the Corporate Sustainability Reporting Directive (CSRD), or (anticipated) changes in the stakeholder network of a company that potentially introduce new internal/external demands or ambitions. In such cases, applying the Guide can also help clarify and express additional support needs regarding targeted sustainability action so that additional support can be sought, e.g., from the literature or other sources.
Second, the Guide can be applied to establish routines that allow one to expand conscious decision making and action to a longer-term focus (or consciously reduce to the short term) coping with uncertainties or conflicts about sustainability demands and continuously executing targeted sustainability action.
Third, the Guide can be used to recalibrate current sustainability action, for example, to adjust to changing demands in volatile contexts, or to make sustainability action more targeted from a company perspective.
These situations are intended to be addressed by the support. Individual use cases can be derived from these situations, as they can gradually evolve into each other over time due to the changing character of sustainability demands.

Sustainability demands are dynamic and highly context-specific. Thus, targeted sustainability action is dynamic and context-specific as well. Moreover, targeted sustainability action is an entrepreneurial endeavor that can have substantial implications for companies. To acknowledge this nature and support decision makers appropriately, the following intentions (use cases) describe what is explicitly NOT covered by the Guide:

- The Guide does not provide a new "definition" or fixed conception of sustainability
- The Guide does not provide an operational process for action on a fixed conception of sustainability or aspects thereof
- The Guide does not support on moral judgments or possible responsibilities

Moreover, this nature of targeted sustainability action implies the following preconditions for its initiation reflected in the features of the Guide:
First, a minimum conviction is required that sustainability demands could be relevant to the company. At least, to invest the time and resources required for a proper application of the Guide that allows for conscious decision making. This application of the Guide can, in principle, lead to the conclusion that sustainability is currently not relevant to the company and the consciously made decision that no action is needed.
Second, while the Guide explicitly addresses uncertainties, they cannot be reduced entirely. Therefore, the results developed during the application of the Guide are very likely to be subject to uncertainties, and decisions under ambiguity will be required. By avoiding oversimplification (which might happen, e.g., through a pre-fixed definition of sustainability or implied moral judgments), the Guide explicitly keeps the freedom of choice for entrepreneurial decisions, e.g., to take risks. Moreover, the Guide allows decision makers, thus, to understand external definitions of sustainability or moral judgments as what they are and to consciously work with them instead of adopting them without reflection. However, this could deviate from the expectations of decision makers regarding the application of the Guide and thus may require an explicit discussion beforehand.
Third, the initiation of targeted sustainability action and, therefore, the application of the Guide is a highly collaborative effort. This requires the appropriate involvement of all relevant decision makers for targeted sustainability action and thus also the facilitation of this collaboration. Thus, the application of the Guide should be facilitated by an individual or a core team that collaborates closely with relevant decision makers. Hence, this role can be taken up by a decision maker, a group of decision makers, or an internal or external facilitator that supports decision makers.
These points are addressed in Step 0 “Preparations”.

How?

This Guide helps to define and initiate practices forming targeted sustainability action

The three steps to initiate targeted sustainability action are executed in two stages. The first stage is the Guide application that represents the initial iteration of the three steps. In this stage, targeted sustainability action is initially understood (1 "Understand"), practices and routines that form targeted sustainability action are defined (2 "Operationalize"), and their implementation is planned (3 "Implement"). In the second stage, the practices and routines which were defined during the guide application are executed and continuously adjusted, representing iterative cycles of the three steps. In this second stage, an application of the Guide is not required anymore; however, facilitation might be helpful until practices are transformed into fully integrated routines. Thus, the application of the Guide (Stage 1) ends with the compilation of the results (Inform) and the facilitation of conscious decision making on the initiation of action (Decide) that leads to in the initial guidance for the organization (Guide). As a result, targeted sustainability action is initiated (Prepare, Enable and/or Act practices), and a second cycle of the three steps is started (Stage 2). Details on the practices can be found in Step 2 "Operationalize".

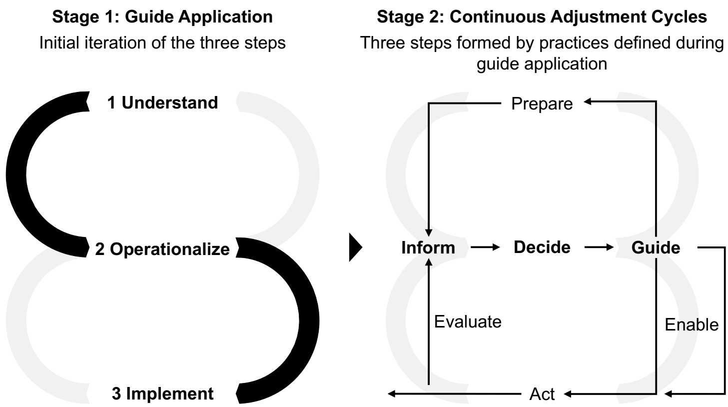

Figure A.2: Stages of Initiating Targeted Sustainability Action

The Guide is structured along the three steps, with five sections for each

The Guide is structured based on the three Steps, 1 “Understand”, 2 “Operationalize”, and 3 “Implement”, preceded by 0 “Preparations”. Each of the three steps follows a consistent structure with five sections. The sections (that are similar to the sections of the Guide’s Introduction, assigned to why, what and how aspects) are explained in Table A.1. The Challenges and Uncertainties (A) allow one to determine whether and why the step should be executed. As the centerpiece of the Guide, the Success Criteria (B) and Guiding Questions (C) help to determine what needs to be done as part of the step. The Success Criteria (B) allow checking the results of each step for their contribution to targeted sustainability action, while the Guiding Questions (C) can be answered to develop these results, thus providing more granular support. The Application section (D) provides the facilitator or decision maker who facilitates the application of the Guide with an exemplary reference on how this step can be conducted, for which the Supporting Materials (E) can be used.

Table A.1: Five Sections for Each Step

Section		Description	Aspect
A	Challenges and Uncertainties	Key challenges to solve in step with uncertainties	Why
B	**Success Criteria**	Characteristics for the result of the step that fosters targeted sustainability action	What
C	**Guiding Questions**	Key decisions to be taken within step	
D	Application	Instructions on how to conduct step operationally	How
E	Supporting Material	Check sheets with details for Success Criteria, templates and input on relevant aspects with interdependencies, conditions and implications of these decisions	

Across the steps, the structure remains the same while the granularity of the supporting material decreases in Steps 2 and 3, as the dependency on previous results increases. The steps build on each other, but an individual focus can be set on one of the steps, depending on previous efforts (e.g., a sophisticated understanding that meets the success criteria is already available). In addition, especially Steps 2 and 3 can be parallelized, e.g., to independently address individual objectives of Step 1 varying in effort, or to prioritize due to limited resources.

Within each step, the sections increase in the granularity of their support, while this obviously comes with a trade-off with generality as presuppositions are introduced. This is why especially the Supporting Material should be checked for its applicability and potentially altered on a case-by-case basis. Moreover, the steps can also be conducted using only selected sections as guidance, e.g., one might only answer the Guiding Questions or check ongoing effort based on the Success Criteria or use different Supporting Materials. This structure is outlined in Figure A.3.

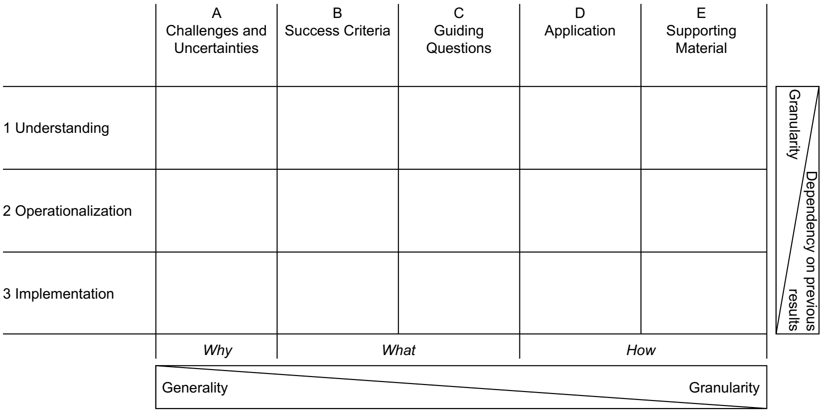

Figure A.3: Structure of the Guide

Based on these dimensions, the modularity across and within steps allows a facilitator to compile relevant sections of the Guide tailored to different needs along its application. For example, the Executive Summary and Introduction to the Guide can be used to provide the required background to a facilitator, but also for top management communication. Step 0 might be used by a facilitator as a reference to evaluate and ensure suitable conditions to apply the Guide. With respect to Steps 1-3, a facilitator might plan the application of the Guide based on the section Application (D). Challenges and Uncertainties (A) and Guiding Questions (C) might be used to shape communication with decision makers. Decision makers may use Success Criteria (B) and Guiding Questions (C) to structure their collaboration and discussions, while these discussions can be inspired, documented, and evaluated using the respective Supporting Material (E).

Success Criteria and Guiding Questions form the core of the Guide

An overview of all the Success Criteria (see Sections 1.B, 2.B, 3.B) for the three steps can be found in Table A.2, and guiding questions as the second core element of the steps (see Sections 1.C, 2.C, 3.C) can be found in Table A.3.

Table A.2: B. Success Criteria. Overview of Success Criteria for All Three Steps of the Guide. The Success Criteria Are Relevant for the Respective Steps as Well as for All Subsequent Steps and Future Iterations. Details Can Be Found in Respective Sections of the Guide

Step	**Success Criteria** for Targeted Sustainability Action
1 Understand	Context-specific, consistent, long-term oriented, evolving, reasoned, explicit
2 Operationalize	Proactive, actionable, collaborative
3 Implement	Boosted, efficient, integrated, traceable

Table A.3: C. Guiding Questions. Overview of Guiding Questions with Sub-questions for All Three Steps of the Guide

Step	Guiding Questions		Sub-questions
1 Understand	**Why** is targeted sustainability action relevant to the company?		Which **risks** are to be avoided?
			Which **opportunities** are to be seized?
			Which **drivers** and conditions are implied?
			Which **uncertainties** are associated?
	What could be achieved through targeted sustainability action at the company?		Which sustainability **objectives** can be set based on opportunities and risks?
			Which **interdependencies** can be expected?
2 Operationalize	**How** can sustainability objectives be acted on at the company?	Which **practices** form targeted sustainability action?	Which **actions** are required to achieve the objectives?
			Which **capabilities** enable the actions?
			Which **guidance** initiates targeted action?
			Which **decisions** define the guidance?
			Which **information** allows fact-based decisions?
			Which **preparations** build the fact base for decision making?
			Which **evaluations** augment the fact base for further decision making?
		How should the practices be **designed** to support targeted sustainability action?	**Who** to solve conflicts and uncertainties through practices?
			When to solve conflicts and uncertainties through practices?
			How to solve conflicts and uncertainties through practices?
			Which **references** can be used?
3 Implement	**How** to implement targeted sustainability action?	How to **implement** practices to achieve objectives?	Which initial/one-off **decisions** are to be made when?
			Which **practices** are to be established when?
		How to **facilitate** the implementation?	

0 Preparations

To support decision makers in addressing uncertainties and initiating targeted sustainability action, appropriate responsibilities and resources must be allocated, and several preconditions for a successful application of the Guide must be met. The main aspects are outlined below, building on the Success Criteria of Steps 2 and 3 as well as the ‘What?’ section of the Introduction:

- Consciously make a decision on whether and why the Guide should be applied at the appropriate level (use cases and delimited intentions can serve as a reference). Secure attention and commitment from top management and ensure the necessary conviction to assign responsibilities and resources for a proper application of the Guide, for example, through a sponsor.
- Assign a facilitator (team) that prepares and leads the application of the Guide. This entails, especially, coordinating the collaboration with decision makers and across levels, but also ensuring that an overview is maintained, progress is documented, and transparency is created through early communication. Only temporarily create new roles where necessary.
- Think through the application (see the Application sections of the steps) and choose an appropriate and known format to allocate the necessary resources for the application (e.g., project, initiative) as this format might (implicitly) affect the solution space for targeted sustainability action. Aspire to quick iterations and prepare to adjust, prioritize, and parallelize during the application of the Guide.
- Establish a network among all relevant decision makers to be involved in understanding, operationalizing and implementing targeted sustainability action (e.g., by answering the Guiding Questions, see Application sections for details), trading off pragmatism and comprehensiveness. Clarify expectations and delimit intentions not covered.

The use case and extent of the Guide’s application significantly impact the need for these preparations.

1 Understand

The initial understanding of targeted sustainability action developed in the first step provides the foundation for decisions to be taken and consists of two results: First, opportunities and risks that arise from sustainability demands and their drivers are identified. These are specific to the company and should be described as specific as possible with the conditions they imply (sustainability aspect, area of application, and timing), as well as uncertainties at the current point in time. Second, potential objectives of targeted sustainability action in product engineering should be defined, with their reasoning (risks/opportunities), interdependencies (synergies, conflicts) and uncertainties (or next steps if known).

Table A.4: Summary of Step 1, "Understand"

Aspect	Section	Summary
Why	**A Challenges and Uncertainties**	Cope with missing materiality amid complexity and uncertainty
What	**B Success Criteria**	Understanding should aim to be context-specific, consistent, long-term oriented, evolving, reasoned, and explicit
	C Guiding Questions	Why is targeted sustainability action relevant to the company? What could be achieved through targeted sustainability action at the company?
How	**D Application**	Answer Guiding Questions through workshops, data collection and interviews
	E Supporting Material	Details and templates for opportunities/risks with conditions (Question 1) and potential objectives (Question 2)

1A. Challenges and Uncertainties

Understanding targeted sustainability action poses the challenge of coping with missing materiality amid complexity and uncertainty in sustainability demands and targeted action on them. Thus, to initiate targeted sustainability action that takes advantage of the opportunities in and mitigates the risks that emerge from that complexity and uncertainty, this missing materiality must be overcome.

Missing materiality
High-level objectives are easy to agree on and often clear, but an unspecific understanding can cause subjective interpretations and lead to no or unspecific action.

Complexity
Sustainability demands and their implications are broadening and can be conceptually difficult. In addition, they can be diverse and inconsistent depending on drivers, perspectives, and company context.

Uncertainties
There is no external frame of reference and, in many cases, no clear market signals. The extended time horizon of sustainability demands leads to additional uncertainties in the development of relevant conditions, such as stakeholder abilities and actions, and implications of sustainability action, like potential value or risks.

1B. Success Criteria

Table A.5: Success Criteria for an Understanding of Targeted Sustainability Action

Success Criteria	Description
Context-specific	Is specific to the company and its opportunities and risks.
Consistent	Breaks down the company perspective integrated with its strategy, but incorporates other relevant perspectives and surfaces inconsistencies.
Long-term oriented	Includes expected future developments for conscious decision making on action or inaction, based on a context-specific time horizon.
Evolving	Takes status quo into account, allows for further refinement over time and acknowledges dynamic nature of targeted sustainability action.
Reasoned	Provides reasoning for each aspect and allows reasoning to be challenged to create materiality, increase acceptance and allow for prioritization.
Explicit	Surfaces interdependencies and uncertainties between aspects, explicates current materiality and translates into objectives, priorities and guidance.

1C. Guiding Questions

Why is targeted sustainability action relevant to the company?

- Which risks are to be avoided?
- Which opportunities are to be seized?
- Which drivers and conditions are implied?
- Which uncertainties are associated?

What could be achieved through targeted sustainability action at the company?

- Which sustainability objectives can be set based on opportunities and risks?
- Which interdependencies can be expected?

1D. Application

Key success criteria are context-specificity and consistency, that require discussions on reasoning and explication of the gained understanding. Therefore, this step should be executed in a workshop format, with data collection in between, to involve perspectives and reduce uncertainties where possible. All results will require further refinement and should incorporate the status quo (evolving) as well as expected future developments (long-term oriented).

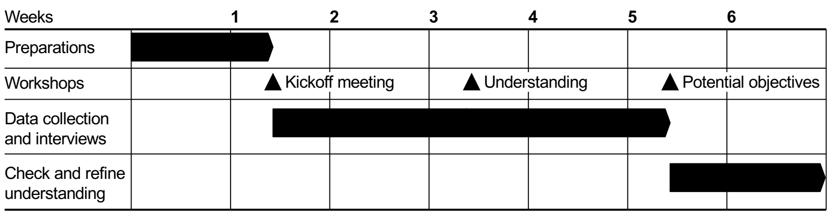

Figure A.4: Potential Timeline of Step 1, “Understand”

Preparations
Decide on whom to involve: Depending on the status quo and organization, relevant decision makers and perspectives on sustainability action from the sustainability, functional, and project perspectives should be represented in this phase.

Workshop 1: Kickoff meeting
Assesses status quo. Relevant questions are: “What is the current company strategy?”, ”What is the current perspective of the company on sustainability?”, ”Is there currently sustainability action?”, “Who are the involved actors?”, …

Workshop 2: Understanding
Answers the first Guiding Question: “Why is targeted sustainability action relevant to the company?”
The results are opportunities and risks with drivers, conditions, and uncertainties.
Template 1 (Table A.7) and the respective Supporting Material can be used as input and the Success Criteria (Table A.5) as reference to answer the Guiding Question and Sub-questions. The supporting materials comprise non-exhaustive lists and instructions for opportunities and risks (Table A.10), drivers (Table A.11) and conditions (Table A.12, Figure A.5).

Workshop 3: Potential objectives
Answers the second Guiding Question: “What could be achieved through targeted sustainability action at the company?”
Results are potential objectives with reasoning, potential uncertainties, synergies, and conflicts.
Template 2 (Table A.13) and the Success Criteria (Table A.5) can be used to answer the question for individual objectives, while Figure A.6 illustrates an overview of the objectives.

Check and refine understanding
Compile an overview and check whether the results of the step contribute to targeted sustainability action using the Check Sheet (Table A.6). Refine if necessary before proceeding to the next step, but acknowledge the evolving character of the understanding that might continue to include uncertainties and conflicts.

1E. Supporting Material

Table A.6: Check Sheet for Step 1, "Understand"

Success Criteria	**Why is targeted sustainability action relevant to the company?** *Opportunities and risks, with drivers, conditions and uncertainties*	**What could be achieved through targeted sustainability action at the company?** *Potential objectives with reasoning, potential uncertainties, synergies and conflicts*
Context-specific	Focus on risks and opportunities relevant to the company.	Derive objectives from risks and opportunities (only).
Consistent	Take company perspective, incorporating other perspectives as drivers. Surface inconsistencies through sustainability aspects and area of application.	Take company perspective. Explicate inconsistencies as conflicts, also with existing objectives (e.g., in strategy).
Long-term oriented	Include expected future developments of opportunities and risks with timing.	Define long-term objectives/ target picture that allow for connection to today's actions.
Evolving	Take status quo into account. Acknowledge dynamic nature of demands and allow for further refinement over time through noted timing and uncertainties.	Take existing objectives and efforts into account. Note known next steps, and/or highlight uncertainties for further refinement.
Reasoned	Reason opportunities and risks through drivers.	Reason new objectives through opportunities and risks. Challenge existing objectives through opportunities and risks.
Explicit	Explicate uncertainties to reflect materiality allowing to resolve them.	Describe objectives in detail. Surface interdependencies as synergies and conflicts. Explicated uncertainties to reflect materiality.

Table A.7: Template 1 – Why Is Targeted Sustainability Action Relevant to the Company?

	– – – – – – – – – →	Conditions			
Risks/Opportunities	← **Drivers**	**Sustainability aspects**	**Area of application**	**Timing**	**Uncertainties**

Table A.8: Template 1: Example 1 – Why Is Targeted Sustainability Action Relevant to the Company?

	- - - - - - - - - →	Conditions			
Risks/Opportunities	← **Drivers**	**Sustainability aspects**	**Area of application**	**Timing**	**Uncertainties**
Winning new customers (Opportunity) and avoiding losing existing customers (Risk) through differentiation from competition (by supporting customers in achieving their own sustainability goals and meeting their regulation)	Customer ambition and regulation relevant to customer	? Unknown, depends on customer and relevant regulation ? Profitability	Product	In upcoming years	Which sustainability aspects are relevant for which customer (and by regulation, or own amibition)? How do implications affect profitability (e.g., premiums, cost)?

Table A.9: Template 1: Example 2 – Why Is Targeted Sustainability Action Relevant to the Company?

	– – – – – – – – – ⟶	**Conditions**			
Risks/Opportunities	⟵ **Drivers**	**Sustainability aspects**	**Area of application**	**Timing**	**Uncertainties**
Cost reductions (Opportunity) through reduction of resource usage in product engineering	Company ambition Cost pressure by competition	Resource efficiency	Product engineering	As soon as possible	Which resources are used where?

Potential risks and opportunities Opportunities for the company arising from the topic of sustainability could be seized through sustainability action. Risks for the company arising from the topic of sustainability could be avoided through sustainability action. Furthermore, sustainability action can also lead to unintended risks, which should also be tracked.

Table A.10: Potential Risks and Opportunities of Sustainability Action

Relation	Potential Risks and Opportunities
Potentially addressed by sustainability action	Fines, additional (future) costs, but also incentives like tax refunds, funding, etc.
	Business development, premiums Competitive advantage or disadvantage, differentiation, missing out Technological advancement/technology leadership
	Market valuation Brand positioning, company image, (negative) publicity Signaling effects
	Urgency to act, being at mercy, limited solution space, Supply shortages/accessibility Experience
Potentially caused by sustainability action	Industry espionage/IP leaks Additional efforts Investments additional, obsolete Loss of profitability, jobs

Potential Drivers Drivers are only relevant if there is a risk or an opportunity for the company caused. Multiple allocations between risks/opportunities and drivers are possible. If there is a trend seen but risks or opportunities for the company are unclear these should be noted as uncertainties.

Table A.11: Potential Drivers of Sustainability Demands. Typical Drivers Seen in Multiple Occasions Are **Bold**

Cluster	**Potential Drivers**
Markets	**Customer** requirements, demand, own ambition, own regulation, value, expectations, requests, contracts
	Markets (new, established, growing, declining), Trends, Changes
	Competition
	Partners
	Financial markets
Industry	Industry associations
	Suppliers (incl. ambition), ability to transform, technology
Company	**Company ambition**, commitments, strategy, reputation, technology, **economic situation**, culture
	Employee identification, motivation
Society	Candidates
	Societal pressure
Authorities	**Regulation**, Reporting
	Standards
	Audits, Certificates, Ratings
Others	Other industries
	Science
	Ideology

Potential sustainability aspects Sustainability aspects are closely interlinked and might require trade-offs or priorities. Therefore, identify the conditions implied by the risks and opportunities as specifically as possible to surface and narrow inconsistencies and interdependencies to resolve them.

Table A.12: Potentially Relevant Sustainability Aspects Addressable by Sustainability Action in Product Engineering. Sustainability Aspects Seen Being Prioritized in Product Engineering in Multiple Occasions Are **Bold**

Potential Sustainability Aspects and Sub-aspects			
Economic	Profitability		
Environmental	Climate	Emissions	**Carbon dioxide**
	Green materials		
	Circularity	Recycling	
		Repairability	
		Remanufacturing	
	Resource efficiency	**Energy**	
		Water	
	Waste		
	Biodiversity		
Social & Governance			

Generic conceptions of sustainability can be used for delimitations and as a reference if used by stakeholders, but not as “driver”. Three pillars and TBL are used in the literature, SDGs by the United Nations and Governments, CSR by companies, and ESG in the finance sector.

Generic sustainability conceptions usable for delimitations:

- Three pillars, Triple Bottom Line (TBL)
- Sustainable Development Goals (SDGs)
- Corporate Social Responsibility (CSR)
- Environmental, Social, Governance (ESG)

Potential area of application Company and product sustainability are closely interlinked, but allocations are difficult and might require completely different approaches in operationalization. Therefore, identify the conditions implied by the risks and opportunities as specifically as possible to surface and narrow inconsistencies and interdependencies to resolve them.

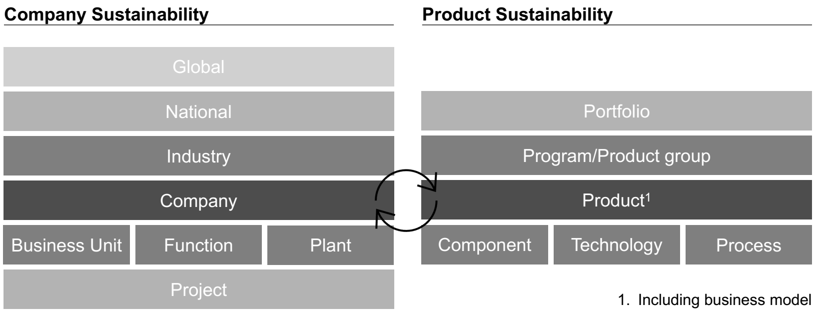

Figure A.5: Potential Area of Application

Table A.13: Template 2 – What Could Be Achieved Through Targeted Sustainability Action at the Company?

Objective	**Reasoning** (e.g., Opportunities, Risks)	**Next steps** (e.g., Information to obtain, decisions)
Uncertainties	**Conflicts**	**Synergies**

Table A.14: Template 2: Example 1 – What Could Be Achieved Through Targeted Sustainability Action at the Company?

Objective	**Reasoning** (e.g., Opportunities, Risks)	**Next steps** (e.g., Information to obtain, decisions)
Support customers in achieving their sustainability objectives and meeting their sustainability requirements (e.g., by regulation)	Differentiation from competition to win new customers (Opportunity) and avoid losing existing customers (Risk)	? Identify customer sustainability ambitions and relevant regulations
Uncertainties	**Conflicts**	**Synergies**
? Customers might have similar uncertainties as we do ? Similarities and differences between customers are unclear ? Interpretation of regulations by customers is unclear and might change	? Potentially between customer requirements (requiring product portfolio decisions)	Building a sustainable reputation with customers ? Meeting own regulations ? Standardization/Modularization

Table A.15: Template 2: Example 2 – What Could Be Achieved Through Targeted Sustainability Action at the Company?

Objective	**Reasoning** (e.g., Opportunities, Risks)	**Next steps** (e.g., Information to obtain, decisions)
Reduce resources used in product engineering	Cost reductions	?_
Uncertainties	**Conflicts**	**Synergies**
Which resources are used where? Where is resource usage needed?	? Regulations for product testing	Company profitability

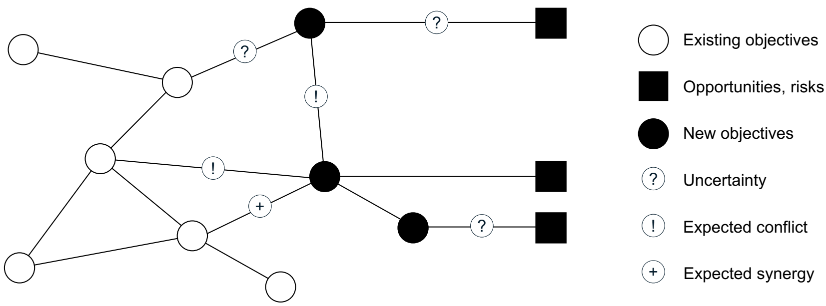

Figure A.6: Visualization of Overview of Objectives Based on Template 2

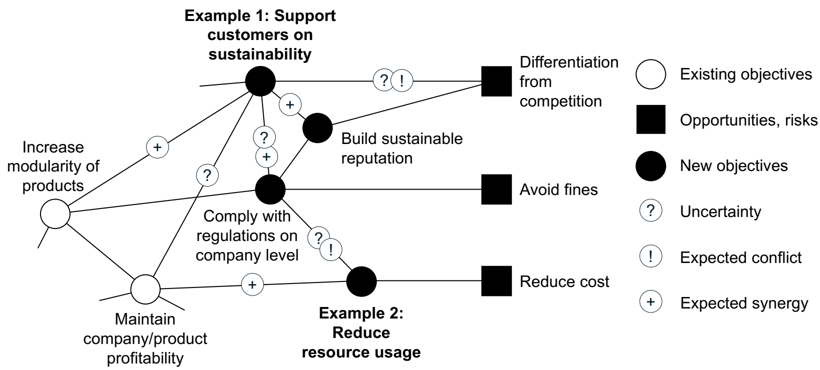

Figure A.7: Visualization of Overview of Objectives Based on Template 2 – Examples 1 and 2 Combined

2 Operationalize

To operationalize targeted sustainability action, the practices that form this action must be defined. On the one hand, these practices are derived from Step 1, “Understand”, and address uncertainties, conflicts, and synergies to achieve the objectives. On the other hand, these practices can contribute to a more mature understanding and allow to adjust action iteratively over time, as the understanding matures or changes. Thus, the practices to be defined can be intended to be executed once or form continuous routines of understanding, operationalizing, and implementing targeted sustainability action. In both cases, conscious decision making is the core of targeted sustainability action.

Table A.16: Summary of Step 2, “Operationalize”

Aspect	Section		Summary
Why	**A**	**Challenges and Uncertainties**	Create clarity despite immaturity and uncertainties
What	**B**	**Success Criteria**	Operationalization of targeted sustainability action should be proactive, actionable and collaborative
	C	**Guiding Questions**	How can sustainability objectives be acted on at the company? • Which practices form targeted sustainability action? • How should the practices be designed to support targeted sustainability action?
How	**D**	**Application**	Answer Guiding Questions in core teams involving relevant expertise
	E	**Supporting Material**	Details and template for practices

2A. Challenges and Uncertainties

Operationalizing targeted sustainability action poses the challenge of creating clarity despite immaturity and uncertainties. To act in a targeted manner, this clarity must be created, but at the same time oversimplification should be avoided, as it can lead to ongoing challenges in implementation.

Clarity

Unclear expectations with respect to sustainability action can lead to helplessness among employees and deprioritization within the organization. Even in the case of a material understanding, creating this clarity can remain a challenge. Moreover, targeted action might be required to develop such a material understanding.

Immaturity

The practices required for targeted sustainability action can be new or unknown to the company, and additional interdependencies can increase the complexity of product engineering.

Uncertainties

The high degree of uncertainty in sustainability action leads to ambiguity in decision making. Decisions based on assumptions can be required as not deciding or not acting also implies assumptions.

2B. Success Criteria

Table A.17: Success Criteria for an Operationalization of Targeted Sustainability Action

Success Criteria	**Description**
Proactive	Fosters conscious decision making on action to exploit synergies, solve conflicts and reduce uncertainties. Establishes continuous cycles of decision making and adjustment in understanding and action independent from radicality.
Actionable	Ensures clear guidance in a comprehensible format for specific action. Allocates responsibilities and resources appropriate to the intended action. Ensures consistency between practices to encourage action.
Collaborative	Involves all relevant expertise and experience. Constructively challenges guidance and reasoning through collaboration across levels.

2C. Guiding Questions

How can sustainability objectives be acted on at the company?

- Which **practices** form targeted sustainability action?
  - Which **actions** are required to achieve the objectives?
  - Which **capabilities** enable the actions?
  - Which **guidance** initiates targeted action?
  - Which **decisions** define the guidance?
  - Which **information** allows fact-based decisions?
  - Which **preparations** build the fact base for decision-making?
  - Which **evaluations** augment the fact base for further decision making?
- How should the practices be **designed** to support targeted sustainability action?
  - **Who** to solve conflicts and uncertainties through practices?
  - **When** to solve conflicts and uncertainties through practices?
  - **How** to solve conflicts and uncertainties through practices?
  - Which **references** can be used?

2D. Application

The success criteria for operationalization that exceed those for Step 1 are: Being proactive, actionable, and collaborative. The results are practices and routines that form targeted sustainability action derived and contributing to the understanding from Step 1 and its objectives. Depending on the materiality of the initial understanding, the breadth and depth of this step should be varied to create clarity on action (see Challenges). This can also mean a split by objective to be acted on (in case of few interdependencies), but also clusters can be formed if needed. In addition, prioritization might be necessary based on capacities that can also require parallelization of Steps 2 and 3. However, all identified objectives should go through Steps 2 and 3 to an extent that provides a profound basis for conscious initial decision making at the end of the Guide's application, which determines whether Stage 2 is entered (e.g., whether to act on the objective or not, see also Step 3 section D). In addition, decision makers might introduce additional objectives during Steps 2 and 3, which should then be integrated and checked according to the success criteria of Step 1, either directly or as part of future iterations of the three steps.

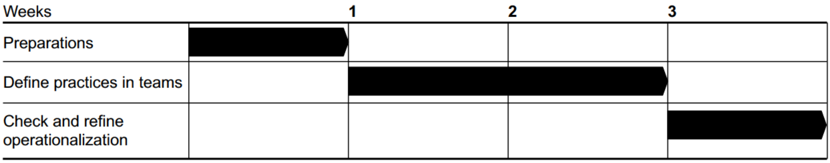

Figure A.8: Potential Timeline of Step 2, “Operationalize”

Preparations

Check the results of Step 1 (answers to the guiding questions) and get an overview of the uncertainties, conflicts, and synergies. Cluster, select or prioritize objectives, assign owners, and assemble teams of decision makers that involve relevant experience and expertise in resolving the respective uncertainties and conflicts and in exploiting these synergies.

Define practices

Answer all Guiding Questions based on the understanding gained in Step 1 and the circumstances at the company.
The result is an overview of the practices that resolve uncertainties and conflicts and exploit synergies to act on the objectives. This includes one-offs as well as lasting routines to be established, which should be differentiated.
The flow of operationalization and implementation of practices differ: While the operationalization starts with the configuration of practices from the action needed for the objectives, the implementation begins with preparations and ends with action. The inversion for operationalization supports the focus on the practices required for the objectives and is illustrated in Figure A.9. The template (Table A.19) and the respective supporting material can be used as input and the Success Criteria as reference to answer the Guiding Questions and Sub-questions. The Supporting Materials comprise an overview of the practices (Table A.22), their interactions (Figure A.9), and detailed descriptions (Tables A.23 to A.29, which already include information on the timing relevant for Step 3).

Check and refine operationalization

Compile an overview and check whether the results of the step contribute to targeted sustainability action using the Check Sheet (Table A.18). Refine if necessary before proceeding to the next step, but acknowledge the evolving character of the operationalization that comes with an evolving understanding and might continue to include uncertainties and conflicts.

2E. Supporting Material

Table A.18: Check Sheet for Step 2, "Operationalize". Table Shows Only Overarching Success Criteria. Practice Specific Suggestions Can Be Found in Details

Success Criteria	**How can sustainability objectives at the company be acted on?** *Practices*
Proactive	Define ongoing cycles of conscious entrepreneurial decision making on action at appropriate level and function. Surface uncertainties, conflicts, and synergies of objectives in Prepare, Evaluate and Inform practices. Exploit synergies, solve conflicts and reduce uncertainties in Prepare, Enable and Act practices to achieve objectives.
Actionable	Describe practices and routines in a comprehensible format for specific action. Allocate responsibilities and resources for execution appropriate to the intended action. Ensure consistency between practices to encourage action.
Collaborative	Involve all relevant expertise and prior experience on synergies, conflicts and uncertainties in practices, collaborating across levels and with supply chain/drivers. Allow to constructively challenge practices and reasoning from all affected perspectives.

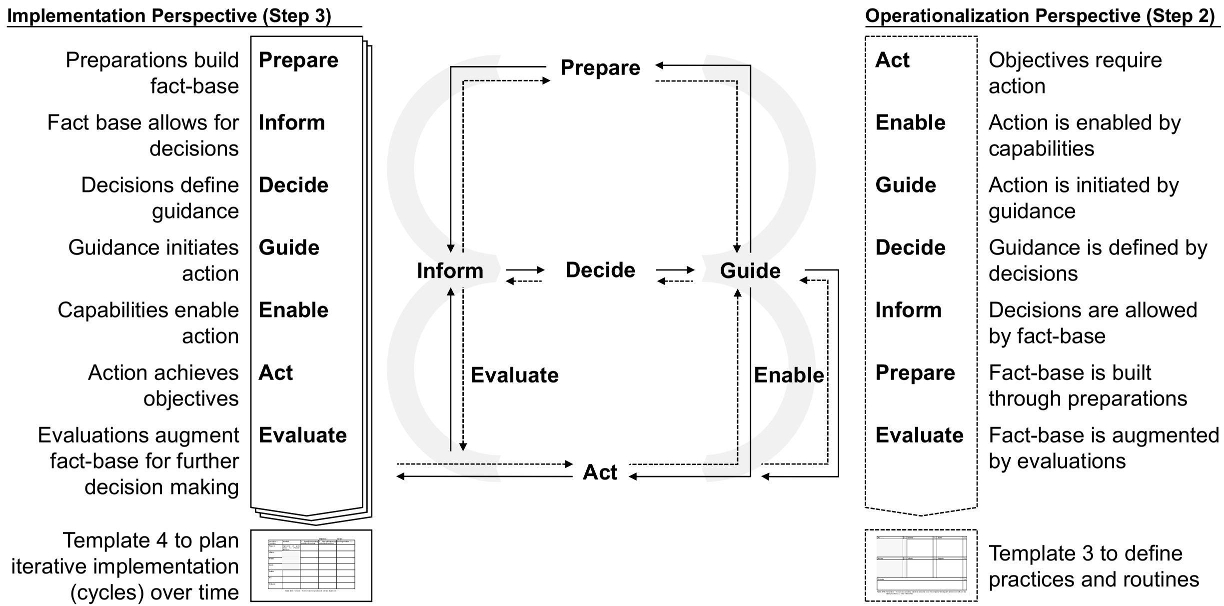

Figure A.9: Flow of Practices: Implementation (left, solid), Operationalization (right, dashed)

Table A.19: Template 3 – How Can sustainability Objectives Be Acted on at the Company? Distinguish Between One-offs (1) and Lasting Routines (∞) to Be Established

Act	1/∞	**Enable**	1/∞	**Guide**	1/∞
Decide	1/∞	**Inform**	1/∞	**Prepare**	1/∞
Evaluate					1/∞

Table A.20: Template 3: Example 1 – How Can Sustainability Objectives Be Acted on at the Company? Distinguish Between One-offs (1) and Lasting Routines (∞) to Be Established

Act	1/∞	**Enable**	1/∞	**Guide**	1/∞
? Incorporate customers' sustainability objectives into product engineering, where applicable	∞	?_		Owner with capacities in product management to drive evaluations and preparations ?_	1 ∞
Decide	1/∞	**Inform**	1/∞	**Prepare**	1/∞
Decide whether opportunity and risk are relevant enough to invest time in research	1	Decision template with cost benefit evaluation	1	Collect known sustainability needs and value potentials Define potential channels to identify additional needs and value potentials Identify relevant regulations for customers	1 1 1
Evaluate					1/∞
Check status quo: Current requests by customers and current situations where opportunities and risks become relevant Dialogue with customers on potential support needs or additional value					1 ∞

Table A.21: Template 3: Example 2 – How Can Sustainability Objectives Be Acted on at the Company? Distinguish Between One-offs (1) and Lasting Routines (∞) to Be Established

Act	1/∞	**Enable**	1/∞	**Guide**	1/∞
Increase share of simulations Reduce number of prototypes Reuse prototypes Avoid introduction of new tests	1 1 ∞ ∞	Provide simulation tool chain Define requirements for introduction of new tests	1 1	Project to identify potentials for resource usage reduction Adjust process descriptions	1 1
Decide	1/∞	**Inform**	1/∞	**Prepare**	1/∞
Decide whether to identify potentials Decide on implementation	1 1	Decision template with expected resource reduction potential with cost implications of measures	1	Check regulatory requirements Estimate simulation efforts Check reuse potentials of prototypes	1 1 1
Evaluate					1/∞
Check status quo resource usage in product engineering					1

Table A.22: Overview of Practices (What and Why). Potential End Products are *Italic*

Act	**Enable**	**Guide**
Exploit synergies, solve conflicts, and reduce uncertainties by • Collaborating with drivers • Changing – Product substance or properties – Technology – Processes …to achieve objectives.	Build expertise, provide tools, develop individual and collective capabilities …to enable action.	Explicate “solution space” for action in a comprehensible format *Target picture/Objectives/Roadmap/Requirements* Initiate targeted action through resource and responsibility allocation appropriate to “solution space” *Initiatives/Project* …to initiate action.
Decide	**Inform**	**Prepare**
Decide • Whether to act on objectives, their uncertainties, conflicts and synergies (or not) • Radicality of intended action (can be varied) • Solution space to act on remaining uncertainties and conflicts (can be limited or expandable) …to define guidance.	Obtain overview and data on demands, drivers, prior decisions, reasoning, company strategy, status quo, investments, options, implications, conditions, ... *Decision templates/business cases/options/scenarios/status quo, …* …to allow decisions.	Collaboratively involve all relevant expertise and prior experience incl. supply chain Create knowledge and intelligence on demands and drivers …to expand fact base and enable further decision making.
Evaluate		
Evaluate through KPIs • Status quo • Implementation of measures • Progress on objectives	… to expand fact base and enable further decision making.	

Table A.23: Practice Description: Act

Act	
What to do?	Exploit synergies, solve conflicts, and reduce uncertainties by • Collaborating with drivers • Changing – Product substance or properties – Technology – Processes
Why to do it?	...to achieve objectives.
Who to do it?	Appropriate level and function, esp. to solve conflicts
When to do it?	Depending on conditions such as lead times and contracts with suppliers Sequenced along new programs and technology or investment fade outs Prioritized based on impact/feasibility In small steps with improvement over time to gain experience
How to do it?	Pragmatic, starting with exploiting synergies Integrated

Table A.24: Practice Description: Enable

Enable	
What to do?	Build expertise, provide tools, develop individual and collective capabilities
Why to do it?	…to enable action.
Who to do it?	Lead by Center of Competence possible
When to do it?	Start early to account for learning curve
How to do it?	Through training and education, tools, but also recruiting
References	Cost engineering

Table A.25: Practice Description: Guide

Guide	
What to do?	Explicate “solution space” for action in a comprehensible format *Target picture/ Objectives/ Roadmap/ Requirements* Initiate targeted action through resource and responsibility allocation appropriate to “solution space” *Initiatives/ Project*
Why to do it?	…to initiate targeted action.
Who to do it?	Along established governance, e.g., meeting cadences Appropriate to intended action on synergies, conflicts, uncertainties
When to do it?	With initial decisions taken, then detail over time, e.g., objective to roadmap
How to do it?	From company perspective, with clear priorities and focus to create clarity Reasoned to allow for constructive challenging and adjustment

Table A.26: Practice Description: Decide

Decide	
What to do?	Decide on • Whether to act on objectives, their uncertainties, conflicts and synergies (or not) • Radicality of intended action (can be varied) • “Solution space” to act on remaining uncertainties and conflicts (can be limited or expandable)
Why to do it?	…to define guidance
Who to do it?	At appropriate level and function, where responsibility for implications can be taken and with top management commitment – Not in parallel
When to do it?	Now, don’t wait for collective wisdom of stakeholders No decision is also a decision
How to do it?	Consciously Entrepreneurial as opportunities are where uncertainty is and “innovation” happens where conflicts are resolved Transparently

Table A.27: Practice Description: Inform

Inform	
What to do?	Obtain overview and data on demands, drivers, prior decisions, reasoning, company strategy, status quo, investments, options, implications, conditions, ... *Decision templates/ business cases/ options/ scenarios/ status quo, …*
Why to do it?	…to allow decisions.
Who to do it?	By Center of Competence or facilitator possible
When to do it?	Early and iteratively, potentially continuously to create a living fact base
How to do it?	Through Preparations, Evaluation of Implementation Integrated in (ERP) systems

Table A.28: Practice Description: Prepare

Prepare	
What to do?	Collaboratively involve all relevant expertise and prior experience incl. supply chain Create knowledge and intelligence on demands and drivers
Why to do it?	…to expand fact base and enable further decision making.
Who to do it?	By Center of Competence possible or facilitator possible Broad network and detailed understanding of organization is helpful
When to do it?	Early, to have answers when needed
How to do it?	Establish network to reduce uncertainties, increase awareness and conviction Think through, conduct dry runs and pilot Without overinvesting, tradeoff between efficient preparations and efficient roll-out

Table A.29: Practice Description: Evaluate

Evaluate	
What to do?	Evaluate through KPIs • Status quo • Implementation of measures • Progress on objectives
Why to do it?	…to expand fact base and enable further decision making.
Who to do it?	Anyone with access and expertise (e.g., controlling), however, decisions should be made along established escalation paths
When to do it?	Status quo as starting point As ongoing feedback, e.g., in decision gates, value chain reviews, or integrated in tools (e.g., immediate feedback on implications of design choices in CAD)
How to do it?	Depending on purpose as evaluations can also be a demand themselves, requiring deviating approaches Consistent and evolving with guidance to avoid deprioritization Potentially automated trading-off one-time and ongoing efforts
References	Controlling

3 Implement

To implement targeted sustainability action in the form of the practices and routines defined in Step 2, “Operationalize”, these practices and routines must be established. Thus, their implementation is planned over time as the initial cycles of Stage 2 together with their facilitation, which follows the Guide’s application until a full integration in product engineering practice has been achieved. A special focus is set on the transition from Stage 1 to Stage 2: The initiation of targeted sustainability action consisting of compiling the results of the Guide’s application into an initial fact base (Inform), the facilitation of conscious decision making on the initiation of action (Decide), and preparing the initial guidance for this action (Guide).

Table A.30: Summary of Step 3, “Implement”

Aspect	**Section**	**Summary**
Why	**A Challenges and Uncertainties**	Acting pragmatically rather than comprehensive under uncertainty
What	**B Success Criteria**	Implementation should aim to be boosted, efficient, integrated and traceable
	C Guiding Questions	How to implement targeted sustainability action? • How to implement practices to achieve objectives? • How to facilitate the implementation?
How	**D Application**	Answer guiding questions to plan implementation and facilitation, then initiate action
	E Supporting Material	Template to plan implementation of practices and routines and check sheet

3A. Challenges and Uncertainties

Implementing targeted sustainability action poses the challenge of acting pragmatically rather than comprehensively under uncertainty. Thus, well-placed pragmatism is essential to moving from mere planning to initiated action.

Pragmatism
Targeted sustainability action must remain manageable to be implemented, while interdependencies with context-specific conditions require a company-specific pragmatic approach. This pragmatism can be conceptually more complex than theoretically comprehensive approaches. These approaches, however, are likely to fail, as coping with company-specific realities becomes critical to initiate and execute targeted sustainability action.

Comprehensiveness
At the same time, targeted sustainability action can require fundamental changes in the organization that lead to a transformational character of the implementation and can pose an existential challenge, especially to smaller companies. In addition, these changes might cause hesitation among employees.

Uncertainties
Whether objectives can be achieved or whether practices lead to intended effects might be uncertain, making it difficult to consciously decide when and where to implement them. Moreover, new practices might require a big leap from known routines that require a learning curve on the individual and organizational level. This again might cause hesitation, resulting in even longer lead times until full integration of routines in which demands and conditions can change again.

3B. Success Criteria

Table A.31: Success Criteria for an Implementation of Targeted Sustainability Action

Success Criteria	Description
Boosted	Ensures top management commitment and attention, focus for action, and quick iterations
Efficient	Prepares to build expertise, pilots to gain experience and rolls out practices selectively and sequentially
Integrated	Integrates practices making use of existing routines, adds new practices only where necessary Adds new (facilitator) roles or Center of Competence only as enabler
Traceable	Maintains overview to facilitate action Documents action and progress Creates transparency

3C. Guiding Questions

How to implement targeted sustainability action?

- How to implement practices to achieve objectives?
  - Which initial/one-off decisions are to be made when?
  - Which practices are to be established when?
- How to facilitate the implementation?

3D. Application

The success criteria for the implementation of targeted sustainability action exceeding those of Step 2, “Operationalize”, are boosted, efficient, integrated, and traceable. The results are initiatives (or alternative known and comprehensible formats) to establish the practices defined and their facilitation, which are then initiated (transition to Stage 2, see below). Depending on the clarity of the practices defined, the breadth and depth of this step should be varied pragmatically. Again, prioritization and parallelization might be necessary depending on the capacities.

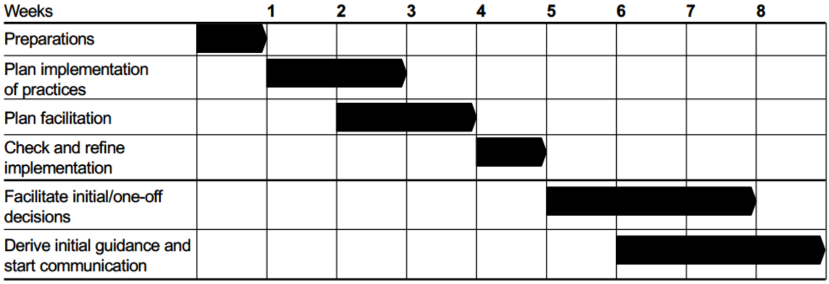

Figure A.10: Potential Timeline of Step 3, “Implement”

Preparations
Check the results of Step 2 (answers to the Guiding Questions) together with the teams and get an overview of the practices and routines to be established. Adjust teams if needed and form a team of decision makers to plan the facilitation.

Plan implementation of practices
Answer the Guiding Questions “How to implement practices to achieve objectives?” in the core team that involves all relevant actors with experience and expertise in uncertainties, conflicts, and synergies.
The results are initiatives (or alternative formats) to establish the practices defined in Step 2 that cover one-offs and routines to iterate uncertainties and conflicts over time. The template (Table A.33) and the success criteria in Table A.31, but also the details of the practices already provided in Tables A.23 to A.29 as part of Step 2, can be used to answer the Guiding Questions. Here, the implementation flow should be followed, which is inverse to the operationalization flow (see Figure A.9). The template suggests a differentiation by practices and iterations from the initial iteration to lasting routines that represent the cycles of targeted sustainability action. Please note that the answers to the Guiding Questions likely exceed the template (which provides the overall structure), and further details might be required for each of the fields to describe the implementation of the practices in a known comprehensible format.

Plan facilitation
Answer the Guiding Question, “How to facilitate implementation?”, according to the Success Criteria (Table A.31). This is highly dependent on the company and should

use existing routines. Results are practices needed to ensure decisions are made and that the resulting guidance is communicated to initiate action (or not).

Check and refine implementation
Compile an overview of the results and check they contribute to targeted sustainability action using the Check Sheet (Table A.32). Refine if necessary before proceeding with the initiation of targeted sustainability action.

This implementation planning marks the end of the initial iteration of the three steps to understand, operationalize, and implement targeted sustainability action (representing Stage 1: Guide application). To initiate this targeted sustainability action and to transition from Stage 1 to Stage 2 (continuous adjustment cycles), the results are compiled (Inform), the initial decision making is facilitated on the initiation of action (Decide), and the initial guidance is derived (Guide).

Transition to Stage 2: Facilitate initial decision making and initiate action
The practices Inform, Decide, Guide should be executed as defined in Step 2, “Operationalize”, and planned in Step 3, “Implement”. Thus, an initial fact base is compiled based on the results of the Guide’s application in a format that allows initial decision making (Inform). These initial decisions on targeted action or inaction made by the respective decision makers are then facilitated (Decide), and actionable guidance is developed and communicated that initiates the second cycle of targeted sustainability action consisting of Prepare, Enable, and/or Act practices (Guide). This also includes informed decisions and guidance on possible further facilitation until full integration of practices and routines.

3E. Supporting Material

Table A.32: Check Sheet for Step 3, "Implement". Detailed Implications on Individual Practices Can Be Found in Step 2, "Operationalize"

Success Criteria	**How to implement practices to achieve objectives?** *Initiatives to establish relevant practices to achieve objectives.*	**How to facilitate the implementation?** *Transformation management depending on company and conditions.*
Boosted	Aim for quick iterations of Decide and Prepare/Act to solve uncertainties and conflicts at appropriate level	Create attention and ensure top management commitment Set clear focus for the initiation of targeted action
Efficient	Prepare to build expertise and plan ahead Pilot to gain experience before scaling up Roll out practices selectively and sequentially	Avoid overinvesting and trade-off between efficient preparations and roll out of action
Integrated	Integrate practices and make use of regular routines, (e.g., set objectives in strategy) Add new practices only where necessary avoiding add-on solutions	Add new (facilitator) roles or Center of Competence only as enabler avoiding parallel organizations Phase out facilitation once practices are integrated in regular routines
Traceable	Document action to sustain progress over time and build capabilities	Maintain overview to stay consistent, avoid double-work and coordinate collaboration Create transparency through early communication

Table A.33: Template 4 – How to Implement Practices to Achieve Objectives?

Objective: **Owner:**

Iterations → Practices ↓	**0. Initial**	**1. One-off/increasing maturity of routines**	**2. One-off/increasing maturity of routines**	**Lasting routines (∞)**
Prepare	*Application of Guide: Steps 1-3 (Practice-definition)*			
Inform				
Decide				
Guide				
Enable				
Act				
Evaluate				

Table A.34: Template 4: Example 1 – How to Implement Practices to Achieve Objectives?

Objective: Example 1 **Owner:**

Iterations → Practices ↓	**0. Initial**	**1. One-off/increasing maturity of routines**	**2. One-off/increasing maturity of routines**	**Lasting routines** (∞)
Prepare	*Application of Guide: Steps 1-3 (Practice-definition)*	Define channels for identification Collect needs and value potentials		?_
Inform	Summarized documentation from Guide's application	Decision template with cost benefit evaluation		
Decide	Decide on relevance of topic to invest in research			?_
Guide	Define owner with capacities to drive evaluations and preparations			?_
Enable				?_
Act				? Incorporate customers' sustainability objectives into product engineering, where applicable
Evaluate	Check status quo: Customer requests and current situations			Dialogue with customers on potential support need or additional value

Table A.35: Template 4: Example 2 – How to Implement Practices to Achieve Objectives?

Objective: Example 2 **Owner:**

Iterations → Practices ↓	**0. Initial**	**1. One-off/increasing maturity of routines**	**2. One-off/increasing maturity of routines**	**Lasting routines (∞)**
Prepare	*Application of Guide: Steps 1-3 (Practice-definition)*	Check regulatory requirements Estimate simulation efforts Check reuse potentials of prototypes		
Inform	Summarized documentation from Guide's application	Decision template with expected resource reduction potential with cost implications of measures		
Decide	Decide whether to identify potentials	Decide on implementation		
Guide	Project to identify potentials for resource usage reduction	Adjust process descriptions		
Enable		Provide simulation tool chain Define requirements for introduction of new tests		
Act		Increase share of simulations Reduce number of physical prototypes		Reuse prototypes Avoid introduction of new tests
Evaluate	Check status quo resource usage in product engineering			

A.2 Interview Guideline

Notation:

Open question

- More specific question based on literature
  - Challenging question
    - Examples based on literature

Notes:
Introduction and closing with formalities etc. are omitted in this version of the interview guideline. [Company] is replaced by company name in the case of decision makers' interviews, and by "the companies you are working with" in the case of consultants' interviews.

Opener

Consultant: What are the companies you are working with currently most concerned about?

Decision maker: In your opinion, how present is the topic of sustainability at [Company]?

First research question

How is the topic of sustainability impacting product engineering at [company]?

        * Impact: Changes in attitudes, actions and conditions

    - How could it impact product engineering? Why and under which conditions?
        * Conditions: Macro-economic changes, societal changes, management changes

- Do you see any implications of (expected) product sustainability on product engineering?
    - Could there be? E.g., driven by stakeholders (objectives or requirements) or intended benefits? Why and under which conditions?
        * Stakeholders: Shareholders, external pressure groups, employees, authorities and government
        * Benefits: Market potential, competitive advantage, employee motivation
- Do you see any implications of (expected) company sustainability on product engineering?
    - Could there be? E.g., driven by stakeholders (objectives or requirements) or intended benefits? Why and under which conditions?
- Are there any stakeholders directly impacting product engineering?
    - Could there be? Why and under which conditions?
- Are there any intended benefits (expected from sustainability) directly impacting product engineering?
    - Could there be? Why and under which conditions?

How is product engineering impacting sustainability at [Company]?

    - How could it impact sustainability? Why and under which conditions?

- Do you see any impact of product engineering on product sustainability?
    - Could there be? Why and under which conditions?

- Do you see any impact of product engineering on company sustainability?
  - Could there be? Why and under which conditions?
- Is there any direct impact on stakeholders by product engineering?
  - Could there be? Why and under which conditions?

Is there a shared understanding of sustainability with respect to product engineering at [Company]?

  - Across all departments?

- Who defines this understanding (esp. in case of multiple understandings)?
  - What are the differences in your personal understanding?

How do you personally understand sustainability?

- How would you conceptualize it with respect to product engineering?
    * Objectives or Requirements, Triple Bottom Line (TBL), Sustainable Development Goals (SDGs), Planetary boundaries, Environmental, Social, Governance (ESG)
  - Do you see multiple understandings as beneficial to an operationalization of sustainability? Why?

Second research question

Where do you see current barriers in product engineering to a sustainability contribution?

- Would you see relevant aspects rather on a strategic, a tactical, or an operational level?
    * Strategic level: Company, business unit strategy
    * Tactical level: Functional strategy, operationalization (Objectives, resources)
    * Operational level: Strategic product planning (Business case of product), product development, production system development
  - Why do you think this barrier exists?
  - How does it affect product engineering?

How would you characterize a way of working in product engineering that is able to cope with your conception of sustainability and provide a targeted contribution?

  - Why do these characteristics make a difference?
    * Characteristics: Proactive and strategic, Systematic and consistent, Integrated and transformational, Context-specific and stakeholder-oriented

How can these characteristics be induced in product engineering?

- Which product engineering practices constitute a way of working inducing these characteristics and, which conditions need to be fulfilled?
    - * Practices: Attitudes, actions and their conditions
  - How would you shape and use Objectives to induce these characteristics? Why?
    - * Company and product objectives, priorities
  - How would you shape and use Capabilities to induce these characteristics? Why?
    - * Collective and individual capabilities
  - How would you shape and use Motivation to induce these characteristics? Why?
    - * Culture, incentives/deterrents
  - How would you shape and use Leadership to induce these characteristics? Why?
    - * Decision making, governance
  - How would you shape and use Organizational structure to induce these characteristics? Why?
  - How would you shape and use Processes and methods to induce these characteristics? Why?
    - * Product engineering process
  - How would you shape and use Collaboration to induce these characteristics? Why?
    - * Partnerships, cross-functional, cross-disciplinary
  - How would you shape and use Technology to induce these characteristics? Why?
  - How would you shape and use Tools to induce these characteristics? Why?
  - How would you shape and use Human Resources to induce these characteristics? Why?
  - How would you shape and use Financing and budgets to induce these characteristics? Why?
  - How would you shape and use Information to induce these characteristics? Why?

Would there be any dependencies between the practices to highlight?

  - Why these?

Third research question

How would you proceed to establish these practices at [Company]?

  - Any differences in the approach to other topics like digitalization, servitization?

Would you have any priorities and why?

  - If not, how would you identify them?

Fourth research question

How could [Company] be supported to contribute to sustainability through product engineering practice?

      * Support: Guidance, approaches, methods, tools

  Does this kind of support already exist?

  - If not, why not?

How could you personally be supported to contribute to sustainability through product engineering practice at [Company]?

- Does this kind of support already exist?
  - If not, why not?

A.3 Surveys

Pre-workshop Survey

Name

Role

What is your **understanding** of sustainability?

In your opinion, which **uncertainties** exist regarding sustainability in product engineering at your company?

How would you describe the current **understanding** of sustainability in product engineering at your company?

How is this understanding currently being **operationalized** and **implemented**?

What **expectations** do you have of today's workshop?

Post-workshop Survey

	Strongly disagree	disagree	neutral	agree	strongly agree
Does the **guide** …					
…focus on key decisions?					
…balance manageability and complex-ity?					
…incorporate the status quo?					
…exclude moral judgements?					

Does the application of the guide support to develop an **understanding** of sustainability in product engineering that is...					
...context-dependent?					
...consistent?					
...explicit					
...reasoned?					
...evolving?					
...long-term?					

Does the application of the guide support an **operationalization** of the understanding of sustain-ability in product engineering that is...					
…proactive?					
…collaborative?					
…actionable?					

Does the application of the guide support an **implementation** of sustainability action that is...					
…boosted?					
…efficient?					
…integrated?					
…traceable?					

Does the application of the guide **reduce uncertainties** regarding targeted sustainability action in product engineering?					

Do you expect that the application of the guideline can enable **targeted sustainability action** in product engineering?					

Further **feedback** on the guide, application and evaluation (please also use backside):

Post-project Survey

	Strongly disagree	disagree	neutral	agree	strongly agree
In your opinion, is the **understanding** of sustainability in product engineering **consisting of opportunities/risks** and derived **objectives**...					
...context-dependent?					
...consistent?					
...explicit					
...reasoned?					
...evolving?					
...long-term?					

In your opinion, is the **proposed action** on the **objectives** presented...					
…proactive?					
…collaborative across different departments?					
…actionable?					
…boosted?					
…efficient?					
…integrated in existing processes at [company]?					
…traceable?					

Is the **checklist** presented for considering sustainability in the definition phase...					
…comprehensibly structured?					
…intuitive to use?					
…contributing to achieving the objective "supporting customers to meet their sustainability requirements"?					

If the **checklist does not contribute to achieving the objective, why not**? (Please also enter any **other comments** on the checklist here)

Is the presented **work instruction** for considering sustainability aspects in product engineering...					
…comprehensibly structured?					
…intuitive to use?					
…contributing to achieving the objective "comply with sustainability regulations"?					

	Strongly disagree	disagree	neutral	agree	strongly agree

If the **work instruction does not contribute to achieving the objective, why not**? (Please also enter any other comments on the work instruction here)

Do the presented results **reduce uncertainties** regarding **targeted sustainability action** in product engineering?					

Do the presented results **contribute to targeted sustainability action** in product engineering?					

Which further **support is needed** to **enable targeted sustainability action** in product engineering?

Further feedback / comments / remarks

Page 2 of 2

Publications Co-Authored by the Author of This Dissertation

Albers, A., Tusch, L., Jäckle, M., Seidler, M., Kempf, C. (2024). Circularity in product engineering – towards a forward-looking approach across product generations. *Proceedings of the Design Society*, *4*, 1–12. https://doi.org/10.1017/pds.2024.3

Jäckle, M., Does, E., Tusch, L., Albers, A. (2025). Sustainability in product engineering - a guide to initiate targeted sustainability action. *Proceedings of the Design Society*, *5*, 2961–2970. https://doi.org/10.1017/pds.2025.10310

Jäckle, M., Seidler, M., Tusch, L., Rapp, S., Albers, A. (2023). Towards a Consistent Understanding of Sustainability in Product Engineering - A Systematic Literature Review and Explication Framework. *Procedia CIRP*, *119*, 770–775. https://doi.org/10.1016/j.procir.2023.03.123

Krüger, M., Jäckle, M., Pfaff, F. (2023). *Teaching Ethics As Practical Reflection In A Project-Based Engineering Course.* European Society for Engineering Education (SEFI). https://doi.org/10.21427/rxtm-f615

Tusch, L., Jäckle, M., Albers, A. (2024, August 12–14). Towards Design for Cross-Generational Remanufacturing: A Literature Review and Concept Proposal. In *Proceedings of NordDesign 2024* (pp. 206–215). Reykjavik, Iceland. https://doi.org/10.35199/NORDDESIGN2024.23

Tusch, L., Nußbaumer, S., Jäckle, M., Düser, T., Albers, A. (2025). Towards design for cross-generational remanufacturing: guidelines to enable a forward-looking circularity. *Proceedings of the Design Society*, *5*, 3181–3190. https://doi.org/10.1017/pds.2025.10332

Tusch, L., Pirc, V., Jäckle, M., Düser, T., Albers, A. (2025). Cross-Generational Remanufacturing: Identifying high-potential subsystems through differential analysis of product generations. *Procedia CIRP*, *135*, 1234–1239. https://doi.org/10.1016/j.procir.2024.12.124

Wilmsen, M., Gericke, K., Jäckle, M., Albers, A. (2020). METHOD FOR THE IDENTIFICATION OF REQUIREMENTS FOR DESIGNING REFERENCE PROCESSES. *Proceedings of the Design Society: DESIGN Conference*, *1*, 1175–1184. https://doi.org/10.1017/dsd.2020.301