

Review

Ecodesign—A Review of Reviews

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Abstract: With the intent of summing up the past research on ecodesign and making it more accessible, we gather findings from 106 existing review articles in this field. Five research questions on terminology, evolution, barriers and success factors, methods and tools, and synergies, guide the clustering of the resulting 608 statements extracted from the reference. The quantitative analysis reveals that the number of review articles has been increasing over time. Furthermore, most statements originate from Europe, are published in journals, and address barriers and success factors. For the qualitative analysis, the findings are grouped according to the research question they address. We find that several names for similar concepts exist, with ecodesign being the most popular one. It has evolved from “end-of-pipe” pollution prevention to a more systemic concept, and addresses the complete life cycle. Barriers and success factors extend beyond the product development team to management, customers, policymakers, and educators. The number of ecodesign methods and tools available to address them is large, and more reviewing, testing, validation, and categorization of the existing ones is necessary. Synergies between ecodesign and other research disciplines exist in theory, but require implementation and testing in practice.

Keywords: ecodesign; literature review; meta review



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1. Introduction

Ecodesign is an approach to include environmental requirements into the product development process. It has the potential to contribute to reductions in greenhouse gas emissions, thus slowing down climate change, and to address several of the 17 Sustainable Development Goals declared by the United Nations [1]. For ecodesign researchers, moving forward requires knowledge and understanding of the past efforts and achievements.

However, the sheer volume of published research in this area may quickly overwhelm a researcher new to the field of ecodesign, such as a graduate student. The task of assessing the state of research is complicated further by the variety of terms used to describe similar or nearly identical concepts, such as design for environment (DfE), life cycle engineering (LCE), or sustainable product design (SPD). Already, a number of reviews of the field exist. However, some of these may be dated, and therefore not include the latest findings [2], or focus only on specific aspects of ecodesign such as tools and methods [3–5]. As the volume of ecodesign research expands with an increasing pace [6], it becomes harder to keep an overview.

The aim of this article is to provide a review of the ecodesign field of research to novice researchers. We seek to cast a wide net and combine various perspectives, by reviewing existing reviews in the field. The two main reasons for choosing this procedure are, as we argue, that (1) the body of literature has grown too large to assess in its entirety and (2) the central findings are expected to appear in existing review articles and studies.

This review differs from other review articles, as it builds upon the analysis of other researchers, hence constituting a “summary of summaries”. By indirectly incorporating

findings from a large number of primary research articles referenced by the reviewed literature, we seek to build our analysis on a solid scientific foundation.

The following research questions, which gradually emerged from the initial scope and the process of reviewing the literature, guide the review and analysis process:

- **RQ1:** Which names exist for concepts that may be considered similar or equal to ecodesign (ED), and what are the distinctions that can be made between the concepts?
- **RQ2:** How did the current understanding of ED evolve over time?
- **RQ3:** What are the barriers and success factors for the spreading and implementation of effective ED practices?
- **RQ4:** What is the current state of research on ED methods and tools with respect to their availability, effectiveness, requirements, and utilization?
- **RQ5:** What are the potential synergies between ED and other approaches and concepts from outside the field?

The structure of this review article is as follows. After elaborating on the methodology in Section 2, we present the results of the literature review in Section 3. In Section 4, we summarize our findings as well as the limitations and delimitations of this study. Section 5 contains the final conclusion.

2. Methodology

We conducted a literature review, which is broadly split up into the two steps of retrieving and then analyzing relevant literature.

2.1. Literature Retrieval

The primary search engines used are Scopus and Web of Science (WoS). Additionally, the search engines of the scientific publishers Emerald, SagePub, ScienceDirect, Springer, Taylor & Francis, and Wiley were used to find additional literature, which might not be indexed by Scopus or WoS. Lastly, Google Scholar (GS) served as the final search engine to identify relevant literature. Since the suitability of GS for conducting a scientific literature review has been debated controversially [7,8], it should be noted that the results of the GS search are meant to fill in the potential gaps in the literature retrieved up until that point. When using GS, we aborted the search after ten pages of search results without any relevant literature for each search term.

The search terms we employed are depicted in Figure 1. The search was conducted as an iterative process, as we discovered new search terms after reviewing the first search results and subsequently included them into the search.

Initially, we included the search terms “eco innovation”, “environmental innovation”, and “green innovation”. However, as these terms provided results that we saw as being out of the scope of this article (see Section 3.2.2), they were omitted. Where the search engines allowed for such a constraint, we limited the search terms to the title, abstract, and keywords of an article.

The type of literature included contains peer reviewed journal articles, conference proceedings, doctoral theses (and licentiate theses (A licentiate is “an academic degree ranking below that of doctor given by some European universities” according to the Merriam-Webster dictionary (<https://www.merriam-webster.com/dictionary/licentiate>))), and reports by major official organizations and/or experienced researchers in the field. Book chapters were not included, as it is the impression of the authors that the relatively young research field of ecodesign does not have a standard book routinely quoted by a majority of researchers. Compare this to the field of product development, where many articles reference the books of either Pahl and Beitz [9] or Ulrich and Eppinger [10]. Neither the year of publication nor the type of journal/conference/research affiliation was subject to limitation.

Next, we reviewed the titles and abstracts of the extracted material and assessed their relevance to our search. As it is difficult to draw a sharp line around the field, the filtering criteria are briefly elaborated on here.

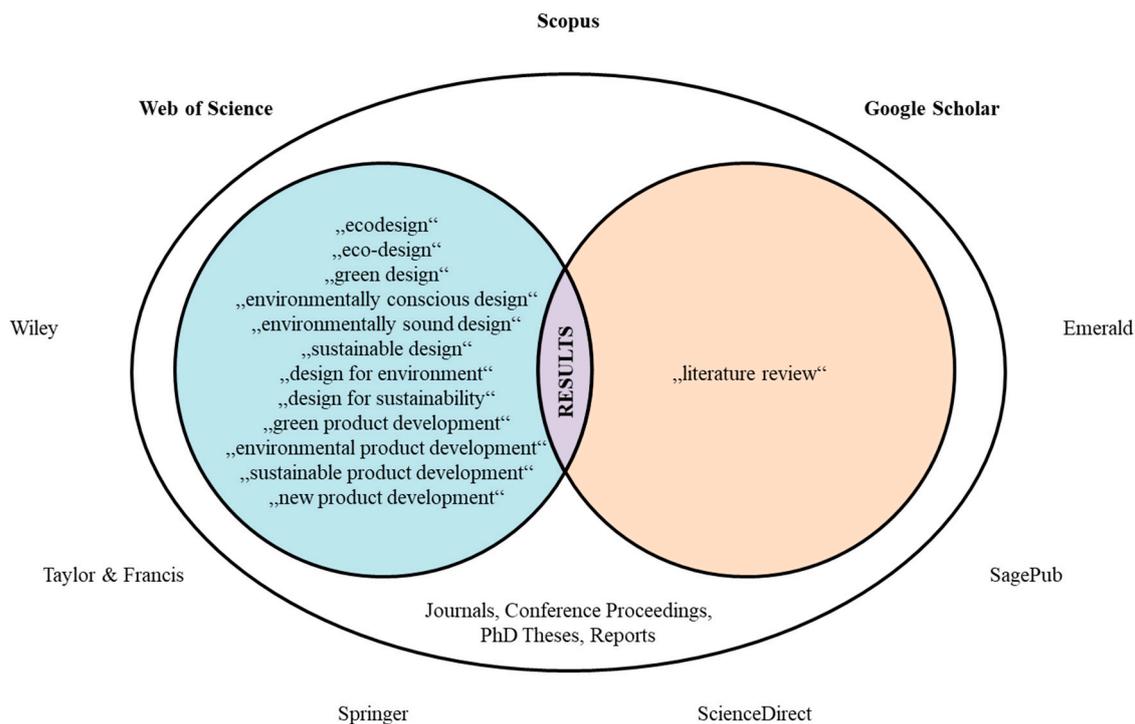


Figure 1. Illustration of the search strategy for the literature review.

To be included, the studies have to be review articles or have to include a thorough literature review (e.g., a doctoral thesis). Other research methods (interviews, case studies etc.) may appear as well, but the literature review should make up a significant fraction of the study. A study has to relate to product development or engineering design in a wider sense, as ecodesign can also be found in urban planning, architecture, or civil engineering, for example. Also, no articles that solely focus on neighboring disciplines of ecodesign/product development/engineering design, such as product marketing or supply chain management, were included. This does not relate to the articles bridging two disciplines, however, where ecodesign/product development/engineering design is one of them.

Research with a too narrow focus was excluded as well. An example would be a review of “design for remanufacturing” strategies, as the topic may be considered part of the ecodesign field. Reviews of product/service-systems (PSS) were included, if they focus on the sustainability aspect of PSS. Studies on “Design for the base of the pyramid”, where the “base of the pyramid” (BoP) stands for the least affluent share of the global human population [11,12], were not within the research focus of this study. No studies focusing only on one company, one industry or one country are included, as to avoid being too context specific.

Finally, we conducted an upstream and downstream search using the identified literature (reviewing citing and cited articles). As a result, 106 separate reviews (as listed in Table A1 in the Appendix A) were identified. We argue that these numbers indicate a solid foundation for extracting research findings.

The 106 review articles were published between 1994 and 2018. Earlier relevant articles may exist, but the literature retrieval process previously described did not identify any. Articles published later than 2018 may have been missed due to the timing of the research process for this review article. The literature retrieval stage was concluded at some point, in order to move on to the analysis, conceptualization, and writing stage.

2.2. Analysis

The analysis primarily covers the content of the articles' abstracts as well as their summary/conclusion section (if existent), except where indicated differently. We argue that in many cases, these sections contain the most important findings of an article. If the conclusion section indicates that key insights are covered in other sections of the article, we analyzed these as well. For theses, the scope is limited to the "state of research" section.

We then extracted statements from the aforementioned sections that passed the inspection using the filtering criteria from Section 2.1. These statements we copied into a spreadsheet containing the publication year, author(s), title, publication type (e.g., journal publication), and publication body (e.g., name of publishing journal) for each publication containing the statements, among other information. The spreadsheet can be found in the supplementary materials.

We sought to include all findings we were able to extract with the described procedure, omitting those that we considered trivial. Using the spreadsheet, we engaged in a quantitative and qualitative content analysis described in detail in the following results section.

3. Results

In the first part of the results section, we conduct a quantitative analysis of the publications which we reviewed, and the statements extracted from them (Section 3.1). In the sections after that, we conduct a qualitative analysis on the content of these statements. Each of the sections cover one of the five research questions (RQs) guiding this review, beginning with Section 3.2 on RQ1 and ending with Section 3.6 on RQ5.

3.1. Quantitative Analysis

We find that the analyzed publications can be classified according to the overall purpose of the article, i.e., "How can the nature and motivation of the publication best be described?" In total, we identified seven primary purposes:

- Provides a general overview of the field of ecodesign;
- Compares different concepts/approaches related to ecodesign (e.g., lean and green manufacturing);
- Combines ecodesign with an approach outside of the field (e.g., project management);
- Identifies barriers and success factors for ecodesign implementation;
- Discusses ecodesign methods and tools;
- Proposes a framework;
- Theses (doctoral and licentiate).

There appears to be a significant overlap between these primary purposes and the RQs, most notably pertaining to methods and tools, as well as barriers and success factors. These purposes serve as a perspective to view the publications under review. An insight into the temporal distribution of the studies reviewed in this article, both overall and split up into the primary purpose of the studies is depicted in Figure 2.

Out of the 106 studies overall, most have been published for the primary purpose of providing a general and/or historical overview of the research area, while the fewest have been theses (doctoral or licentiate). The trend indicates that the number of studies relevant to this review has been increasing over the years, especially those studies combining two fields. The years with the most studies are 2012, 2014, and 2015, with ten articles published in each of these years.

The following analysis departs from the article level and descends to the level of individual statements. From the references, we extracted 608 statements in total. The full list of statements can be retrieved from the online version of this article in the supplementary materials. The analysis shows in which year the article from which the statement stems from was published, the region of the publication's primary author's affiliation, the type of publication, and the primary purpose of the publication. A Sankey diagram illustrates the result of this analysis, shown in Figure 3.

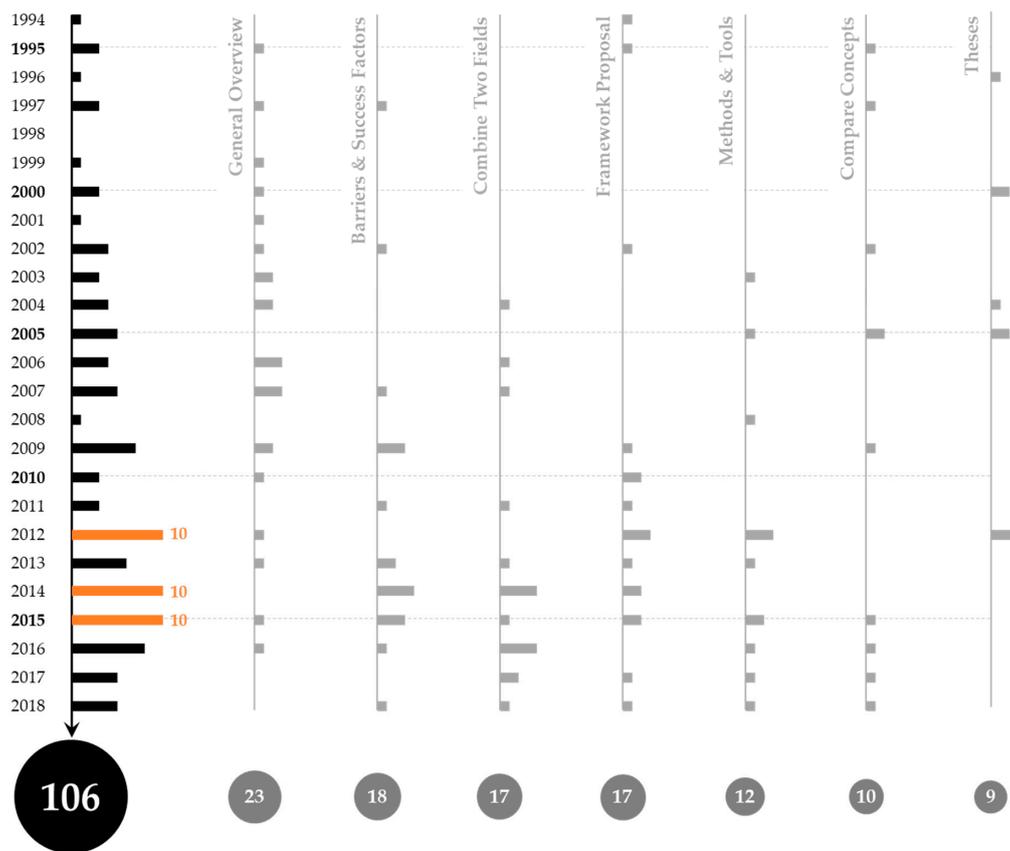


Figure 2. Number and publication year of references that were retrieved and analyzed for this review, in total (black) and by primary publication purpose (grey).

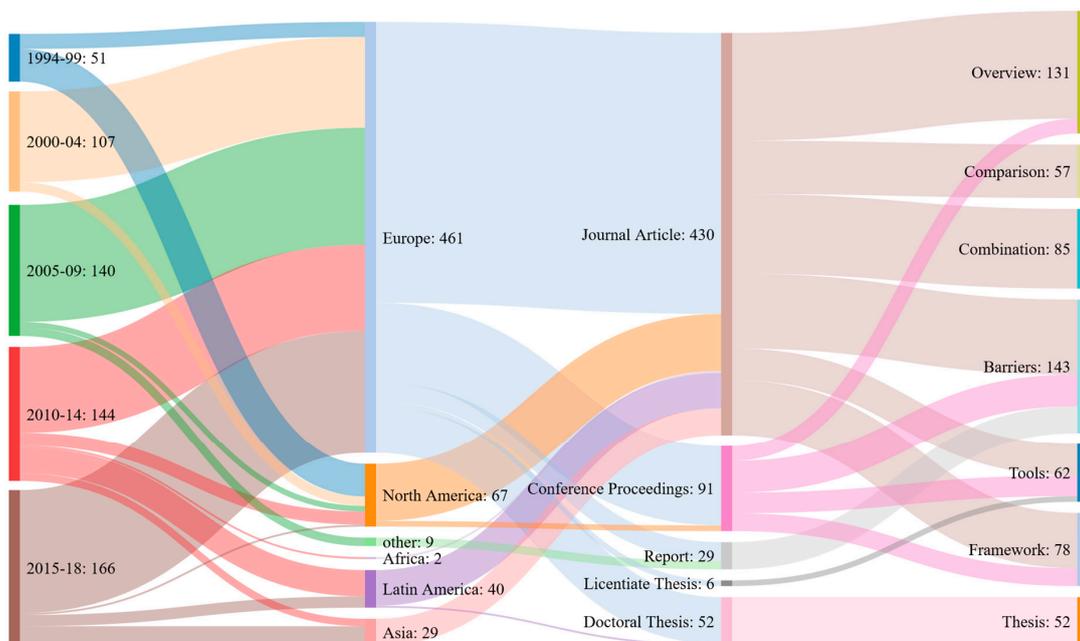


Figure 3. Sankey diagram on the origin of 608 statements extracted from 106 review articles on ecodesign. From left to right: publication year of the article from which the statements were extracted; location of the institution the primary author of the publication was affiliated at the time; type of publication the statement appears in; primary purpose of the publication the statement appears in. The Sankey diagram was created using the free online tool SankeyMATIC by Steve Bogart (www.sankeymatic.com).

By far the most statements originate from Europe, more than from all other regions combined. However, in recent years, an increasing share of statements has been originating from Asia (including Australia and Oceania) and Latin America. Most statements stem from journal articles, followed by conference proceedings and doctoral theses. The distribution is less skewed for the primary purpose of the publications from which the statements originate. Most statements are from publications with the primary purpose of discussing barriers and success factors for ecodesign implementation (143 out of 608 statements).

For the final analysis in this section, we direct our attention toward the purpose of the individual statements. To this end, the statements were categorized according to the research question (RQs) they address. Some of the statements relate to multiple RQs. Figure 4 shows a bar chart depicting the results of this analysis.

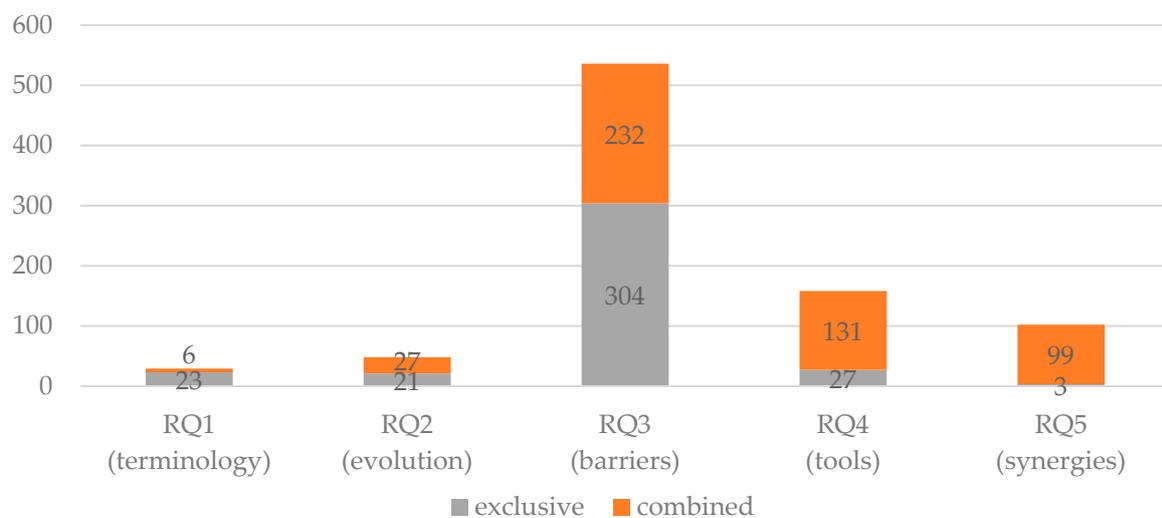


Figure 4. Analysis of 608 statements extracted from 106 review articles on ecodesign, categorizing the statements by the research question (RQ) they address. The RQs are stated in full in the introductory section of this article. “Exclusive” describes statements which only relate to one of the RQs, whereas “combined” refers to a statement that touches on multiple RQs. Because of this overlap, the sum of all values adds up to more than 608 (the number of statements in total).

By far the most statements relate to barriers and success factors for ecodesign implementation, followed by statements on methods and tools. Statements on ecodesign terminology rarely touch on other RQs as well, while statements pertaining to synergies between multiple fields of research almost always do.

To sum up, the quantitative analysis reveals that there has been an increase in recent years for ecodesign review articles. Most of the statements summarized in the Sections 3.2–3.6 originate out of Europe, were published in journal articles, and address barriers and success factors for ecodesign implementation. Moving on to the qualitative analysis, we follow the logic of the initially stated five research questions. Hence, the next section covers terminological aspects of ecodesign (RQ1).

3.2. Terminology

This section is intended to clarify the concept of sustainability, and provide an overview of the definitions for ecodesign and other related approaches aiming to achieve sustainability based on the references analyzed in this review.

3.2.1. What is Sustainability?

Full sustainability, in its strictest sense, is impossible to achieve. Because of the second thermodynamic law, which states that the entropy within the universe increases over time, there is no way—as far as we currently know—to achieve a truly sustainable state at large timescales [13]. Therefore, sustainability may be considered a time-dependent

property. A system can be considered sustainable over a time period of one month, but unsustainable when expanding this time period to one decade [14]. The definition of the Brundtland report, to name a frequently cited definition of sustainable development, includes a timespan covering multiple (human) generations (“[meeting] the needs of the present without compromising the ability of future generations to meet their own needs”) [15].

Second, sustainability is a systemic property. Therefore, a product, a process, or a company, cannot in itself be considered sustainable. Instead, these entities should be seen as parts of systems, which in turn may serve as the basis for assessing sustainability [11]. These systems may be technical, social, biological/environmental, or a mix (e.g., socio-technical). In fact, it seems that ecodesign researchers seem to focus mainly on the technical aspects, and neglect social (and other) aspects of potential solutions [16,17].

This leads to the third aspect of sustainability discussed here: sustainability is widely accepted to encompass economic, environmental, and social aspects. These should not be viewed in isolation, as researchers suggest, but instead interdependencies among them should be the subject of ecodesign practice and studies [6,18–21]. Trade-offs among the different aspects will often be inevitable [22,23], which may be addressed by an integrated approach [18,24]. Other researchers describe the three aspects as being more or less equivalent (“three pillars”, “triple bottom line”) [25,26]. These varying perspectives often lead to differing opinions on how to weigh environmental, social, and economic criteria against one another, which further complicates the trade-offs which inevitably arise [26,27].

Closely related to the time-dependency of sustainability are the concepts of absolute vs. relative sustainability, effectiveness vs. efficiency, and radical vs. incremental improvements [28–31]. As stated above, absolute sustainability can only exist for a predefined period of time. Relative sustainability is a weaker qualifier and may be used to compare two different systems, where one is relatively more sustainable than the other (but does not specify if one or both systems are sustainable in an absolute sense). Arena describes how definitions of relative sustainability may change over time, as newer and cleaner technologies become available [32]. In order to achieve absolute sustainability, effective solutions are required [33,34]. Efficiency increases, however, by definition provide only relative improvements. The Organisation for Economic Co-operation and Development (OECD) describes efforts that are more radical than conventional ecodesign as “eco-innovation” [16]. Some authors doubt that technological improvements alone suffice to reach a sustainable state, considering the population growth trends [34].

3.2.2. Product Development Approaches to Reach Sustainability

For this section, we extend the scope of analysis beyond the abstract and the conclusion section of the reviewed research articles, since terminology is rarely discussed in these sections. Before providing definitions for ecodesign and related approaches, it should be noted that multiple scholars find that these clear definitions do not exist and/or have not received widespread recognition [29,35,36]. This poses a challenge for researchers seeking to identify the relevant literature in the field [37]. More specifically, Lenox and Ehrenfeld [38] argue DfE consists of multiple concepts, tools, and practices; however, a widely accepted approach on how to employ them in order to increase DfE capabilities is missing. Keoleian and Menerey [24] extend this lack of definitions to system boundaries, goals, objectives, principles, and metrics of and in ecodesign. Tonelli et al. [29] proposed a collaborative effort of industry, government, and academia in developing a common definition, coupled with an assessment and reward system for sustainable industrial practices. Mattioda and colleagues [39] suggest that acknowledging a universal model for the product development process (PDP) may be a first step in the right direction. O’Hare and McAloone [40] see a widely accepted typology as a potential solution to the problem.

We propose that *ecodesign* is characterized by three central aspects: (1) it refers to the design and development of products; (2) it is aimed at reducing the environmental impact of these products; and (3) it takes the complete product life cycle into account. These characteristics reflect the general research consensus. More disputed is whether

the “eco” in ecodesign only stands for “ecological”, or if it also refers to “economical”, as for example Karlsson and Luttrup propose [33]. The majority of studies focus on the former [33,41], while paying relatively little attention to the latter. Profitability is a product aspect not typically optimized within ecodesign, while the environmental impact of the product is. The same can be said for product function and performance. Social aspects are rarely addressed in ecodesign [27]. Hübner suggests that ecodesign is an instrument, not a strategy, for achieving environmental goals, and should therefore not be used to set these goals. She also identifies the life cycle principle as the origin for ecodesign criteria [27]. While most ecodesign activities may originate from engineering design research and product development departments, it ultimately affects other research domains and company departments, including production, logistics, recycling, and many more. Explicit definitions of the term ecodesign are stated for example in [33,42–48].

Other terms related to ecodesign include:

- Life Cycle Design;
- Life Cycle Engineering;
- Design for Environment (DfE);
- Environmental Design;
- Environmentally Conscious Design;
- Green Product Development;
- Ecological Design;
- Sustainable Innovation;
- Sustainable Product Development;
- Sustainable Product Design;
- Industrial Sustainability;
- Design for Sustainability;
- Eco Innovation;
- Sustainable Design;
- Sustainable Life Cycle Design;
- Sustainability Oriented Innovation;
- Whole Systems Design;
- Environmentally Friendly Product Design;
- Environmentally Sustainable Product Innovation;
- Product Development Oriented to Sustainability;
- Green Product Innovation;
- Design for System Innovation.

Most of these terms describe concepts very similar to that of ecodesign. The different naming can partially be explained by the various research disciplines from which the researchers come from (e.g., engineering, design, economics). “Innovation” has a wider scope and can refer to, among others, products, processes, and organizational aspects [49]. While “sustainable” may encompass also economic and social aspects, it mostly refers to environmental sustainability in the body of literature examined here. Ceschin and Gaziulusoy provide an overview of approaches, which they classify according to their scope, which ranges from product level to socio-technical systems level [12].

Product-Service-Systems (PSS) differ from the terms described above, as they extend beyond physical product to include non-material aspects of service provision. Tukker and Tischner provide a definition: “[a PSS] consists of a mix of tangible products and intangible services designed and combined so that they jointly are capable of fulfilling final customer needs” [50]. In principle, PSS have the potential to provide the same results as products with less material input and thus less environmental impact [51,52]. Ceschin finds that PSS are mostly radical innovations requiring a change in customer habits, organizational structures, and regulation, which may explain why their diffusion has been slow [53]. As for PSS research, Tukker states that the concept of PSS has matured, and is a subject of study within multiple research disciplines [51]. According to Baines et al., most PSS case studies seem

to emphasize on environmental and social aspects, while fewer demonstrate economic success [54].

3.3. The Evolution of Ecodesign

Having proposed a definition in the previous section, we seek to provide some perspective on how the field of ecodesign has evolved in the past and reached its current state. After all, Boks' and McAlloone's statement on the value of being aware of the historical context and successive transitions within the field of ecodesign may well be extended beyond product designers, and include researchers as well [55].

Ecodesign is still at an early stage of evolution. Initially stated by Dewberry in 1996, this statement has been repeated multiple times over the years up until the present day [47]. Variations of it refer to both the development of the concept of ecodesign as well as the implementation of ecodesign practices in product development. In their 2007 report, Charter and Clark include in their findings regarding the general level of ecodesign application the unfamiliarity of most product designers with the topic, and a stagnation of ecodesign uptake in some countries/companies (while growing in others, such as Japan) [30]. As of 2008, Telenko and Seepersad find that new ecodesign principles are still being discovered, and expects inspirations from other domains such as building architecture [56]. In 2013, Mattioda and colleagues judge the implementation of ecodesign into the product development process to still be in a discussion phase [25]. Three years later, Thomé and colleagues note that themes related to ecodesign are still not well developed [27]. Finally, in 2018, de Medeiros et al. support Mattioda's findings regarding the inclusion of ecodesign into the PDP, and emphasizes on the greatest potential during the early stages of the process [57].

The lack of speed in the development of the ecodesign concept and its application does not appear to be due to a lack of external forces pushing in this direction. Researchers agree that the pressure on companies to adopt ecodesign is growing. It stems from consumers demanding "greener" products [23,58], grass roots organizations, and NGOs pushing for a change in industrial practices [58], increasingly stringent legislation and regulation [23], as well as companies' fears of being sued for environmental consequences of their business activities [23]. Besides avoiding negative outcomes, the application of ecodesign may also increase the likeliness of positive outcomes by improving a company's competitiveness [4,23]. Hauschild et al. lament a lack of "hard legislation", and found that existing regulation, such as the integrated product policy (IPP), mostly relies on incentives rather than punishment [20].

As for how to address environmental issues, the approaches of companies have changed from "end-of-pipe" solutions to holistic pollution management, and from dealing with point sources to diffuse sources of emissions. Site-specific pollution issues (point sources) have mostly been addressed successfully, and in many cases led to a decentralization of pollution (diffuse sources) by shifting toward the consumer [59]. Environmental strategies and management systems have helped in addressing environmental issues within the company and fostered the uptake of a product life cycle perspective [16]. More recently, this perspective has been enriched by systemic and long-term thinking [11,12], accompanied by researchers and practitioners framing sustainability as a socio-technical challenge instead of a problem with purely technical solutions [12]. Simultaneously, policies and regulation have gradually moved away from pollution prevention at the source and toward addressing environmental issues along the whole life cycle, specifically during product use [60].

Not just regulators, but also industry are gradually adopting life cycle thinking and increasingly expected to do so in the future. Altig expects life cycle engineering (LCE) to spread across industries and companies of all sizes, namely small and medium sized companies [58]. In 2005, Hauschild et al. found that a number of large corporations have started to engage in life-cycle-oriented management and sustainability [20]. The OECD,

in their report on eco-innovation, also emphasize the need for focusing on the whole product life cycle [16].

Perhaps not surprisingly, ecodesign theory is ahead of practice. This translates into a lack of practical guidelines [47] and the absence of ecodesign practices in mainstream industry [55]. It also causes a mismatch between which life cycle phases are most frequently targeted by (theoretical) guidelines (primarily production), and which phases are typically addressed by practical measures (use and after-use) [61]. Nonetheless, based on past trends, Pigosso et al. expect the number of scientific publications on ecodesign to increase further [6].

The PSS concept, originating from Scandinavia [54], has evolved in parallel to ecodesign. In his review article, Tukker finds that the PSS concept has matured and ongoing developments of methodologies occur within a largely fixed framework [51].

Ecodesign has been evolving at a different speed in various regions of the world. Starting out with the burden of a minority of the global population which causes the majority of the environmental impact [48], the developed countries were the first to undertake efforts in environmental management and ecodesign. In practical terms, Asian countries seem to be lagging behind their European peers in adopting environmental strategic approaches [62]. In academia, Europe, Asia, and South America are home to the institutions with the highest publication track record on ecodesign methods and tools, while researchers from the United States have the highest number of published journal articles on this topic [6]. The consensus appears to be that mutual learning between developing and developed countries should be fostered in ecodesign. Concrete advice entails the use of shared taxis and rickshaws [63], learning from the previous mistakes (regarding the use of harmful substances) of the industrialized world [21] and, aimed at multinational corporations, the exporting of environmental and social standards from industrialized to developing nations [20].

3.4. Barriers and Success Factors

By far the most statements extracted from the references (536 out of 608 in total, see Figure 4) refer to barriers that stand in the way of successful spreading and adoption of effective ecodesign (ED) practices, or named measures that are considered necessary or beneficial to it. We split up these findings according to their perspective. Those measures that are most relevant for practitioners (product developers, designers, ED experts and managers within companies designing and making products) can be found in Section 3.4.1, measures relating to research and educational activities in Section 3.4.2, and measures which should be addressed by policymakers in Section 3.4.3. Barriers specifically referring to ED methods and tools are discussed in Section 3.5 (Methods and Tools).

3.4.1. Practitioner Perspective

Val Segarra-Oña and colleagues found that implementing ecodesign can make a company more competitive, cost-effective, better at developing new products and improve its image [42], and may even affect the behavior of its customers [64]. However, it also adds an additional layer of complexity to product development [24]. There is no consensus on the extent to which sustainability issues are currently considered in product development [22].

The following statements sum up how a company should (and should not) go about adopting ecodesign practices, according to findings from the literature review. This section is split up into issues related to (a) a company's strategy and management, (b) collaboration and communication issues, and (c) issues concerning the product development department.

(a) Strategy and Management

Make sustainability a strategic issue within a company, and implement it at multiple levels (strategic, tactical and operational) [6,39,41,65–67]. Product requirements can be found at the operational level, practical guidelines and systems to link strategic objectives at the tactical level, and the decision on how sustainability should be integrated into an organization at the strategic level [16,41]. Currently, top-down and bottom-up approaches

to reducing environmental impact are not coordinated, according to Baumann et al. [2]. A starting point may be a company's technology strategy, which should encompass environmental issues, and to address these issues as business issues [45,68,69]. Strategies should also be flexible, to anticipate technological and societal changes [17]. A mission and a shared vision should guide the company's strategy [30]. For comprehensive strategic planning, a systems perspective and backcasting—the method of deriving action steps from a desired future outcome—may serve to be useful [21,66]. The higher-level strategic support can provide ecodesign efforts with goals and support [61] and with suitable business models [65]. With the Circular Economy receiving an increasing amount of attention, the focus lies especially on resources, their recovery, and appropriate design strategies, all of which are guided by strategic decisions [28]. Collaboration and communication may be critical in establishing strategic support for ecodesign [68], which we discuss in detail a few paragraphs down. While the individual strategic approaches to sustainability may vary between companies [32,62], already more than 50% of those investigated by Albino et al. in 2009 are developing green products. Those that do are supported by environmental strategic approaches to a higher degree than those that do not [62]. Still, a better understanding is needed on how drivers on environmentally responsible behavior by companies (which includes ecodesign) work [70].

Implement ecodesign into management practices [30,71]. At the time, Robèrt et al. found that relevant indicators such as the results from life cycle assessment (LCA) rarely influence business decisions [21]. Watz and Hallstedt find that companies treat environmental requirements either as separate product requirements (such as legal compliance), or they relate them to traditional design requirements (e.g., "low product weight") [41]. Managers should coordinate product development teams through training and by using gatekeepers [37,38], set the direction for ecodesign efforts, define goals and allocate resources [45,72], and provide commitment and support [45]. Especially when aiming for higher degrees of sustainability, the management of product development becomes crucial [33]. Beyond product development, management efforts should stretch across technologies, operations and supply chains [54], and coordinate ecodesign efforts across the whole product portfolio [22]. Managers should take an interdisciplinary approach, consider the complete life cycle, weigh functionalities against one another, and take into account stakeholder interests [73]. The difficult task of ecodesign managers is complicated further by the fact that they need to, and should, seek acceptance for ecodesign in their work environment [74]. Finally, the list of tasks is completed by strategic envisioning, tactical networking, operational innovation and reflexive monitoring and evaluation [14]. Risk analysis and management may be a place to look for inspiration—see also Section 3.6.2 for more on risk management [20].

Match ecodesigned products with viable business models. Especially when shifting toward service orientation (see Section 3.4.2 on product service systems), economic incentives for manufacturers may change (e.g., from selling a product to providing a function) [52]. As a result, companies have to rethink their business case [30]. For that to happen, sufficient drivers need to be in place [59]. In fact, the prospect of gaining a competitive advantage, cost reduction and market benefits appear to be the most important antecedents of ecodesign [75]. Seizing the occasion, companies should explore opportunities not just for economic, but also environmental value creation [30]. Ecodesign business models should clearly define the role and direction for design [65]. Furthermore, to avoid product obsolescence and resource scarcity, these new business models should reflect a system's perspective by attaching an appropriate value to resources at every stage of the product life cycle [65]. Bocken and colleagues strengthen the connection between ecodesign and business models by categorizing eight types of sustainable business model archetypes [76], as they argue that multiple business models and design strategies are required for a sustainable way of doing business [77]. A possible result of adopting new business models may be a fundamental change in how businesses operate [60], including business partners along the supply chain and within the wider service provider network [65]. More specifically,

producers need to think about how a repeated capture of over time may look like (e.g., for remanufacturing), how reverse logistics supply chains should be configured, and how to retain economic control of their product along these processes [28]. Examples for such business models already exist, their variety reflecting the whole range of Design-for-X strategies (X = longevity, reparability, upgradability) [78].

Adjust organizational structures and routines [64]. Ecodesign can become part of standard work processes by including environmental impact assessment in decision-making (e.g., at review gates) conducting environmental audits, and fostering interaction between environmental experts and product developers [30,72]. Especially when these routines are difficult to imitate, ecodesign capabilities may become a competitive advantage [38]. Other organizational needs include vision and leadership, a different culture, new roles and responsibilities, and the development of existing capabilities [30]. Documents outlining a specific plan for each project within an organization and procedures for communication among multidisciplinary teams can support this transformation process [67]. On a more strategic level, companies should align the development of the organization as a whole with its ecodesign activities [66].

Take “soft factors” into account that influence the behavior of employees [79]. Psychological and social factors are often overlooked, even though they tend to comprise the most significant obstacles for ecodesign implementation [79]. Employee behavior is affected by the alignment of personal responsibility, societal development, and company activities [72]. Encouraging them to take an active part in ecodesign implementation may improve their motivation [45]. Communication, language, and personal views and objectives should play a key role in this process [79].

Justify the product purpose—focus on human needs [21]. Instead of looking at how a product is produced, companies should question what they produce—and whether the product function justifies the resulting environmental impact [52]. While there is already some legislation regarding the former, no laws currently govern the latter aspect [20]. Putting more emphasis on actual human needs and wants, deriving from them required functions, mapping the required resources, and finding creative ways of fulfilling these needs, should be the way forward to meet current and anticipated demand [33,48,80]. In order to ensure the survival of the company, these needs-oriented products should contribute to the financial bottom line early on [21]. The most efficient way to do this is still the subject of ongoing research [19]. This discussion is in close relation to the concept of “eco-efficiency” and “eco-effectiveness”.

Be proactive, not reactive. Keoleian and Menerey emphasize on the need for a corporation’s environmental management system to be responsive—and thus reactive—to external forces such as legislation, the market, scientific development, and the state of the environment [24]. However, studies published later highlight the importance of proactivity, e.g., regarding the development of skills in environmental issues [72] and strategic planning. It appears that proactive companies are less affected by regulatory measures and can focus more on innovating to meet market demands, strengthening their competitiveness [81] and ultimately improving their financial bottom line [21]. Those innovations aimed solely at addressing legislative requirements seem to be more short-lived and defensive [14]. Being proactive also benefits an organization seeking to engage in radical innovation to achieve eco-effectiveness [49].

Nominate an environmental champion. Someone personally committed to environmental issues should be included in the ecodesign change process to increase the likelihood of a successful outcome [45,72]. Ideally, this person is not just motivated, but also knowledgeable regarding environmental issue, and thus an environmental specialist [45]. Furthermore, starting out with pilot projects as learning opportunities may be ideal for companies to get started with ecodesign [30].

Differentiate between process and product innovation. The concepts and methodologies of life cycle assessment (LCA), life cycle costing (LCC), and ecodesign primarily refer to the former, while eco-efficiency, cleaner production, and environmental management

systems (EMS) are mostly discussed within the former [81]. The interrelationship between the two types of innovation appears to be rarely discussed within ecodesign research [68].

Monitor and model resource flows. By gathering information on the inputs, outputs and internal flows of energy and physical resources, companies can lay the necessary groundwork for process efficiency improvements and strategic decisions related to business development [71,72].

(b) Collaboration and Communication

Foster collaboration between different departments within a company. In order to implement ecodesign successfully, it is not enough for only the product development department to be involved, [2,4,31,67]. Instead, product developers should work closely with designers [30,47,82,83], marketing and sales [6,63,64], manufacturing [82] as well as the purchasing, finance, and service department [6]. Collaboration should ideally extend even beyond the company [75]. Future research in this area should focus on the impact of the degree of interfunctional collaboration on the market success of ecodesigned products [70].

Extend collaboration along the supply chain. An issue that is currently under-addressed [62,64] relates to close relationships with suppliers appears to be an important success factor for ecodesign [45,67,75]. The configuration of the value chain also significantly affects the environmental impacts of PSS [84]. Since usually no representative takes responsibility for the product system across multiple companies, an important driver for this issue is often missing [2]. Pro-active companies, however, engage in innovation together with partners along the value chain [49,81]. Collaboration may take the form of vertical integration, strategic partnerships, and reverse supply chain activities [29]. In her study on the role of collaboration in green product innovation, Melander elaborates on aspects such as partner selection, types of collaborations, characterization of collaboration partners, and the contribution of partners. She finds that while one study claims the opposite, most studies conclude that collaboration is beneficial for ecodesign [68].

Implement information management systems. Databases and/or expert systems [69] and product life cycle management systems including interoperable models containing environmental information [82] can support an organization in gathering, storing, organizing and updating information necessary for developing products with lower environmental impacts, but so far receive only limited attention [68]. An open research question is how to effectively map company information flows [19].

Ecodesign knowledge does not need to be created, it already exists. The challenge is how to share the knowledge with the right people and how to provide it in a useful manner [23,79]. Companies could learn from one another on how to do ecodesign successfully, and what they need to do it [19].

(c) Product Development and Design

Embrace the role of designers and engage in design thinking. Designers have a crucial role in ecodesign, and they require appropriate training, tools, and methods as well as inspiring examples [30]. They have to solve trade-offs situations that frequently arise [22]. Some consider sustainable design to be a philosophical approach to almost any design activity [85]. Many design approaches aimed at sustainability share common attributes, such as a multiplicity of perspectives, collaboration, and design thinking [36]. The latter has been found to be useful in business model innovation for ecodesigned products as well [40].

Change product development culture and processes. Ecodesign requires establishing a new mindset [45], one that moves away from the throwaway products to those that support a more sustainable business model [28]. A seamless integration into existing practices is challenging [31], as it requires new design briefs [28], information sources and an action learning approach [72], environmental checkpoints, reviews and milestones [45], company-specific design principles, rules and standards [45], and education and training [45].

Those that are good at product development tend to be good at ecodesign as well. A way to get good at both is to assess your current state and capabilities, your motivation

as a company, and the target level you are aiming for [31]. Companies that are successfully doing ecodesign utilize examples of good design solutions [45] as well as sustainability criteria and indicators, which they correlate with design requirements in quality function deployment [41]. It may be helpful to view ecodesign integration as two separate aspects: integrating environmental aspects into product development, and integrating product development into the management system of a company [59]. Future research should focus on the correlation between general product development and ecodesign skills and capabilities [75] and collaborative aspects of both [68].

Address environmental issues at the early stages of the product development process. This is crucial, especially when aiming for more radical environmental improvements [44,83], but also with respect to the “soft side” of ecodesign [79] as well as ecodesign in general [45,86]. This approach offers the highest gains regarding environmental impact, especially in areas where regulation and consumer awareness is lagging behind [82]. Perhaps as a result of these findings, a study from 2014 finds that most ecodesign approaches focus on the (early stages of) informational and conceptual design [39], e.g., using functional analysis [84].

Address the complete product life cycle. Burden shifting (e.g., from production to end-of-life) can be avoided if product developers analyze the complete life cycle, from cradle to grave [71,72], e.g., by employing life cycle thinking and assessment [20]. A life cycle stage that is typically under-addressed is distribution, see Gómez-Navarro et al. [87]. It remains the responsibility of the product developer to prioritize and to handle trade-offs between different types of environmental impacts [72], which is complicated by the fact that ecodesign criteria are often interrelated and not independent from one another [61].

Close the loop. Designers should even think beyond a single life cycle, and consider multiple product life cycles by designing for durability, modularity, recycling, disassembly, remanufacturing, and reuse [28,29,58,71,78,88,89] as well as using renewable energy and material sources [90]. In the past few years, these strategies have been subsumed under the term “Circular Economy” [6,28,78]. Not prematurely focusing on a single recovery option may result in promoting the most competitive end-of-life treatment options and reduce the environmental burden [88]. The overarching goal should be to preserve economic value and product integrity [28], which is reflected in the concept of the resource management hierarchy [78]. Challenges arise from the current level of material mixing in products, and a lack of processes to reverse it [58]. At the macro-level, this issue may be addressed by an appropriate product architecture [86].

Make long-lasting, intensively used products. Product lifetime appears to be under-addressed in product development, and potentially negatively influenced by marketing efforts [66]. For products relying on rapidly evolving technology, however, a sooner replacement may be in some cases preferential [28]. In any case, utilizing a product to its fullest potential is generally preferable, as one product can replace multiple products with a lower utilization rate this way [48]. The challenge for designers is to determine the point at which a product becomes obsolescent, as this is often quite subjective [28].

Focus on the customer. As with product development in general, it is a good idea to listen to what the customer wants and provide it [33,45,64]. By making products more user-friendly and convenient [63], understanding how customers value a company’s services [54], and even training the customer with regard to environmental issues [45]—e.g., how to use the product in a sustainable way [61]—companies can avoid making products nobody buys, or which do not have the intended environmental effect. Specific strategies such as modularization rely heavily on user decisions to have the intended effect [24,91]. This user-centered design may be coupled with a responsible research and innovation approach to close the gap between consumption and production [60].

Customers want greener products, but won’t pay more for them. In some markets, green products or product aspects have become mainstream, or even an integral part of a “good” brand or company [30]. This has led to customers increasingly expecting companies to act in a more responsible way, e.g., by producing more sustainable products [30].

Gaining new, “eco-conscious” customers seems to be a key driver for companies, while at the same time, these companies fear that market awareness, readiness, and incentives are lacking [30,71]. The finding that there is little evidence for the willingness of customers to pay even slightly more for a more sustainable product appears to confirm this perception [22]. More research should be conducted on this topic, including the consumers’ decision-making process in the context of sustainable products in general [70].

Try out more radical solutions. Major reductions in environmental impacts require more than incremental solutions to existing designs and products [63,64]. This, in turn, affects the way in which products and services are developed [44]. On the other hand, radical solutions should not be used as an excuse to delay action, even if current solutions are not (yet) truly sustainable [17]. In any case, innovation should be positive and specific, instead of seeking to correct previous mistakes [56]. For radical innovation, there still seem to be opportunities for future research [81], such as on how these innovations take place, on the role of experiments in introducing them, and on upscaling [53]. Within the current economic system, incentives appear to be lacking for radical innovation [14,78].

Engage in systems thinking. Producers should consider moving away from products to product service systems, integrating business model and product development, and using information about society, technology, and customers [34]. Taking into account the interdependency of product and production processes [81] is a vital aspect of systems thinking, as is a systemic, long-term perspective, and deriving short-term measures [14]. Yet, push and pull factors seem to be lacking for companies to consider these aspects [80].

Use life cycle assessment (LCA) to quantify the environmental impact of products. While it requires substantial resources, especially for data collection [58], LCA is useful to direct engineering activities toward the hot spots of a product and to avoid burden shifting [20,69]. LCA can provide the “rigorous, clearly defined measurements” which are essential to guide product development [82]. There still appears to be uncertainty, however, which actor should conduct an LCA, how, and when [40]. Also, value judgements regarding the weighting of different environmental impact categories are likely to remain a challenge for the objectivity of LCAs [24]. The prediction that LCA may someday become a legal requirement in some jurisdictions [20] does not appear too far off, considering the current efforts of the European Commission to assess product environmental footprints (PEF).

In any case, the sobering conclusion is that investments made in ecodesign cannot guarantee positive returns, i.e., a lower environmental impact [61]. Developments such as the rise of nano technology, increasingly complex products, and increasing production rates make it even more difficult to assess and mitigate the environmental impacts from products [92].

3.4.2. Research and Education Perspective

This section covers the statements most relevant for researchers as well statements on ecodesign education and training. Findings are grouped into sub-sections on (a) sustainability from an ecodesign perspective, (b) product service systems, (c) the role of collaboration, and (d) a research agenda.

(a) Sustainability from an Ecodesign Perspective

In Section 3.2, we defined the central aspects that describe the term sustainability: its systemic nature; the environmental, social, and economic dimension; and the difference between absolute and relative sustainability. In this section, we sum up all the findings that describe a research agenda pertaining to these central aspects.

Most research and development efforts have a scope that is too narrow to address the system level, with the consequence that rebound effects are ignored [52,77]. Approaches suggested by researchers include society frameworks and models that include interactions between different actors and sectors [6,90,93], and solutions building upon these models and frameworks [80], including complex systems approaches [82]. Rivera et al. [65] and Watz and Hallstedt [41] propose a holistic analysis of product systems and product development using system dynamics. Obstacles that prevent the implementation of system level

solutions include a lack of triggers and drivers for change, the inertia of current systems, and a lack of breakthrough technologies [30]. Approaches aimed at addressing the system level, such as whole systems design, remain largely undefined and ambiguous [35], or they meet the required criteria (e.g., systems thinking, radical innovation, long term planning) only partially [11]. Researchers suggest further research on how actions at various levels (micro, meso, and macro) interact with one another, with micro level actions referring to engineering, and macro level describing the policy perspective [14,70]. Using a different type of classification that distinguishes between the system and success level, the strategy level, the action level and the tools level, Paulson finds that most challenges and fewest trends are found on the system and success level [19]. Gaziulusoy proposes that researchers should seek to identify synergies between existing frameworks and develop novel frameworks for addressing systemic transformation, as well as tools and methods associated with these frameworks [11].

As for the three pillars of sustainability, the social side of sustainability appears to receive less attention than the environmental and economic side [27,39,49]. In fact, it is quite common that not all three aspects are addressed [77].

Most ecodesign efforts seem to achieve only incremental improvements, as tools for more innovative (and thus potentially more effective) approaches are lacking—but needed [33,83]. Also, design methodologies currently do not address the gap between incremental and radical solutions [94]. Dangelico suggests that future research should distinguish more clearly between radical and incremental ecodesign [75].

(b) Product Service Systems (PSS)

PSS and ecodesign research overlap in many areas, but both fields also have their distinct insights and challenges. This sub-section covers all findings that relate specifically to PSS research and implementation.

Assessing the environmental impact of PSS is challenging because of the complexity and uncertainties [36,52]. As a result, there is a gap between the design and evaluation of PSS, which may be addressed by multi-level methods supporting PSS designers at progressing stages of the PSS design process [84].

Barriers to PSS implementation are users' preference for ownership, a lack of customer focus, imperfect business models, major upfront cost for PSS providers, a lack of PSS design skills and processes, and the current regulatory framework. Consumers often place a high value on owning a product, as opposed to merely being able to use it, which stands in the way of PSS acceptance [51,54]. Furthermore, convenience and cost for the customer should be highly prioritized [51,53,54,63]. If PSS providers follow this advice, the reward may be increased customer loyalty [53] and innovative approaches to meet the customers' needs [30]. On the other hand, PSS providers need to make sure that the underlying PSS business model is capable of generating sufficient revenues—e.g., by diversifying income streams—instead of rushing to the market for a first mover advantage [34]. The high cost of transitioning to PSS, especially results-oriented PSS, high labor intensity, and rapid innovative progress hampering the re-use of products pose significant challenges to constructing sustainable PSS business models [51]. A system approach, as well as embracing the fact that radical innovation comes hand in hand with creative destruction, can be helpful in the PSS context just as in ecodesign in general [50]. This requires coordination of design, development, testing and implementation, and new design skills [51,53], but manufacturers lack guidance on how to design, implement, and sustain PSS [54]. On the regulatory side, supportive policies could accelerate the uptake of PSS [51].

PSS have the potential to reduce environmental impact, but it is not a given. Researchers agree that focusing on service provision instead of product sales may, in general, be preferential from an environmental perspective [34,50,52,95]. The argument that the greatest reductions in material input can be achieved at the end of the value chain appears to boost the environmental potential of PSS [52]. However, major improvements (4x or even 10x reductions of environmental load) should not be expected [52]. The environmental bottom line depends on how the PSS is designed and implemented [50,52,53], with

results-oriented PSS (as opposed to product- or use-oriented PSS) having the greatest potential [51]. Yet, PSS may still end up increasing the environmental impacts after all [84,96], and additionally decrease the social interactions [84].

Future PSS research should focus on gathering more empirical evidence, studying PSS design and implementation, standardization, and using more robust scientific methods. Researchers argue that more empirical evidence for the eco efficiency of PSS is needed [52,77], and more experimentation on, as well as more evaluation of, PSS [51]. Especially use- and results-oriented PSS should be the subject of studies, in order to find out if and how the transfer of ownership from user to provider contributes to sustainability [96]. Furthermore, scholars should investigate what makes successful PSS attractive for all actors within the PSS network [96]. Instead of making up completely new PSS, a promising path may be to improve upon existing services [52], e.g., by information and communication technology [63]. In addition, researchers could still learn more on how and why services are developed, adopted, and scaled [52,53], e.g., using surveys, statistical data analysis, and meta-reviews [51]. Harmonizing the terminology between business and academia would further advance the field [53], as would efforts towards standardization, and a common ontology [51]. Tukker and Tischner also demand more scientific rigor, and the integration of multiple scientific disciplines [50]. Finally, more research is required on tools, on integrating tools into the PSS design process, and on risk management during the transition from product to PSS [51].

(c) Collaboration

Several studies highlight the importance of collaboration to reach sustainability goals, e.g., collaboration between producers, consumers, and stakeholders [60]. The different types of collaborative relationships mentioned in the literature are grouped together and briefly described below, with the exception of collaboration within a company and along the value chain, which Section 3.4.1 covers.

Researchers from different disciplines. A lot of ecodesign research is already multidisciplinary [6]. The scientific fields mentioned most frequently include engineering/manufacturing [2,40,54], design [40,46,54], business/management [2,54], environmental science [40] and policy [2,40]. Synergies, a shared perspective, knowledge and experience sharing, a more holistic perspective, and an increased effectiveness of the developed methods are named as benefits of researchers collaborating [21,60].

Researchers and companies. When working together with industry, researchers should be careful to listen, and not just talk [73]. Researchers could benefit from a better understanding of knowledge flows, data on product performance and closed-loop knowledge [65]. Klewitz finds that for small and medium-sized enterprises (SMEs) seeking to foster radical innovation, engaging with researchers might be more important than with value chain partners [81].

Developing and developed countries (see also Section 3.3). On a level that focuses less on actors, and more on the actors' context, several studies highlight the importance and benefits of collaboration between countries of the developed and the developing world. Since the latter consumes an increasing amount of resources, and become ever more critical parts of global supply chain, it appears wise to extend ecodesign research and application [86]. However, until recently, most ecodesign research has been conducted in North America, Europe, and Asia [70,86]. Further research could help understand if and how antecedents, outcomes, and success factors of ecodesign implementation in developing countries differ from those in developed countries [75].

Various stakeholders. A large variety and combination of stakeholders have been identified as potential collaborators in ecodesign research and implementation. These include collaborations between:

- Politicians, economists, scientists, and designers/engineers [58];
- Many diverse organizations [63];
- Researchers and policymakers [69];
- Industry and society [93];

- Companies and their customers [34];
- Companies, their supply chain partners, retailers, business partners, NGOs and public organizations [14,34];
- Universities, other research institutions, companies both small and large [82];
- Producers and consumers, government, business and service providers [65].

Possible future research directions for the role of collaboration in ecodesign include drivers for inter- and intra-firm factors for collaborative ecodesign, studies on collaboration beyond suppliers and customers, the role of each collaboration partner, and the management of actors in a collaborative ecodesign value chain/network [68].

(d) Research Agenda

Foster the systematization, sharing and spreading of ecodesign knowledge, information and data. Environmental data should have the same quality and availability as cost and performance data, for the ecodesign to be effective [38]. If ecodesign efforts built on these data are successful, this should be documented in a systematic way that indicates the circumstances and outcomes of the implementation [60,61]. Finally, more research on how to scale up and transfer successful ecodesign practices should be conducted [60].

Conduct more case studies and include negative results. Expected benefits from more case study research include knowledge about effective communication and feedback between ecodesign managers and product developers [72]; insight on the effectiveness of the different design approaches [36], including modular design [91]; understanding the relationship of ecodesign with supply chain management [67,77], enabling technologies and infrastructure [77]; and a better judgement on the scale of improvements that may be achieved by ecodesign [65]. O'Hare and McAloone add that more reporting of case studies about failed ecodesign implementation would be beneficial [40].

Move away from generic principles. Most researchers agree that generic principles are usually not helpful in implementing ecodesign [2,73], yet they are the outcome of many studies [2]. A suggested way forward is an increased level of customization of these principles in order to improve ecodesign implementation [73].

Adapt ecodesign to the special situation of SMEs. Small and medium sized enterprises operate under circumstances that vary significantly from those of larger companies. These include reduced knowledge about relevant regulation and ecodesign research [31], pressure from large business customers [31], a short-term planning perspective [20], and a lack of resources [81] and motivation to implement ecodesign [20]. A way to address these issues is to focus more on the unique strengths of SMEs, and how they may benefit from ecodesign efforts [81]. As for their strategic behavior with respect to sustainability, SMEs range from resistant to sustainability-rooted [49]. More studies on SMEs would benefit researchers' understanding and the effectiveness of ecodesign implementation [86]. Special attention may be given to "ecopreneurs", environmentally oriented entrepreneurs [81].

Focus on education and training. Researchers are often also involved in education, and can shape the educational agendas with their findings. Focus areas where education and training could support ecodesign in a wider sense include implementing environmental awareness in school curricula [20]; training citizens, customers, and employees in life cycle thinking [20]; overhauling the traditional image of ecodesign within research institutes [73]; specifying and teaching the skills and abilities needed to implement ecodesign [22,36]; creating a learning and collaboration environment for SMEs [81]; and collaborative, problem-solving research and education programs between industry and academia [29].

3.4.3. Policy Perspective

Policy can be a major driver for change. In this section, we summarize the findings from the literature review that relate to ecodesign policy and regulation.

Researchers agree that more, and more stringent regulation is needed to support ecodesign implementation, and efforts to work toward sustainability in general. Policy and regulation appears to be important, if not the most important driver, of ecodesign adoption and effective implementation [11,68,75,78,97]. Yet, policy goals still appear to be

lacking or unclear in some areas [30]. Policy areas mentioned in studies include emission regulation [71], energy-related regulation [63], electronic waste [20], green public procurement [30], regulation affecting the early product design stages [82], policies to stimulate collaboration among companies [69], and policies on material efficiency [78].

Focusing less on topics, and more on the general policy design, Charter and Clark recommend that policy should address the following issues [30]:

- Clarify terms and definitions;
- Have positive focus on opportunities;
- Provide a policy framework;
- Set priorities;
- Foster learning from experience;
- Consider multiple scenarios;
- Consider multiple contexts (e.g., developing countries);
- Recognize limitations of policy and regulation.

Company strategies solely aimed at regulatory requirements may however only be successful in the short-term, as opposed to more proactive and innovative strategies [11]. Some researchers therefore suggest integrating environmental and innovation policy [16,30].

Furthermore, several studies point out that effective policy should address system level interventions and integrate the perspectives of all stakeholders. They should take into account the economic consequences, and involve suppliers, manufacturers, consumers, waste managers, regulators, and the public [24]. Also, these policies should consider the circumstances of globalization and changing consumption patterns [30]. Instead of creating isolated policy instruments, holistic policymaking would take into account the whole actor network and all material flows [2]. Ideally, such policies would be able to mobilize key audiences and create a mindset shift—e.g., moving from products to services [30,52]. Such system level intervention may take the shape of long-term agreements, reducing risk and providing a planning perspective for all actors [30]. Holistic policy instruments should be aimed at fostering cooperation and consider how new solutions may be integrated into existing systems [30]. Creative input on how to design such holistic policy frameworks may come from the field of behavioral economics [60].

Increasing producer responsibility may be a viable way to reducing the environmental impact of products. Industry is arguably in a unique position to reduce the environmental footprint of products (and services), as the design and production is their responsibility [20]. An example of producer responsibility is the integrated product policy, IPP [30].

A measure that would greatly affect producers is the pricing of negative externalities, e.g., a tax on greenhouse gas emissions. By including these costs in their internal calculations, companies would automatically steer toward products and services with lower environmental impact [58,71]. As systems to track their finances already exist within companies, they would not have to track resource use and emissions separately with this approach [69]. The price of the negative environmental externalities should be set so that it reflects the cost of restoring the environmental damage caused [13]. Legislation such as the European Emission Trading Scheme (ETS) and a carbon tax, which several countries have implemented in recent years, at least partially address these concerns.

Resource policy should reflect resource scarcity, renewability and pollution. Resource scarcity will have to be weighed against other, conflicting requirements [23], and the utility they can provide to meet human needs [48]. Chemical substances should be evaluated regarding the compatibility with nature (i.e., non-toxic, non-polluting) and their renewability [48].

Consider introducing central material databases and/or agencies, accessible to anyone. The role of such an institution would be to support the evaluation of a product's environmental impact, by collecting and providing information on material properties, limitations, compatibility, and related processes, for both virgin and recovered materials [71]. This agency may be seen as acting on behalf of the flows of material resources [2].

Economic policy recommendations include the shaping of tax structures, charges, certificates, labels, subsidies, custom duties, and priorities for research and development [21]. Furthermore, existing disincentives for introducing radically more efficient solutions should be abolished [30,52]. Finally, policies that ecodesign implementation would benefit from include those aimed at quantifying the market potential for ecodesigned products, green public procurement, and support for “ecopreneurs” [30].

Finally, the importance of standardization for ecodesign should not be underestimated. The upcoming introduction of the ISO 14000 series was expected to have a significant ripple effect at the time [31]. This was confirmed by Ammenberg’s and Sundin’s observation of a beneficial relationship between environmental management systems and management standards and audit schemes [59]. However, they also find potential to improve ISO 14001 with respect to its applicability [59]. Practical guidelines, such as ISO/TR 14062, may serve as a valuable resource for a summary of practical resources to be used by researchers, see Boks [79]. Using the example of material efficiency, Tecchio and colleagues argue that a lack of standards results in a lack of ecodesign requirements [78]. A lack of standards (and best practices) may also negatively affect the life cycle cost, according to Ramani et al. [82]. Policymakers and standards organizations should work together to develop standards where they are still missing, e.g., standards on material efficiency, see Tecchio and colleagues [78].

3.5. Methods and Tools

Ecodesign methods and tools, such as checklists and guidelines, have been supporting the operationalization of ecodesign since the inception of the field. Hence, they have received a fair amount of attention by researchers. The following sections will summarize the findings on the availability, effectiveness, requirements, prerequisites and success factors, and utilization of/for ecodesign methods and tools.

3.5.1. Availability

Researchers widely agree that a large number of ecodesign methods and tools exist today [3,4,23,30,31,98–100]. In fact, Rousseaux and colleagues count 629 methods and tools in their review [3]. Some go as far to say that enough of them exist and no more new tools are needed [87,101], or even that in fact too much tool development is occurring [2,79]. Lenox and Ehrenfeld [38] argue that efforts spent on tool development hamper other, more effective ecodesign measures, while Karlsson and Luttrupp point out that developing ecodesign tools is less important than goal setting [33].

Yet, in 2015 Pigozzo and colleagues noted that interest in tool development is (still) growing [6]. This may come as no surprise, when over the year researchers have continuously stated the need for additional or modified tools for specific purposes. These purposes include:

- Qualitative assessment tools [23,24];
- Strategic tools [21,96];
- Tools for the early stages of the product development process [92];
- Tools to support radical ecodesign [87] and eco-innovations [70];
- Tools for project preparation, action plan elaboration and process evaluation [87];
- Tools for PSS design, -implementation and -operation [51,54,84];
- Managerial tools [32];
- Interfaces between conventional design software and ecodesign software [100,102];
- Tools to support heterodox thinking [26];
- Tools for industrial designers [5];
- Tools that enrich the robust design methodology with sustainability criteria [97];
- Tools to support the development of products with multiple life cycles [88];
- Tools to translate sustainability criteria into product requirements [41].

Some scholars have reached the conclusion that the focus of research efforts should lie on categorizing, reviewing, refining, and validating existing ecodesign methods and

tools [40,56,93]. It appears that existing reviews are scarce and sometimes contradictory [5]. On categorization, Pigosso [43] elaborates that a method for selecting the most suitable ecodesign practice for a specific case or purpose is missing. A possible solution may be a consolidated model for ecodesign [70]. Telenko proposes to distinguish between ecodesign principles (goals) and guideline (actionable suggestions for achieving these goals) [56]. Birch et al. classify ecodesign methods and tools according to their output mechanisms [103].

3.5.2. Effectiveness

There is an agreement among researchers that methods and tools are generally helpful and effective in reaching ecodesign goals [26,36,42,45,65,70,72,104]. Lindahl finds that designers are mostly satisfied with the functionality of the tools they utilize [105]. The fact that some companies are developing their own tools [30] might serve as further proof of the effectiveness of tools in general. However, a central contradiction of many tools remains unsolved: to be most effective, many tools should be used early during the product development process. However, they often require detailed input data which are not available until much later during product development [39,106]. This holds true for LCA as well, which Ljungberg identifies as the potentially most effective way of determining environmental impacts of products [13]. Yet, Hübner argues that assumptions, especially regarding the use and after-use phase, remain uncertain even when using LCA [61]. In their classification by output mechanism, Birch et al. found that strategy-specific ecodesign methods and tools are less effective than product-specific ones [103].

3.5.3. Requirements

Investigating the requirements that ecodesign methods and tools should fulfil, Lindahl found that aims and requirements are largely absent from the literature [105]. Over the subsequent years, however, researchers (including Lindahl) have formulated several requirements, some of which are contradictory.

Methods and tools should require few resources to implement. This entails that they are easy to learn and use, and cost little or nothing [99,105]. Hübner finds that these requirements are not always met for LCA [61]. A potential solution may be streamlined and/or simplified tools [4,6,49], or tools adopted from other domains, such as general product development [5] or risk management [107]—see also Section 3.6.2.

Upon implementation, ecodesign methods and tools should be effective [105]. Besides supporting developers in designing products with a lower environmental impact, that includes shortening the development time [105]. This can be achieved by involving designers into the tool development process [101,105], and other company representatives of the enterprise where the tool is to be deployed, to ensure practical orientation [4]. Tool developers should be aware that cultural differences might have an effect on the requirements for tools [105].

In order to be effective, methods and tools should assist during the complete product development phase, with a special focus on the early phases [83,99,105]. As described in Section 3.4.1, the conceptual and embodiment design stages are crucial for determining the environmental impact of a product, hence methods and tools should support designers here [56]. The theory of inventive problem-solving (TRIZ) and variations of this method have been proposed as suitable approaches for this task [41].

To avoid burden shifting and identify goal conflicts, methods and tools should consider the complete product life cycle and multiple criteria [96,99]. An example is the conflict between reparability, upgradability, and durability in designing products [56]. Established methods for multi-criteria decision-making have been proposed to address these issues [41].

Modeling and databases may support ecodesign activities. Models, and suitable interfaces for designers to handle them, as well as design data—e.g., of past products—might help designers in creating novel products [82]. Two applications that combine both

aspects are computer-aided design (CAD) and LCA. Both together may support design activities, if they are integrated to combine product and process-related data [86].

Ecodesign methods and tools should address uncertainty. As assumptions and data for sustainability assessment will include some amount of uncertainty, it is important to include this uncertainty in decision-making [82]. An example is the underlying uncertainty of LCA data [86], be it data included in commercial databases or primary data from measurements. An existing solution to handle uncertainty is fuzzy logic, which can translate qualitative statements into quantitative variables [41].

Suitable metrics should support decision-making [82]. These metrics should fit the design process, and reflect inherent uncertainty [86]. The planetary boundaries, which provide absolute limits for environmental stress, are an example of a global metric to include into ecodesign [6,108].

Methods and tools should address all three dimensions of sustainability (see Section 3.2.1). An increasing number of studies find that not just environmental, but also economic and social aspects should be reflected in ecodesign tools [4,6,18,60,77,106], which for some include LCA [86]. Especially the social dimension appears to be under-addressed [18]. A considerable challenge remains in considering not just each of the three dimensions separately, but instead to model interdependencies among them [18].

Different opinions emerge on the issue of generic vs. specific tools. While some argue that generic tools are easier to implement [99], others find that many tools are too generic and thus not useful to companies [98]. Birch et al. conclude in their review that product-specific tools are more effective than strategy-specific ones [103]. Regarding sector specificity, Rousseaux and colleagues found that roughly as many sector specific tools exist as there are generic ones [3]. Perhaps the key is flexibility, where a tool can adapt to a company's individual circumstances [59].

A brief research outlook for ecodesign methods and tool requirements concludes that an integrated methodology integrating multiple scopes, perspectives, and systems may be useful to researchers and practitioners [86]. Such a methodology should also include other activities within a company (apart from the design process), in order to be considered in strategic decision-making [94]. Watz and Hallstedt [41] find that tools used at the operational level of companies show most room for improvement. Sherwin [83] remarks that methods and tools to support radical, innovative solutions are still lacking.

3.5.4. Prerequisites and Success Factors

While the previous section summed up findings on the criteria that ecodesign methods and tools should fulfil, this section covers prerequisites and success factors for implementing these tools. Financial support, education, and training can ease and accelerate the successful uptake of ecodesign tools [105]. Especially analytical tools require extensive knowledge from their users and detailed input data to provide good results [98]. However, more research is needed on how to efficiently implement tools in companies and the barriers that hamper tool adoption [72,98]. Lindahl [105] also recommends a wider adoption of follow-up procedures in companies, to ensure that the tool helped achieve the intended goal, and was used for the right purpose. Zetterlund and colleagues recommend the use of tools that feature what they call "*the most complete and science-based integration of the full scope of sustainability*" and analyze and address the issues obstructing their adoption [107]. As for the environmental dimension of sustainability, LCA might be the method of choice for this task [4].

3.5.5. Utilization

Undisputedly, for ecodesign methods and tools, the level of utilization in companies remains low [3,4,32,97–101,105]. No decisive answer could be found that explains this fact, and researchers recommend to investigate it [98]. Purposes for using ecodesign methods and tools were found to be communication, knowledge sharing, and integration into the PDP [105] as well as identifying environmental impacts, suggesting measures for

improvement and supporting conceptual design [87]. Yet, the tool selection process in companies remains largely unstructured [96,105], and SMEs are mostly unaware of existing tools [57]. Ahmad and colleagues stress the fact that in order to successfully integrate multidisciplinary ecodesign tools, support by researchers, governments, educators and practitioners is required [106].

3.6. Synergies Between Ecodesign and Other Research Disciplines

Ecodesign research does not occur inside a vacuum. Instead, it is frequently injected with ideas and methods from other research disciplines. Several studies acknowledge that ecodesign may benefit from this exchange of ideas, e.g., through an increased uptake of ecodesign practices. This section summarizes findings on such potential synergies, grouped into the domains of design, management, and lastly, psychology and sociology.

3.6.1. Design

Modular products may result in lower environmental impacts compared to products with an integral architecture, as they are generally easier to maintain, repair, upgrade, and recycle. Other benefits include the reuse of components, and resource savings from a product platform strategy [86]. Therefore, modularity affects the complete product life cycle [91,109]. Beneficial side effects may include economic and social gains [109]. With PSS, incentives to reap the benefits of a modular product architecture tend to be greater than for privately owned products. PSS themselves, which include a service component, may benefit from modular design as well [51]. An important issue for designers to keep in mind (for both products and PSS) is the speed of progress of technology, which can make products obsolete at an uncertain point in time [89]. Similar to ecodesign, modular product development originated from the domain of engineering design, and now extends to other areas such as supply chain management [109]. Current research on modular product design focuses on the production phase [91]. More evidence for the effectiveness of modular design in reducing the environmental impact of products is needed, which includes a better understanding of the products entire life cycle [91]. This will allow for informed decision-making on whether and which modularization strategies to choose [91].

Robust design methodology (RDM) originates from quality management, and is aimed at reducing variations among units of the same products, as these tend to reduce customer satisfaction [110]. If one includes impacts on the environment into this description of product quality, then RDM may be a suitable approach to contribute to the goals of ecodesign. In an effort to “*integrate a number of different works on the same topic, [summarize] the common elements, [contrast] the differences, and [extend] the work in some fashion*” [110], Gremyr and colleagues investigated the overlap of ecodesign and RDM. They find that RDM has the potential to integrate sustainability considerations throughout the PDP, and to contribute to all life cycle stages. It needs to be adapted, however, and focus more on the early product development phases [110].

3.6.2. Management

Ecodesign management is an important success factor for successful and effective ecodesign implementation, as the findings summed up in Section 3.4.1 show. Several researchers note that bridging the gap between management and ecodesign could provide some useful insights [40,75].

A standard management instrument are key performance indicators (KPIs). The OECD argues that clear and consistent KPIs are necessary to accelerate corporate sustainability efforts and deepen the understanding of ecodesign [40]. Existing KPIs that take into account environmental performance are mostly product-related, not process-related indicators. More of the latter are needed, in addition to a review of existing KPIs by experts and more practical insights on the application of KPIs [95]. Also, future research should focus on KPIs with a wider sustainability perspective, and how these indicators can be implemented in an organization [41,95].

Naturally, environmental management systems (EMS) have a significant overlap with ecodesign. Since there is no generally agreed upon definition for either of the two, it is often difficult to distinguish between them. Since the ISO 14001 standard on EMS claims that the intended outcomes of EMS include the “*enhancement of environmental performance*” and the “*achievement of environmental objectives*”, perhaps it makes sense to classify ecodesign as a subset of EMS activities [111]. Unlike with ecodesign, products are typically not at the center of attention for EMS activities [59,81]. Dangelico finds that EMS are among the factors for which it is unclear whether and to which extent they benefit ecodesign activities within a company [75]. According to Ammenberg and Sundin, EMS could benefit from the life cycle perspective of ecodesign, making it a more useful tool for achieving sustainable development through its wider scope, while ecodesign efforts could become more permanent, consistent, and systematic through EMS [59]. Integrating both approaches may also improve the relations of an organization with its stakeholders, along with its supply-chain and across its own departments [59]. While the viability of integration has been verified in theory, more research is required on its effect on environmental performance [59].

Implementing ecodesign within an organization often requires major organizational changes, which may explain why change or transition management repeatedly appears in studies on ecodesign. Gaziulusoy finds that several sustainability transitions within organizations have been progressing from the predevelopment to the taking-off phase, and from there to the acceleration phase [11]. However, a consistent prescriptive change model for managing the transition of an organization toward the integration of ecodesign still appears to be lacking [112]. Future research should include an exploration of the synergies between existing ecodesign frameworks in the context of systemic transformation for sustainability, the development of a novel ecodesign framework referring to systemic transformation for sustainability, and the development of tools and methods related to this framework, which support actors in product, service in strategy development [11].

Only few publications cover project management from an ecodesign perspective [113]. This may be a limiting factor for companies in considering environmental aspects within their projects [113]. Project management seems to fall into a gap between ecodesign methods and tools, primarily aimed at engineers and designers, and general strategic management issues related to ecodesign, aimed at top management [113]. Future research should focus on the relevant variables for ecodesign project management and on visualizing how project management could improve the environmental performance of products [113].

Risk management methods and tools are among those that seem to be well implemented both in the general operations and in product development processes within a company [107]. Suggested future research includes a roadmap for the economic risks associated with ecodesign implementation [19], and for including sustainability criteria in established risk management tools and methods to support ecodesign activities [107].

Lean product development (LPD) and ecodesign share several characteristics, including a holistic systems perspective of processes, people, and tools [114]. They differ in their goal and focus, value construct, process structure, performance metrics, and in the methods and tools used [114]. Applying LPD does not generally lead to products with an improved environmental performance, just as engaging in ecodesign does not improve the efficiency of the product development process [114]. Both fields could learn from one another, and it has been proposed to integrate both disciplines instead of implementing them separately within an organization [114].

3.6.3. Psychology and Sociology

Psychological and sociological aspects—described by Boks as the “*soft side*” of ecodesign—may have a significant impact on the spreading and effectiveness of ecodesign in practice [79]. Based on the interviews with company representatives, it was found that obstacles to implementing ecodesign mostly relate to socio-psychological aspects, while success factors tend to be more conventional value chain issues. These socio-psychological

factors appear to have been largely neglected in ecodesign research so far. They play the most important role during the early stages of the PDP, where information dissemination has a top priority. Boks argues that enough information on how to do ecodesign is already available, but more effort is needed to spread this information to the right people, e.g., by involving psychologists and experts on business organizations. Such efforts should be informed from the industry's experience with practical guidelines such as the ISO TR 14062, and emphasize on communication, language, personal views, and objectives [79,115].

4. Summary and (De-)Limitations

Here, we summarize the findings discussed in Section 3, putting them in the context of the research question they address. Furthermore, we discuss the external influences and author choices that affect the quality of this review article.

4.1. Summary

The quantitative analysis provides an overview of the reviewed publications and the statements extracted from them. The trend indicates an increase in ecodesign review articles over the years. Most analyzed statements originate out of Europe and are published in journals. The purpose of the articles in which these statements appear varies, with most articles addressing barriers and success factors. Similarly, the purpose of the statements themselves is in most cases the discussion of barriers and success factors as well, by a wide margin.

As for the qualitative analysis, the review has been able to answer the initially stated research questions.

- **RQ1:** Which names exist for concepts that may be considered similar or equal to ecodesign (ED), and what are the distinctions that can be made between the concepts?

We find that a multitude of names exist for quite similar concepts, with ecodesign being the most popular. The definition we put forth emphasizes on the aspect of product development, the life cycle principal and the incorporation of environmental aspects. Product service systems (PSS) are often, but not always, motivated by environmental considerations as well. They differ from classic ecodesign insofar as they integrate physical products and services, while ecodesign typically only addresses the former. Eco innovation (and similar terms) is sometimes used to describe a concept similar to ecodesign, but more often extends beyond product development. There is an ongoing discussion in ecodesign research on the topics of radical vs. incremental improvements, eco effectiveness vs. efficiency, the inclusion of economic and social aspects, and the breadth and scope of ecodesign efforts (concrete product improvements vs. systemic transformation).

- **RQ2:** How did the current understanding of ED evolve over time?

Ecodesign is a relatively young research discipline (the first analyzed reference is from 1994). Both research efforts and applications have moved from end-of-pipe solutions (point sources of pollution) to life cycle thinking, systemic approaches, and diffuse sources of pollution. The pressure for companies to adopt ecodesign practices has been steadily increasing through regulatory intervention, customer demand, NGO activities, and stakeholder demands. Theory remains ahead of practice, yet for a significant share of theoretical research, it seems unclear whether and how it may benefit changes in practice. The alternative may be thorough case study research, yet it remains scarce. The importance of communication and collaboration among actors in implementation, research, policymaking, and education has been highlighted with increasing frequency over time, and appears to be one of the central aspects for success. This includes mutual information sharing and learning between developing and developed regions.

- **RQ3:** What are the barriers and success factors for the spreading and implementation of effective ED practices?

As mentioned, collaboration among actors is a key success factor for successful ecodesign. Yet, there are actor-specific aspects to consider as well. Practitioners should view ecodesign not just as something that affects the design and development department, but instead the whole organization. Consequently, a strategy and management efforts should accompany the introduction and uptake of ecodesign within this organization. Researchers can support this process with reporting of ecodesign case studies, including those generating negative results, to foster information spreading and learning. Furthermore, their focus should lie on organizing the existing ecodesign knowledge, adapting it to specific contexts (e.g., SMEs), and supporting education and training with insights from research findings. Policymakers are advised to put forth more and more stringent, and well-designed environmental regulation to support ecodesign efforts. This regulation should support systemic solutions, focus on producer responsibility, encompass the whole product life cycle, price negative externalities, address resource scarcity, promote central information databases and standardization.

- **RQ4:** What is the current state of research on ED methods and tools with respect to their availability, effectiveness, requirements, and utilization?

A wealth of research effort has been invested in the development of ecodesign methods and tools, resulting in hundreds of them now being in existence. They are generally considered to be helpful in supporting ecodesign activities. Uptake by ecodesign practitioners remains relatively low, for reasons not entirely clear. However, before developing yet another one, tool developers may want to make sure that the intended solution does not already exist. Testing, validating, and categorizing these methods and tools should be a worthwhile time investment for ecodesign researchers. An ecodesign method or tool should be effective in reaching environmental goals, resource efficient (time, money, physical resources), address the complete product life cycle, support decision-making under uncertainty and the handling of trade-offs, and be available during the crucial early phases of the product development process.

- **RQ5:** What are potential synergies between ED and other approaches and concepts from outside the field?

Multiple researchers have sought to establish links and identify synergies between ecodesign and other research disciplines and concepts. While this review certainly does not cover all of these attempts, a rough picture emerges of the domains into which they tend to fall: design, management, and the social sciences. Most of these bridging studies intend to identify solutions to ecodesign problems within other disciplines (and vice versa). In many cases, the potential to address known issues within ecodesign (e.g., implementing ecodesign in a company's management and strategy) exists in theory, but requires application and empirical confirmation as a next step.

4.2. (De-)Limitations

By limiting the scope to review articles on ecodesign (and theses that include a review of the state of research), we may have missed important findings stated in case studies, or other types of research publications. Similarly, extending the scope beyond the abstract and conclusion section (and, in the case of theses, the state of research section) may have uncovered additional statements relevant to the five research questions. Because of the large number of terms in existence to describe concepts with varying degrees of similarity to ecodesign, it is almost certain that we have missed some terms, and therefore potentially some relevant articles. Also, by including research articles from different disciplines with different terminologies and definitions, we may have aggregated findings that describe separate things, and thus should not be aggregated. This potential problem is exacerbated by the fact that we rely on existing reviews, therefore, multiple instances of aggregation may influence the quality of the results. With our decision not to discriminate by publication date or number of citations, we run the risk of including outdated and/or niche findings in our analysis. Finally, while the research questions serve as guidance for the structure

at the top level, the structuring of the findings remains largely subjective. One could find plausible reasons to cluster and arrange the extracted statements in a different way, potentially affecting the emerging narrative.

5. Conclusions and Outlook

From our review of 106 existing ecodesign review articles, we were able to extract 608 statements relevant to the initially stated five research questions (RQs). These RQs cover ecodesign terminology, evolution, barriers and success factors, methods and tools, and synergies with other research disciplines. Having analyzed the references and statements both quantitatively and qualitatively, and having summarized the key findings in the fourth section of this article, we provide an overview of the field of ecodesign. To foster transparency, and perhaps as a starting point for further research, we have attached a spreadsheet containing all references and statements, which can be found in the supplementary materials.

Supplementary Materials: The following are available online at <https://www.mdpi.com/2071-1050/13/1/315/s1>.

Author Contributions: M.S. conducted the literature search and analysis, wrote the manuscript, and designed the figures; M.L. reviewed the manuscript and provided continuous feedback; both the authors formulated the research questions. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1 contains a list of all references that were analyzed in this review.

Table A1. List of 106 references analyzed in this review article.

Year	Author(s)	Title
1994	Keoleian, Menerey	Sus. Dev. by Design: Review of Life Cycle Design & Rel. Appr.
1995	Alting, Legarth	Life Cycle Engineering and Design
1995	Lenox, Ehrenfeld	Design for Environment: A New Framework f. Strategic Decisions
1995	van Weenen	Towards sustainable product development
1996	Dewberry	Ecodesign
1997	Bras	Incorporating Env. Issues in Product Design and Realization
1997	Lenox, Ehrenfeld	Organizing for Effective Environmental Cooperation
1997	Zhang et al.	Env.conscious design and manufacturing: A state-of-the-art survey
1999	Lofthouse et al.	Effective Ecodesign: Finding a Way Forward for Industry
2000	Ritzén	Integrating Env. Aspects into Product Dev.—Proactive Measures
2000	Roy	Sustainable Product-Service Systems
2000	Sherwin	Innov. ecodesign: an explor. & descr. study of ind. design practice
2001	Stevens	Application of EcoDesign: ten years of dynamic development
2002	Baumann et al.	Mapping the green product dev. field: eng., pol. and bus. persp.
2002	Johansson	Succ. Fact. f. int. of ecodesign in prod. dev.: A rev. of state of the art
2002	Robert et al.	Strategic sus. dev.—selection, design and synergies of applied tools
2002	Rounds, Cooper	Dev. of product design req. using taxonomies of env. issues
2003	Ernzer et al.	An int. study on util. of design f. env. methods (DfE)—a pre-study
2003	Heiskanen, Jalas	Radical Eco-Efficiency: Review of the Debate and Evidence
2003	Sun et al.	Design for Env.: Methodologies, Tools, and Implementation
2004	Ammenberg, Sundin	Products in env. mgmt. systems: Drivers, barriers and experiences
2004	Bhamra	Ecodesign: the search for new strategies in product development

Table A1. Cont.

Year	Author(s)	Title
2004	Shu-Yang et al.	Principles and practice of ecological design
2004	Wigum	Human and ecol. problem solving through radical design thinking
2005	Hauschild et al.	From Life Cycle Assessment to Sus. Prod.: Status and Perspectives
2005	Jeswiet, Hauschild	EcoDesign and future environmental impacts
2005	Lindhahl	Eng. designers/des./engs.' Req. on Design f. Env. Methods & Tools
2005	Navarro Rizo et al.	[...] Classification of Ecodesign Tools Acc. to Their Funct. Aspects ¹
2005	Rocchi	Enhancing sustainable innovation by design. [...] ¹
2006	Boks	The soft side of Ecodesign
2006	Karlsson, Luttropp	EcoDesign: what's happening? [...] ¹
2006	Maxwell et al.	Funct. and sys. asp. of the sus. prod. & serv. dev. approach for ind.
2006	Tukker, Tischner	Product-services as a research field: past, present and future. [...] ¹
2007	Baines et al.	State-of-the-art in product-service systems
2007	Boks, Stevels	Essential persp. for design for env. Exp. from the electr. industry
2007	Charter, Clark	Sus. Innov.: Key concl. from Sus. Innovation Conferences [...] ¹
2007	Ljungberg	Materials selection and design for dev. of sustainable products
2007	Mulder	Innovation for sus. dev.: from env. design to transition mgmt.
2008	Telenko et al.	A Compilation of Design for Env. Principles and Guidelines
2009	Albino et al.	Env. strat. & green prod. dev.: An overview on sus.-driven comp.
2009	Arena et al.	A state-of-the-art of industrial sus.: definitions, tools and metrics
2009	Boks, McAloone	Transitions in sustainable product design research
2009	Coley, Lemon	Expl. the design and perceived benefit of sus. solutions: a review
2009	Lee-Mortimer, Short	The PDP Roadbl. that is Restr. the Wides. Adopt. of Des. for Sus.
2009	OECD	Sus. Man. and Eco-Innovation: Framework, Practices and Meas.
2009	Sutcliffe et al.	Dev. of a framework for assessing sus. in new product dev.
2010	Dusch et al.	Dev. a Framework for Mapping Sustainable Design Activities
2010	Ramani et al.	Integrated Sustainable Life Cycle Design: A Review
2010	Rio et al.	A framework f. ecodesign: an interf. betw. LCA & design process
2011	Klewitz, Hansen	Sus.-orient. innov. of SMEs: A sys. rev. of exist. pract. & actors inv.
2011	Soylu, Dumville	Design for env.: The greening of product and supply chain
2011	Val Segarra-Oña et al.	A Review Of The Lit. On Eco-Design In Man. Industry [...] ¹
2012	Birch et al.	Structure and output mechanisms in Design for Env. (DfE) tools
2012	Blizzard, Klotz	A framework for sustainable whole systems design
2012	Bovea, Pérez-Belis	A taxon. of ecodesign tools f. int. env. req. into the prod. des. proc.
2012	Ceschin	The intr. and scaling up of sus. Product-Service Systems [...] ¹
2012	Chiu, Chu	Review of sustainable product design from life cycle perspectives
2012	Gagnon et al.	From a conv. to a sus. eng. design process: different shades of sus.
2012	Hübner	[...] ¹ 20 years of ecodesign—time for a critical reflection
2012	Pigosso	[...] ¹ A framew. to sup. comp. in t. sel. & impl. of ecodesign pract.
2012	Poulidikidou	A lit. rev. on methods and tools f. env. friendly prod. des. and dev.
2012	Thompson	Int. a Strat. Sus. Dev. Persp. in Product Service System Innovation
2013	Gaha et al.	Ecodesigning with CAD features: Analysis and proposals
2013	Hallstedt et al.	Key elements for impl. a strat. sus. persp. in the prod. innov. proc.
2013	Lindhahl, Ekermann	Structure for Categorization of EcoDesign Methods and Tools
2013	Mattioda et al.	Principle of Triple Bottom Line in the Int. Dev. of Sus. Products
2013	Tonelli et al.	Industrial sustainability: challenges, perspectives, actions
2013	Zhang et al.	Toward an sys. nav. framework to int. sus. dev. into the company
2014	Baouch et al.	Ident. the Req. for a Knowledge-sharing Platform in Ecodesign
2014	Bocken et al.	A lit. and practice review to dev. sus. business model archetypes
2014	Brones et al.	Ecodesign in project management [...] ¹
2014	de Medeiros et al.	Success factors for env. sus. prod. innovation: a sys. lit. review
2014	Dunmade	Issues in the sustainability of products designed for multi-lifecycle
2014	Gremyr et al.	Adapt. the Robust Design Methodology to support sus. prod. dev.
2014	Johansson, Sundin	Lean and green product development: Two sides of the same coin?
2014	Klewitz, Hansen	Sustainability-oriented innovation of SMEs: a systematic review
2014	Mattioda et al.	Thoughts on Prod. Dev. Oriented to Sus. in Org. Overview
2014	O'Hare, McAloone	Eco-Innovation: The Opportunities for Eng. Design Research
2015	Blok et al.	[...] ¹ Adv. and chall. in the trans. to global sus. prod. and cons.
2015	Brones, de Carvalho	From 50 to 1: Integrating literature toward a sys. ecodesign model

Table A1. Cont.

Year	Author(s)	Title
2015	Dangelico	Green Product Innovation: Where we are and Where we are Going
2015	Doualle et al.	Investigating Sus. Assessment Methods of Product-service Sys.
2015	Gaziulusoy	A crit. rev. of approaches avail. for des. and innov. teams [. . .] ¹
2015	Gaziulusoy, Brezet	Design for system innovations and transitions [. . .] ¹
2015	Go et al.	Multiple generation life-cycles for product sus.: The way forward
2015	Paulson, Sundin	Challenges and trends within eco-design
2015	Pigosso et al.	Char. o.t. SOTA & Id. of Main Tr. f. Ecodesign Tools & Meth. [. . .] ¹
2015	Tukker	Product services for a resource-eff. and circ. economy—A review
2016	Bocken et al.	Product design and business model strat. for a circular economy
2016	Ceschin, Gaziulusoy	Ev. of des. for sus.: From prod. des. to des. f. sys. innov. and trans.
2016	Ma, Kremer	A sys. lit. review of mod. prod. des. (MPD) from the persp. of sus.
2016	Rivera, Lallmahomed	Env. impl. of planned obsolescence and prod. lifetime: a lit. review
2016	Rodrigues et al.	Proc.-rel. KPI f. meas. sus. perf. of ecodesign impl. into prod. dev.
2016	Rossi et al.	Review of ecodesign methods and tools [. . .] ¹
2016	Thomé et al.	Sustainable new product development: a longitudinal review
2016	Zetterlund et al.	Impl. Potential of Sus.-oriented Decision Support in Prod. Dev.
2017	Brones et al.	Reviews, action and learning on change mgmt. for ecodesign trans.
2017	den Hollander et al.	Prod. Des. in a Circ. Econ.: Dev. of a Typ. of Key Conc. & Terms
2017	Melander	Achieving Sus. Dev. by Collaborating in Green Product Innovation
2017	Rousseaux et al.	“Eco-tool-seeker”: A new & un. bus. gd. f. choos. ecodesign tools
2017	Tecchio et al.	In search of stand. to sup. circ. in prod. policies: A sys. approach
2018	Ahmad et al.	Sus. prod. des. & dev.: A review of tools, app. & research prospects
2018	de Medeiros et al.	Prop. of a Novel Ref. Sys. for the Green Prod. Dev. Process (GPDP)
2018	Gbededo et al.	Towards a Life Cycle Sus. An.: A Sys. Rev. of Appr. to Sus. Man.
2018	Sonego et al.	The role of modularity in sustainable design: A systematic review
2018	Watz, Hallstedt	Integrating Sustainability in Product Requirements

¹ Title shortened/truncated to fit table.

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