Received: 29 October 2020 | Revised: 7 March 2022 | Accepted: 6 May 2022

DOI: 10.1111/jpim.12642

ORIGINAL ARTICLE

JOURNAL OF PRODUCT INNOVATION MANAGEMENT pdma

Reviewing the intellectual structure of product modularization: Toward a common view and future research agenda

Kai G. Mertens[1] | **Christoph Rennpferdt**[2] | **Erik Greve**[2] | **Dieter Krause**[2] | **Matthias Meyer**[1]

[1]Institute of Management Accounting and Simulation, Hamburg University of Technology, Hamburg, Germany

[2]Institute of Product Development and Mechanical Engineering Design, Hamburg University of Technology, Hamburg, Germany

Correspondence
Kai G. Mertens, Hamburg University of Technology, Institute of Management Accounting and Simulation, Am Schwarzenberg-Campus 4, 21073 Hamburg, Germany.
Email: kai.mertens@tuhh.de

Associate Editor: Anna Shaojie Cui

Abstract

Product modularization in new product development has attracted considerable interest among scholars and practitioners from diverse fields of specialization. This has resulted in cross-disciplinary diversity in the field, diverting attention from its overall intellectual structure and hindering the development of a common view and shared concepts. Extant research lacks an integrative review, transcending a focal discipline that could identify gaps and ambiguities while making recommendations to advance the field. Considering a period of 30 years (1990–2020), we generate a data set of 2988 citing publications to which we apply a co-citation analysis. Thereby, we uncover the intellectual structure of the field and find three research perspectives that represent key knowledge bases: (1) product system, (2) production system, and (3) organizational system. Delimiting the data set into four periods, we can track developments over time, where we notice an increasing disintegration of the product system perspective, which is rooted in the discipline of engineering design. Within the two other perspectives, we document extensive dynamism in terms of publications, especially in the two most recent periods, indicating an active discussion and a potential receptivity to new trends. For these periods, we also identify an emerging cluster of fundamental publications and an increasing emphasis on the concept of system architecture. Leveraging the synthesis of these results, we forge links between neighboring disciplines and recommend avenues for further research, ideally to develop a more common view.

KEYWORDS

innovation, modularity, modularization, new product development, platform, review

1 | INTRODUCTION

Product modularization in new product development (NPD) is often recommended to achieve product variety at reasonable costs. It decomposes products and rearranges them into redesigned components, modules, or platforms, ideally while reducing interdependencies between them. This results in modular product architectures (Ulrich, 1995) with more sharable and often larger assets (Baldwin & Clark, 2000), allowing firms to supply a wider variety of products and services to customers while managing complexity. Because product modularization promises economic benefits (e.g., Fixson, 2005), strategic flexibility (Sanchez & Mahoney, 1996), and innovation (e.g., Ethiraj & Levinthal, 2004; Langlois, 2002; Schilling, 2000), it receives a great deal of attention in practice and research and it is addressed in various management and engineering disciplines (Cabigiosu & Camuffo, 2016; Fisher et al., 1999; Fixson, 2007; Gawer, 2014; Mikkola, 2007).[1] Still, the resulting proliferation of publications makes it difficult to grasp the field's intellectual structure (Torraco, 2005), which may have exacerbated the fragmentation of research (e.g., Van der Have & Rubalcaba, 2016).

Fragmentation can jeopardize the development of a research field. Without conceptual clarity and shared concepts, it is harder for researchers to attain significant novelties and generalizations (Raasch et al., 2013; Torraco, 2005; Tranfield et al., 2003). Similarly, scholars face higher transaction costs when searching for others' contributions in complex fields, prompting them to stay in their own narrow fields (Birnbaum, 1981). This gives researchers narrower cognitive frames, as they tend to maintain a single perspective while neglecting others (Martin et al., 2012). For example, new research projects may easily neglect the discipline-crossing outcomes of product modularization that require more than one perspective. Thus, they overlook possible synergies and thereby hamper research efficacy. Likewise, without a global view of the knowledge generated by distinct perspectives, practitioners, and other stakeholders underestimate the scope of the field. This may repress the field's theoretical development and the effective application of modularization strategies and projects.

Some narrative reviews already facilitate a better organized and more inclusive discourse (e.g., Campagnolo & Camuffo, 2010; Jiao et al., 2007; Ravasi & Stigliani, 2012). However, they do not sufficiently address the various knowledge bases and their cross-disciplinary relationships, which we term "research perspectives." Only a few studies permeate disciplinary borders, suggesting different units of analysis such as products, production, and organization (e.g., Campagnolo & Camuffo, 2010; Frandsen, 2017). Likewise, Fixson (2007) disentangled the topics of product, process, organization, and innovation. Although these studies aim for a broader view, they are more narrative in nature, rely on fewer disciplines, and are likely associated with small samples (Chen et al., 2019). In sum, they are unlikely to provide a global view of the field's intellectual structure.

This study, therefore, aims to review the intellectual structure of product modularization from a multidisciplinary perspective and move toward a common view. It forges links between neighboring disciplines and recommends avenues for further research. We complement earlier narrative reviews with a comprehensive, empirical analysis of perspectives, outline their inherent structure, and create a more coherent understanding of the field's central concepts.

To this end, we conduct a bibliometric analysis of 2988 publications covering the period 1990–2020 and disentangle product modularization into distinct research perspectives. Delimiting the data set into four periods, we

Practitioner points

- Firms may not only capture the benefits from product modularization in terms of cost advantages and flexibility, but also potential positive outcomes are increasing sustainability, improved digitalization, new paths for innovation, and better collaboration.
- The scope of product modularization moves beyond product architecture in its design implications, potentially encompassing—among others—services, digital technologies, production, organization, supply chains, and industries. This is denoted by the emerging concept of system architecture.
- The migration toward system thinking in product modularization requires interdisciplinary skills for design professionals, helping them to cross-functional and disciplinary boundaries when applying product modularization.
- Innovation professionals should not see product modularization as a threat to innovation but also as a potential enabler, for example, for digital and green innovations.

[1]Using the SCOPUS database, we identified 9229 publications with the search syntax "modular*" AND "product$" in the subject areas of management (3019) and engineering (8021). Publications can be assigned to both subject areas. Later, we provide a more detailed analysis on the multidisciplinary nature of the field and use a more refined search syntax.

can track key developments in the field over time. Bibliometric analyses are fruitful because they sample across disciplines and depict knowledge exchanges through citations, complementing narrative reviews. Thereby, we provide a transparent, integrative review that investigates the field with reference to publications, journals, research perspectives, disciplines, research foci, and key concepts for knowledge integration.

We use co-citation analysis, which generates a network of cited publications, representing the intellectual structure of a field through separable clusters, which we leverage as research perspectives. The clusters capture influential publications and allow us to characterize the inherent perspectives of product modularization, while unpacking them by delineating disciplines and unraveling research foci and key concepts. We believe this study provides a comprehensive picture of the field and clarifies some of the current ambiguity, enabling product modularization to progress from fragmentation toward a common view.

Our contribution is threefold. First, we contribute to a common perspective by synthesizing the intellectual structure of the entire field. This provides a stylized organizing framework consisting of three distinct perspectives—product, production, and organization—complemented by a selection of fundamental publications. Although there are many reviews of product modularization (Bonvoisin et al., 2016; Campagnolo & Camuffo, 2010; Fixson, 2007; Frandsen, 2017; Simpson, 2004), none empirically organizes and integrates knowledge from various disciplines and perspectives. We hope our study will save knowledge-gathering effort for future scholars and foster knowledge integration toward a common perspective on product modularization.

Second, by mobilizing data on the dynamics of the field, we summarize its evolution in terms of three previously undocumented developments. (1) We show how the field gradually differentiated into more clearly defined perspectives. Nevertheless, this maturation has been accompanied by a disintegration of the product system perspective and the related discipline of engineering design. (2) We find that the scope of product modularization has expanded and an emerging center of gravity of fundamental publications has emerged. To our knowledge, this is the first empirical evidence of such a development. In particular, the concept of system architectures has grown in presence, and could become an umbrella for the entire field. (3) We also complement previous research (Bonvoisin et al., 2016; Campagnolo & Camuffo, 2010; Fixson, 2007; Frandsen, 2017; Simpson, 2004) by emphasizing recent developments. In the two most recent periods, we document a substantial change in publications in the established research perspectives of product, production, and organizational systems, which indicates an active discussion and a potential receptivity to new trends such as sustainability, collaboration, and digitalization.

Third, we respond to the *Journal of Product Innovation Management's* (JPIM) call to unravel the linkages and gaps between neighboring disciplines (Sarin et al., 2018) and highlight the knowledge of the engineering design discipline. For instance, we point to discussions on specific modularity measures and modularization techniques, which can benefit business disciplines. In turn, engineering design can benefit from the organizational view, which focuses on innovation processes, knowledge, and teams. In conclusion, our integrative review of product modularization facilitates knowledge exchange and integration toward the development of shared concepts (Rousseau et al., 2019; Shaw et al., 2018) and suggests future research avenues.

2 | THEORETICAL FRAMEWORK

Product modularization is seen as a promising NPD strategy (Meyer & Lehnerd, 1997) because it changes the design of firms' products and services toward more modularity and promises various advantages. The resulting modular product architectures are known to offer more flexibility, short NPD durations, and higher quality while still satisfying customers' requirements at a reasonable cost (Jacobs et al., 2007; Jacobs et al., 2011; Krishnan & Ulrich, 2001; Lau et al., 2007). However, there is still no self-evident understanding of product modularization. For the purposes of this study, we rely on Parnas (1972), who describes modularization as a set of design decisions to decompose systems into modules. To attain modularity as a design principle, these modules must be loosely coupled, independent, and equipped with accessible interfaces (Baldwin & Clark, 2000; Salvador, 2007). Accordingly, product modularization is the process of decomposing a product system into modules.

2.1 | Components, modules, and platforms

Product modularization results in modules—a term that is used differently across disciplines. Earlier studies mainly discussed modules in the context of modular software development (Sanchez & Mahoney, 1996) or considered them as a subform of platforms (Baldwin & Clark, 2000). Some recent studies forego the term "module" and focus exclusively on components or platforms (Colfer & Baldwin, 2016; Furlan et al., 2014). Components are seen as the most granular units and are considered as not being limited to physical elements

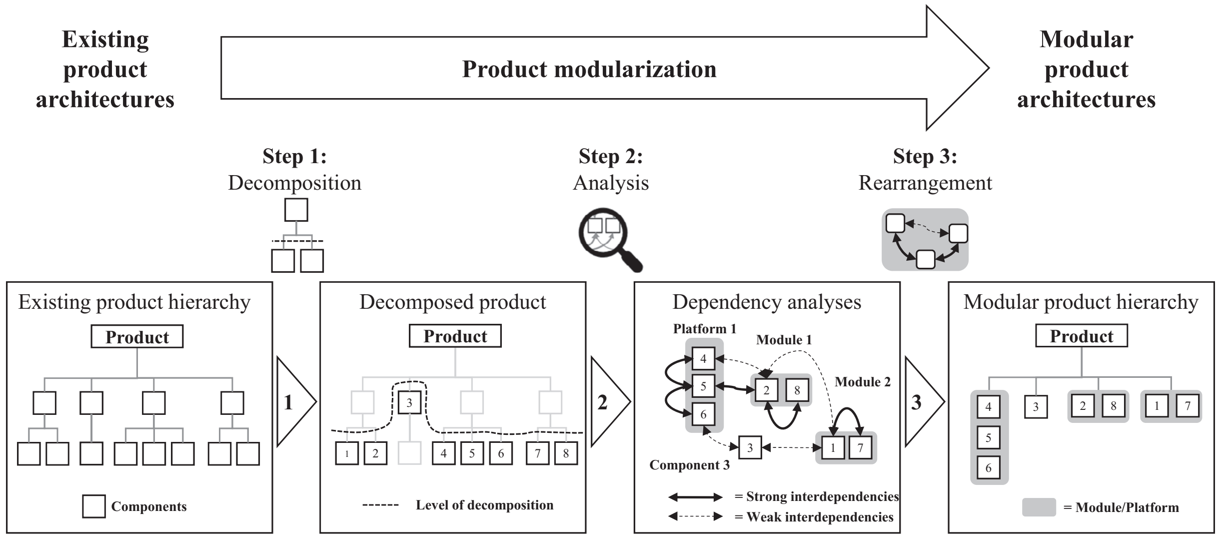

FIGURE 1 Product modularization.

(Baldwin & Clark, 2000; Kota et al., 2000). They form a primitive unit in the field (Collier, 1981; Gerchak et al., 1988), as they are used to define modules and platforms in design considerations. Because modules as well as platforms are considered as consisting of a certain number of components, they are often understood in similar ways (Gawer, 2014; Muffatto, 1999). For instance, Robertson and Ulrich (1998, p. 2) see a platform as a "*collection of assets* [i.e., components] *that are shared by a set of products*," while Meyer and Lehnerd (1997, p. 8) describe it as "*a set of common components, modules, or parts*." Salvador (2007, p. 223) defines a module as a "*kit of components*," similar to Jiao et al. (2007, p. 9), who relate a module to "*a physical or conceptual grouping of components that share some characteristics*." Overall, these descriptions indicate how platforms and modules are conceived similarly in the literature, in the sense that they group components into larger assets and do not have a sharp mark.[2]

2.2 | The process of product modularization

Figure 1 depicts the process of product modularization and subdivides it into the three steps of decomposition, analysis, and rearrangement (e.g., Otto et al., 2016). During decomposition (1), a product's hierarchy is decomposed into its components to a certain level. Here, organizations need extensive knowledge of products' components and interdependencies.[3] This requires a major investment of effort that compels stakeholders to discover and explicate existing product architectures (Cabigiosu et al., 2013; Ulrich & Eppinger, 2012). Ulrich (1995, p. 419) defines product architecture as "*the scheme by which the function of a product is allocated to physical components*," in which the first step decomposes those components.

As a second step, the firms carry out an extensive analysis (2), using components to generate alternative concepts for modular product architectures (Mertens et al., 2021). Starting from the given interdependencies between components, concept generation involves rearranging the existing product architecture by integrating redesigned components, modules, platforms, standardized interfaces, and independent functionalities. Each product concept has different advantages in terms of flexibility, life cycle effects, strategic relevance, and economic consequences, among others. Hence, NPD managers select the most suitable concept in accordance with their aims (Cooper, 2019; Markham, 2013). Finally, the existing product architecture is duly rearranged (3) to ensure greater modularity through multiple design decisions at the component level. Product modularizations usually shape entire product systems, therefore, their main outcomes are modular product architectures (Mikkola & Gassmann, 2003; Ulrich, 1995), as illustrated with one product in Figure 1.

[2]Indeed, research accentuates other characteristics of platforms and modules. For example, a platform comes with greater stability in terms of well-designed interfaces, to be used for longer periods across product families, product generations, and specific industries (Gawer, 2014; Magnusson & Pasche, 2014). A module is seen as a critical unit that increases combinability over product families, to enhance the advantages of modularity.

[3]This study uses "interdependencies" interchangeably for mappings, couplings, and dependencies between units.

The chosen modular product architecture typically affects the architecture of other systems such as the organizational system (Garud & Kumaraswamy, 1995; Sanchez & Mahoney, 1996) and the production system, with the latter encompassing the supply chain (Fixson, 2005) and manufacturing (Salvador et al., 2002). These wide-ranging, interdependent effects help explain the broader interest in product modularization as well as the fragmentation of research in this field. Nevertheless, this may as well lead to disciplinary tensions, for example, concerning the understanding, the conceptualization, the measurement, and/or the scope of modularity (Campagnolo & Camuffo, 2010; Fixson, 2007). We therefore believe that revisiting, structuring, and integrating the existing literature can help fields to develop, and provide valuable insights for researchers as well as firms (Shaw et al., 2018; Torraco, 2005).

3 | METHOD

3.1 | Research approach

Our aim is to identify the intellectual structure and corresponding knowledge bases in the field of product modularization. We decided on a bibliometric analysis to create a global overview of the extant literature by identifying focal research perspectives. Such methods have the advantage of drawing an intellectual map of a field that is not limited to a single focal discipline (Chen et al., 2019; Hopp et al., 2018). In fact, a bibliometric analysis suits the aim of an integrative review, as it complements existing, more specific reviews (e.g., Bonvoisin et al., 2016; Campagnolo & Camuffo, 2010; Jiao et al., 2007; Simpson, 2004; Simpson et al., 2001) with a global view. Thereby, we can identify important publications, corresponding perspectives, and developments in the field of product modularization.

Over the years, researchers' choice of units and procedures for bibliometric analysis has continuously evolved (Gmür, 2003; Small & Sweeney, 1985; Van Eck & Waltman, 2009). Bibliometric analyses need to decide on a "unit of analysis" (i.e., publications, patents, authors, or journals), a network mapping procedure (i.e., bibliographic coupling or co-citation analysis), and a method to identify clusters, such as the Newman or modularity algorithm (Newman, 2006; Newman & Girvan, 2004). For instance, studies focusing on collaboration analyze co-citations among authors (Raasch et al., 2013), while publications reveal underlying similarities in scientific discussions (Meyer et al., 2011). While both bibliographic coupling and co-citation analysis uncover intellectual structures, bibliographic coupling unravels the links between the citing publications, and a co-citation analysis those between cited publications. While bibliographic coupling is predicated on the assumption that two publications with a larger share of commonly cited publications are more similar, co-citation analysis exploits the possibility that if two publications are often cited together in the same document, citing researchers perceive them as being related. Both methods are considered to reflect the collective judgment of a research community in terms of similarity, and both can identify the intellectual structure of a field equally well (Boyack & Klavans, 2010; Yan & Ding, 2012). As we want to consider the knowledge bases of the field of product modularity in terms of the seminal literature, we employ co-citation analysis to identify research perspectives based on cited publications.

3.2 | Data collection

To derive the co-citation networks of related publications, we followed the steps described in Figure 2. First, we defined a search syntax to gather publications that cover product modularization: (*modular** OR *commonal** OR *product-platform**) AND (*product$*). This syntax balances the trade-off between specificity and the broad scope of the field. It also encompasses the terms "*modularization*," "*modularity*," "*modular*," and "*commonality*." Because our author team is multidisciplinary, we discussed our syntax to ensure its face validity and completeness from the perspectives of management and engineering disciplines. For example, we changed "*platform*" to "*product-platform**" to narrow the relative weights of unwanted categories such as chemical or electrical engineering (see Appendix S1). Furthermore, we added "*product$*" because it helps us to sharpen our focus on the NPD theme, while also partially excluding the disciplines of biology, chemistry, and physics in nonrelevant multi- and interdisciplinary categories.[4]

In the second step, we extracted the data set from the Web of Science (WoS) database. We used WoS because of its relatively high quality (Martín-Martín et al., 2018). We set the overall time horizon between 1990 and 2020. We chose this timeline because the scientific discussion on modularization took off after 1990[5] and several

[4]We considered adding "NPD" to our syntax, but it would weaken the focus, as general NPD literature superimposes product modularization by increasing the data set to 6720 publications. Using "NPD" as an alternative term for "product$" yields 3209 publications but did not substantially change the resulting networks and clusters. The final data set does not exclude 183 proceedings covered by WoS, as they are considered very relevant in engineering and computer science. Excluding them did not result in substantial differences.

[5]For the period 1945–1989 we found only 56 additional publications.

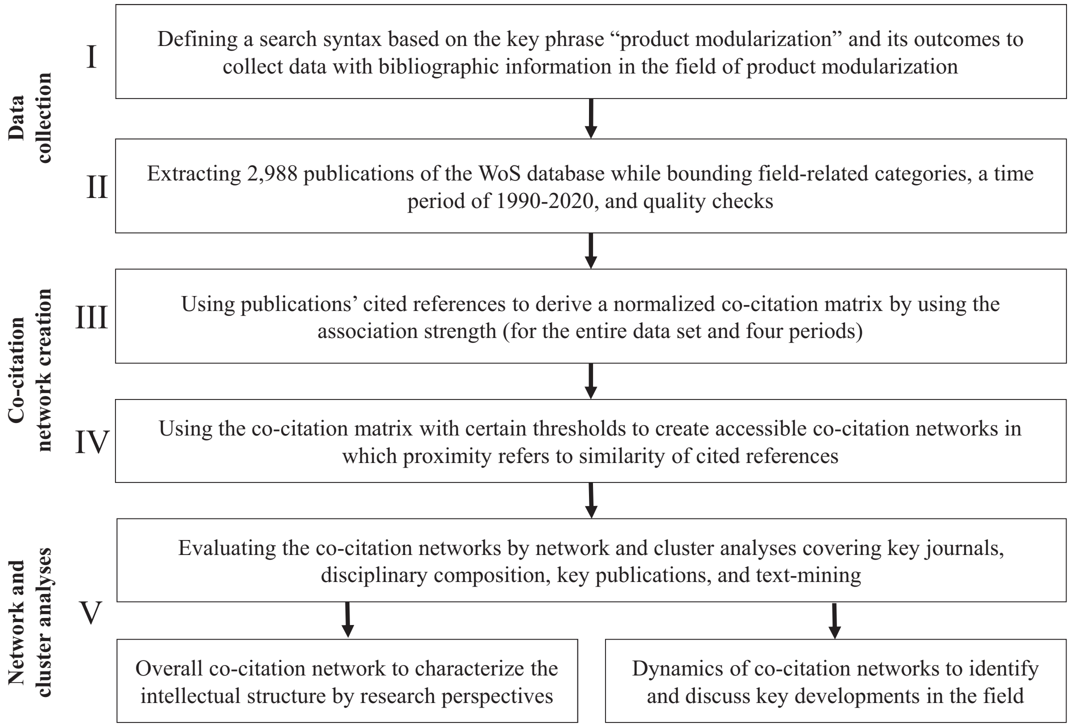

FIGURE 2 Research design with data collection, co-citation network creation, and network and cluster analyses.

influential articles were published in that year, including Henderson and Clark (1990), Clark and Fujimoto (1990), Kekre and Srinivasan (1990). Because we analyze references, earlier cited publications, such as Simon (1962), could however still appear in the network.

Next, we checked the data set for nonrelevant disciplines and typographical errors. We deselected natural science categories based on Ronda-Pupo and Katz (2017) and corrected inconsistencies such as variations in authors' names.[6] Overall, the resulting data set comprises 2988 citing publications, with 84,164 unique cited publications.

3.3 | Co-citation network creation

As a third step, we derived a co-citation matrix—an adjacency matrix listing the number of co-citations between cited publications. We counted each publication co-cited in one citing publication as one co-citation. The more co-citations, the higher the co-citation strength. Next, we normalized the matrix using association strength (Van Eck & Waltman, 2009) to offset the similarity-distorting effect of highly cited references (Gmür, 2003). The normalized matrix could then be used to create a co-citation network reflecting the perceived similarity between cited references.

In the fourth step, we used the normalized matrix and applied the VOS layout approach to visualize the co-citation network (Van Eck & Waltman, 2010). VOS places similar references closer together in the network, providing an intuitive graphic interpretation of publications' similarities. We followed prior studies' recommendations and carefully set the minimum thresholds for citations and co-citation links (Meyer et al., 2011; Raasch et al., 2013) to exclude less influential publications (Randhawa et al., 2016; Van der Have & Rubalcaba, 2016) and ensure clarity and comparability. We present publications with ≥45 citations and ≥10 co-citations; when we later split the data set into four shorter periods, we use the thresholds of ≥17 citations and ≥10 co-citations (for a similar approach, see Randhawa et al., 2016; Van der Have & Rubalcaba, 2016). These thresholds allowed us to focus on noncoincidental relationships, aiming to create robust linkages that depict the intellectual structure of the field. To further ensure the robustness of the co-citation network's structure, we varied the thresholds, aiming at an appropriate balance of the number of publications and co-citation linkages without overlooking clusters of relevant publications (Ehls et al., 2020).[7]

[6]We provide a list of the corrections made upon request. We also checked for books published in several editions and created unique references. For example, the book by Ulrich and Eppinger has several editions, and we consistently refer to the authors as Ulrich and Eppinger (2012).

[7]We provide robustness tests to substantiate our choice of 45 as a threshold. Please consult the Appendix S1 for more information.

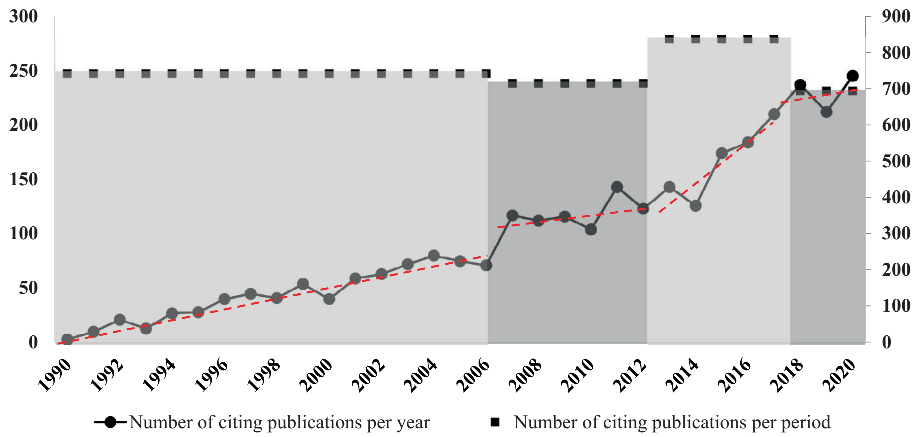

FIGURE 3 Number of citing publications on product modularization per year from 1990 to 2020. The left *y*-axis shows the number of citing publications per year, while the right one shows the number of citing publications per period. The red dashed lines are based on independent linear regressions for each period to indicate the period's single trends.

3.4 | Network and cluster analyses

In the fifth step, we analyzed the networks in terms of key publications and clusters. A cluster represents a group of publications that are more densely linked to each other, while being sparsely linked with other clusters (Emmons et al., 2016). To determine clusters, we applied the smart local moving algorithm of the VOS viewer program (Van Eck & Waltman, 2017), which is frequently used (e.g., Cash-Gibson et al., 2018) and recommended in scientometric studies (Cobo et al., 2011; Van Eck & Waltman, 2009; Waltman & van Eck, 2013).[8] By applying the algorithm, we could identify clusters of cited publications that were more densely connected, representing focal perspectives in the broader context of the network.[9] To identify underlying disciplines in clusters, we referred to the journal-discipline categorization of Sarin et al. (2018) (*Technology and Innovation Management* = TIM, *Management* = MGT, *Operations Management* = OM, and *Organization Science* = ORG) and extended it with the discipline of *Engineering Design* ("ED").[10] The categorization provides a one-to-one mapping from journals to disciplines.[11] Identifying key publications of clusters by their centrality and their number of citations helps to substantiate their focus. In addition, we delved into the key underlying themes of each cluster by identifying five words used most frequently and used uniquely in its publications through text mining, which counts the word stems of meaningful words (Randhawa et al., 2016). Frequently occurring word stems can be used as indicators to differentiate key concepts.

[8]In their comparative analysis of clustering algorithms, Emmons et al. (2016) identify the smart local moving algorithm as the best-performing one overall. We also considered the newly developed Leiden algorithm. However, as confirmed in correspondence with Udo Waltman, one of its developers, this algorithm only offers an advantage in exceptionally large networks.

[9]From this point on, we use the term "publication" to denote "cited publications" or "references."

[10]The categorization of journals to disciplines is presented in the Appendix S1.

[11]Like Gawer (2014), we designate engineering publications involving industrial and mechanical engineering as the discipline of engineering design.

4 | RESEARCH PERSPECTIVES OF PRODUCT MODULARIZATION

4.1 | Descriptive results

Figure 3 shows the development of the number of citing publications in the field of product modularization from 1990 to 2020. Overall, we observed an increase in citing publications per year over time. To analyze the development of the field, we created four periods. Conducting citation and co-citation analyses over time requires roughly comparable periods in terms of citing publications and the number of publications per paper. Generally, the number of citing publications specifies the maximum number of citations that a publication can receive in a data set. With each additional citing publication, the chance of a given publication being cited increases. In addition, a greater number of publications in a citing publication (i.e., a longer reference list) increases the chance of other publications being cited in the same document, which affects co-citations. Both these factors affect co-citation networks.

Table 1 presents descriptive statistics that substantiate our choice of periods, each with an approximate

TABLE 1 Descriptive statistics over the four chosen periods

Periods	1990–2006	2007–2012	2013–2017	2018–2020	Overall
Citing publications	742	715	837	694	2988
[%]	24.82%	23.92%	28.00%	23.25%	100%
Publications	15,133	21,018	29,949	30,294	84,164
Average number of references per citing publication	20.39	29.40	35.78	43.59	28.16
Publications ≥45 citations	—	—	—	—	112
Publications ≥17 citations	34	95	100	59	—

Note: The table also reports descriptive statistics about publications used in the co-citation networks. For instance, there are 112 publications with ≥45 citations in the overall co-citation network.

proportion of citing publications.[12] This choice balances several aspects described above. First, it splits the periods into a comparable number of citing publications, with split points only set to whole years (e.g., Meyer et al., 2011). Second, ideally, differences in the number of citing publications can be balanced somewhat by differences in the number of references per citing publication. For instance, the 2018–2020 period has the fewest citing publications compared with the other periods but has the highest average number of references per publication. Table 1 further reports the number of publications above the 45 and 17 minimum citation thresholds, which is relevant for the overall co-citation network and the networks of the periods. As in comparable studies (Meyer et al., 2011), most publications are rarely highly cited, which allowed us to focus on the most-cited references as inputs in our analysis, improving its readability (Randhawa et al., 2016).

The development depicted displays certain typical characteristics of growth patterns documented in other fields (Chen & Song, 2019; Van der Have & Rubalcaba, 2016). First, we have *emergence* (1990–2006), characterized by a slow but steady increase in citing publications. This phase embodies the formation of the field, and the growth shows increasing attention to the topic. Other studies have reported similar developments (e.g., Van der Have & Rubalcaba, 2016). After 2007, the number of citing publications reached a plateau—a pattern also discerned by Chen et al. (2019), among others. Like them, we refer to this as the *fermentation* phase (2007–2012). Next, we have a *take-off* phase (2013–2017) with faster growth. Take-off periods are commonly found in bibliometric analyses. They indicate an acceleration in scholarly activities (e.g., Chen et al., 2019)—suggesting, in our case, that the field receives more attention and gains in significance (Parolo et al., 2015). Finally, we identified a period of *consolidation* (2018–2020). This phase exhibits lower growth, yet still includes an active discussion in terms of the number of contributions.

[12]We used a four-period scenario to also include periods depicting the most current developments in the intellectual structure. We conducted robustness analyses to check our results when having alternative variations in terms of years and publications (e.g., four-period with different years, three-period, or two-period scenarios). We scrutinized each cluster and intellectual structure of the networks to check whether our main conclusions with respect to the three trajectories in the field remained observable and qualitatively stable (see Appendix S1). Still, given these choices we do not interpret the number of publications in the networks of the four periods and refrain from reporting density measures.

4.2 | Overall analyses

Table 2 ranks the most-cited journals and the most frequently used keywords. The top 15 journals account for approximately 18% of all citations and serve as a first glance at the disciplinary composition of the research field. For example, *Research Policy* and *JPIM* indicate the relevance of TIM. Table 2 also documents the most frequently used keywords. This allowed us to verify our search syntax and to find unexpected keywords (Randhawa et al., 2016). The keywords "*modularity*," "*commonality*," "*product*," "*product development*," and "*architecture*" were expected to appear most because they relate to our syntax. Surprisingly, neither "*modularization*" (#83) nor "*platform*" (#32) made the top 15, but "*innovation*," "*performance*," "*systems*," and "*integration*" were among the highest-ranked keywords. These unexpected keywords indicate that research on product modularization may be embedded in broader discourses on innovation, systems, integration, and performance. In sum, Table 2 reveals the multidisciplinary foundation of the research field, thereby supporting the relevance of our data set for potential integrative discussions and conceptualizations beyond individual disciplines. The keywords also show that the field relates to the innovation context, even though the term did not explicitly appear in the search syntax.

TABLE 2 Most-cited journals and most frequent keywords

	Most-cited journals and their discipline				Most frequent keywords	
No.	Journal	Cited	%	Discipline	Keyword	Count
1	*Management Science*	3437	2.60	MGT	*Design*	607
2	*Strategic Management Journal*	2612	1.97	MGT	*Modularity*	562
3	*International Journal of Production Research*	2261	1.71	OM	*Innovation*	312
4	*Research Policy*	1837	1.39	TIM	*Management*	300
5	*Journal of Operations Management*	1613	1.22	OM	*Performance*	269
6	*International Journal of Production Economics*	1607	1.21	OM	*Systems*	247
7	*Harvard Business Review*	1431	1.08	MGT	*Mass customization*	239
8	*Journal of Product Innovation Management*	1324	1.00	TIM	*Commonality*	225
9	*Organization Science*	1304	0.99	ORG	*Model*	223
10	*European Journal of Operation Research*	1265	0.96	MGT	*Product*	216
11	*International Journal of Operations & Production Management*	1163	0.88	OM	*Architecture*	201
12	*Academic Management Review*	1143	0.86	MGT	*Optimization*	198
13	*Journal of Mechanical Design*	1136	0.86	ED	*Product development*	159
14	*Journal of Engineering Design*	1053	0.80	ED	*Integration*	155
15	*Research on Engineering Design*	1040	0.79	ED	*Flexibility*	153
Total		132,301	100			26,863

Note: We use the categorization of Sarin et al. (2018), extended with an *Engineering Design* (ED) category. The other disciplines are TIM = *Technology and Innovation Management*, MGT = *Management*, OM = *Operations Management*, and ORG = *Organization Science*.

To explore differences between the areas of management and engineering, we split the data set in publications belonging to management and engineering with their respective related disciplines.[13] Our data set of 2988 publications consists of 1352 management (45.75%) and 1636 engineering (54.75%) related publications, indicating the relevance of product modularization for both areas.[14] Table 3 contrasts the most-cited journals for management and engineering. Several journals are frequently cited in both areas and depict potential spaces for knowledge diffusion and integration between the areas. Still, most journals are specific, already indicating fragmentation and potential disciplinary tensions in the field.

[13]We used the Web of Science categories to classify the areas of management and engineering. The Appendix S1 contains further details.

[14]In the Appendix S1, we document that the data sets for management and engineering mainly consist of journals while engineering has a higher number of proceedings (48 vs. 135 proceedings), reflecting their higher standing in engineering. We also provide a table with the most-cited publications and prominent theories for both areas.

4.3 | Product modularization as a research field

Figure 4 depicts the overall co-citation network for the whole period, providing a global view of the field of product modularization. To characterize the network, we first report its density and key publications. Second, we detect clusters representing the field's knowledge bases (Waltman & van Eck, 2013) and decompose their disciplinary background. Furthermore, we present the most-cited publications of the clusters and apply text mining to narrow the thematic core. Collectively, the results are used to identify and label focal research perspectives.

4.3.1 | Network analyses

We applied the VOS technique to our normalized co-citation matrix to create the co-citation network. The network depicted in Figure 4 comprises 112 publications and has a density of 0.293, which can be termed sparse (Ehls et al., 2020). Sparse networks are regarded as fragmented, indicating a field featuring limited, timely knowledge diffusion (Rafols, 2014; Van der Have &

TABLE 3 Most-cited journals in management and engineering

	Management and related disciplines			Engineering and related disciplines		
No.	Journal	Cited	%	Journal	Cited	%
1	**Management Science**	**3030**	**4.23**	Journal of Mechanical Design	846	1.39
2	Strategic Management Journal	2555	3.57	**International Journal of Production Research**	**826**	**1.35**
3	Research Policy	1586	2.22	Research in Engineering Design	714	1.17
4	**International Journal of Production Research**	**1469**	**2.05**	Journal of Engineering Design	709	1.16
5	Journal of Operations Management	1410	1.97	CIRP Journal of Manufacturing Science and Technology	661	1.08
6	Organization Science	1292	1.81	Journal of Cleaner Production	658	1.08
7	Harvard Business Review	1250	1.75	Journal of Intelligent Manufacturing	604	0.99
8	**International Journal of Production Economics**	**1170**	**1.63**	International Journal of Advanced Manufacturing Technology	518	0.85
9	Journal of Product Innovation Management	1141	1.59	**International Journal of Production Economics**	**459**	**0.75**
10	Academy of Management Review	1108	1.55	**Management Science**	**422**	**0.69**
11	International Journal of Production & Operations Management	1016	1.42	Concurrent Engineering: Research and Applications	391	0.64
12	Administrative Science Quarterly	1004	1.40	Computers & Industrial Engineering	365	0.60
13	**European Journal of Operation Research**	**922**	**1.29**	**European Journal of Operation Research**	**363**	**0.59**
14	Academy of Management Journal	822	1.15	Computers in Industry	317	0.52
15	IEEE Transactions on Engineering Management	609	0.85	Robotics and Computer-Integrated Manufacturing	307	0.50
Total		71,577	100		61,061	100

Note: Journals in bold are among the top 15 in both management and engineering.

Rubalcaba, 2016) that merits an integrative review (Torraco, 2005).

Table 4 lists the 15 most-cited publications and their disciplines, as well as closeness and betweenness centrality measures that single out the most influential and central. Regarding their ranking, only a few publications differ in respect of the three measures. Overall, the measures draw a picture of some fundamental monographs complemented with articles across TIM, MGT, ED, and OM, confirming the multidisciplinary nature of the network. Specifically, Gershenson et al. (2003), Martin and Ishii (2002) are decisive for the discipline of ED, while Salvador et al. (2002) and Fixson (2005) are pivotal to OM. In addition, although the TIM references—for example Langlois and Robertson (1992) and Ulrich (1995)—exhibit a high closeness and betweenness centrality, the presence of innovation discussions is more noticeable in MGT, for example Henderson and Clark (1990) and Schilling (2000).

A persuasive argument in the field is that organizations and products (Baldwin & Clark, 2000; Simon, 1962) can be conceptualized as complex systems in which modularity is useful. Ulrich (1995) as well as Baldwin and Clark (2000) provide definitions of modularity and modularization. Meyer and Lehnerd (1997), Ulrich and Eppinger (2012), and Gershenson et al. (2003) conceptualize the stages of product modularization's application. Sanchez and Mahoney (1996) and Worren et al. (2002) discuss the interdependencies between products, processes, and organizational modularity. The field places particular emphasis on documenting application cases (Baldwin & Clark, 1997; Robertson & Ulrich, 1998). Interestingly, influential theories such as the knowledge-based view (Kogut & Zander, 1992) and dynamic capabilities (Teece et al., 1997) are less central compared with application cases. This is supported by publications referring more to complex systems (Schilling, 2000; Simon, 1962): an approach closer to design questions than other general theories.

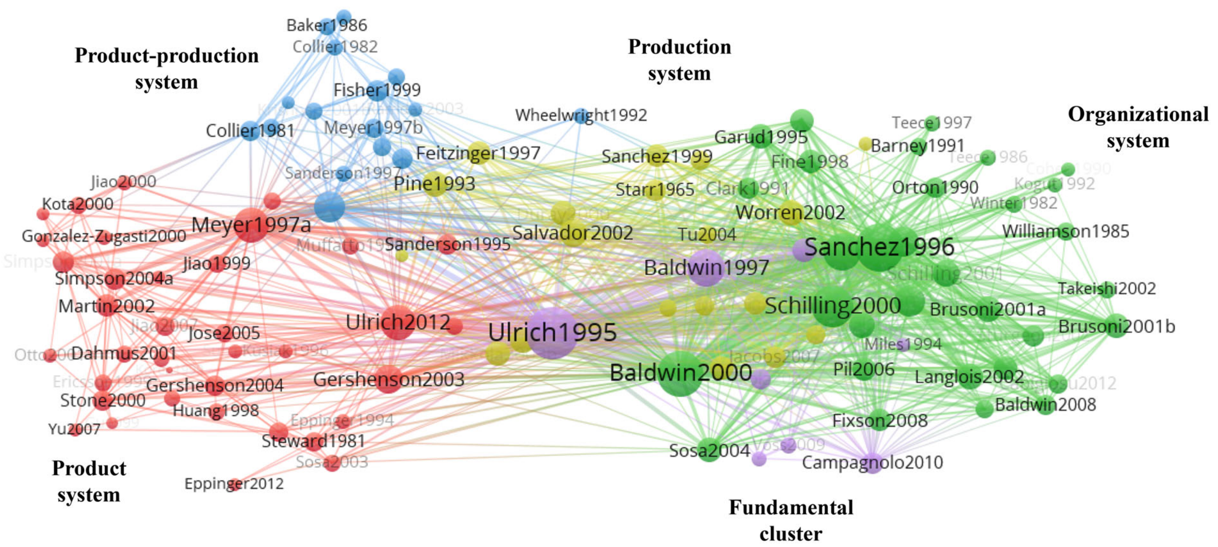

FIGURE 4 Overall co-citation network with clusters. The graphic representation of the VOS viewer denotes the similarity of publications in a network through proximity, for example, the publications in the red cluster are more like the ones in the yellow cluster than those in the green cluster. The co-citation network is based on a citation threshold of ≥45 and focuses on linkages with ≥10 co-citations. Links represent the number of co-citations: the thicker the path between two publications, the more co-citations there are. Each node is a cited publication of our data set, where its size denotes the total number of co-citations in the network. This is the sum of all individual links, with their number of co-citations. Abbreviations of the cited publications are in the Appendix S1. The cluster identification is based on the VOS technique, red = product system; blue = product-production system; green = organizational system; yellow = production system; purple = fundamental cluster.

4.3.2 | Cluster analyses

To discern distinct research perspectives in the field, we applied the VOS clustering algorithm to the network. We identified five clusters and found that each cluster was very robust.[15] Notably, Clusters 1 (red), 2 (blue), 3 (yellow), and 4 (green) are grouped around Cluster 5 (purple).

To examine the perspectives of the clusters, we start by analyzing their disciplinary composition. Cluster 1 (red) is dominated by journals such as *Research on Engineering Design*, *Journal of Engineering Design*, and *Journal of Mechanical Design*, and represents a large share (46%) of ED. It also contains OM (19%) and TIM (16%). Cluster 2 (blue) focuses on MGT (69%), mainly in *Management Science*, while Cluster 3 (yellow) is composed of OM (37%), MGT (26%), and TIM (21%). Cluster 4 (green) is more mixed and includes MGT (47%), ORG (25%), and TIM (9%). This is the only cluster that contains ORG. Finally, Cluster 5 (purple) is dominated by MGT (50%) and TIM (25%), but also includes OM (13%). Clusters 4 and 5 specifically relate to interdisciplinary discussions, as their intellectual roots are not dominated by a single focal discipline. ED is only documented in Cluster 1, while TIM is the only discipline in all clusters, playing a potentially integrative role. Overall, the results support a mix of disciplines with some disciplinary fragmentation.

The consideration of key publications in each cluster further reveals their intellectual roots. The center of Cluster 1 contains reviews and textbooks (Meyer & Lehnerd, 1997; Simpson, 2004; Ulrich & Eppinger, 2012) on the design and development of product families and platforms. Robertson and Ulrich (1998), Fisher et al. (1999), and Krishnan and Ulrich (2001), crucial in Cluster 2, elaborate on the effects of modular product designs in production environments. The critical publications in Cluster 3 are all closely linked to manufacturing, including component sourcing (Salvador et al., 2002), mass customization (Pine et al., 1993), and supply chain decisions such as postponement (Fixson, 2005). Cluster 4 shows high disciplinary heterogeneity, reflected in key publications that discuss topics such as innovation trajectories (Henderson & Clark, 1990; Schilling, 2000),

[15]The robustness analyses span a range of varying characteristics (see Appendix S1). First, we controlled for different filter settings during data collection (e.g., with/without proceedings) and checked for a comparable data set in the SCOPUS database. Second, we checked the cluster identification by lowering the citation threshold (55, 50, 45, 40, 35, 30, 25, and 20). Even with >1000 publications in the network, the number of clusters and their core publications remained as depicted. Third, we used other normalizations, but still found the same clusters (e.g., Modularity and Fractionalization). Fourth, we checked for different resolutions (1, 1.08, 1.15, 1.23, and 1.30) and found that the clusters stay within their initial boundaries and only decompose into smaller subclusters within each cluster. These subclusters cannot be related to new research perspectives.

TABLE 4 Focal publications in the co-citation network by number of citations and centrality measures

	Citations			Closeness centrality			Betweenness centrality		
No.	**Publication**	**Value**	**Disc.**	**Publication**	**Value**	**Disc.**	**Publication**	**Value**	**Disc.**
1	Ulrich (1995)	*466*	*TIM*	Ulrich (1995)	*0.991*	*TIM*	Ulrich (1995)	*0.179*	*TIM*
2	Sanchez and Mahoney (1996)	*369*	*MGT*	Baldwin and Clark (2000)	*0.887*	*Book*	Baldwin and Clark (2000)	*0.089*	*Book*
3	Baldwin and Clark (2000)	*347*	*Book*	Ulrich and Eppinger (2012)	*0.809*	*Book*	Ulrich and Eppinger (2012)	*0.062*	*Book*
4	Meyer and Lehnerd (1997)	*272*	*Book*	Sanchez and Mahoney (1996)	*0.803*	*MGT*	Meyer and Lehnerd (1997)	*0.050*	*Book*
5	Schilling (2000)	*252*	*MGT*	Schilling (2000)	*0.759*	*MGT*	Sanchez and Mahoney (1996)	*0.047*	*MGT*
6	Ulrich and Eppinger (2012)	*241*	*ED*	Baldwin and Clark (1997)	*0.753*	*MGT*	Baldwin and Clark (1997)	*0.032*	*MGT*
7	Henderson and Clark (1990)	*231*	*MGT*	Meyer and Lehnerd (1997)	*0.738*	*Book*	Schilling (2000)	*0.032*	*MGT*
8	Baldwin and Clark (1997)	*224*	*MGT*	Henderson and Clark (1990)	*0.719*	*MGT*	Gershenson et al. (2003)	*0.032*	*ED*
9	Robertson and Ulrich (1998)	*181*	*OM*	Gershenson et al. (2003)	*0.710*	*ED*	Robertson and Ulrich (1998)	*0.031*	*OM*
10	Pine et al. (1993)	*163*	*Book*	Robertson and Ulrich (1998)	*0.701*	*OM*	Henderson and Clark (1990)	*0.020*	*MGT*
11	Gershenson et al. (2003)	*146*	*ED*	Simon (1962)	*0.675*	*MISC*	Salvador et al. (2002)	*0.011*	*OM*
12	Simon (1962)	*134*	*MISC*	Langlois and Robertson (1992)	*0.663*	*TIM*	Martin and Ishii (2002)	*0.011*	*ED*
13	Simpson et al. (2001)	*132*	*ED*	Salvador et al. (2002)	*0.663*	*OM*	Pine et al. (1993)	*0.010*	*Book*
14	Eisenhardt (1989)	*126*	*MGT*	Schilling and Steensma (2001)	*0.651*	*MGT*	Simon (1962)	*0.008*	*MISC*
15	Salvador et al. (2002)	*122*	*OM*	Worren et al. (2002)	*0.640*	*OM*	Fixson (2005)	*0.007*	*OM*

Note: Closeness centrality expresses the closeness to all other publications in the network. The higher the dimensionless value, the more central a publication is in the network, indicating a decisive role for the field. Betweenness centrality denotes the influence of a publication over the flow of information in the network. The higher the value, the more important its role as a potential bridge between publications in network (Bonacich, 1987; Newman, 2006).

the interplay between products and organizations (Sanchez & Mahoney, 1996), and drivers of complexity in systems (Schilling, 2000; Simon, 1962). Lastly, Cluster 5 contains the most central publications, such as Ulrich (1995) and Baldwin and Clark (1997) and refers to the roles and effects of product and service architectures (Mikkola, 2006; Ulrich, 1995; Voss & Hsuan, 2009). Overall, the clusters' key publications allude to distinct knowledge bases.

Finally, we use text mining of abstracts and keywords to substantiate the research perspective of the clusters (see Table 4 and Appendix S1 for more details). In general, as expected, all clusters are dominated by the terms "*modular*," "*design*," and "*architecture*," but they differ in other terms. For example, publications in Cluster 1 rely on "*family*" and "*develop*," and are unique in using the terms "*platform*," "*module*," and "*method*." As expected, we find that all clusters collectively have a similar thematic core, which accords with the syntax but differs in unique word stems, reflecting the distinctiveness of the clusters.

4.3.3 | Summary of the focal research perspectives

The summarization of the results of our cluster analyses in Table 5 shows that each cluster in the field can be related to three focal research perspectives on product modularization, namely (1) product system, (2) production system, and (3) organizational system, complemented by fundamental publications in a cluster.

TABLE 5 Focal research perspectives of the co-citation network

Clusters	Five most frequent journals	Disciplines [share%]	Five most cited publications	Five most frequent words and five most frequent, unique words	Focus on product modularization	Research perspective(s)
1: *Methods of modular product family design and platform development* *N* = 37 Years = 1981–2012 Ø Year = 2001 (red)	*Research on Engineering Design, Journal of Engineering Design, Journal of Mechanical Design, Concurrent Engineering, IEEE*	ED [46%] OM [19%] TIM [16%]	Ulrich and Eppinger (2012), Meyer and Lehnerd (1997), Gershenson et al. (2003), Martin and Ishii (2002), Simpson (2004)	*Design, family, modular, develop, common* *Platform, module, method, function, variety*	Effective development of modular and platform-based product families and product modularization methods	Product system
2: *Component commonality and product variety management* *N* = 18 Years = 1981–2003 Ø Year = 1994 (blue)	*Management Science, Production and Operations Management, Research Policy, Sloan Management Review*	MGT [69%] OM [13%] TIM [6%]	Robertson and Ulrich (1998), Fisher et al. (1999), Krishnan and Ulrich (2001), Collier (1981), Meyer et al. (1997)	*Common, component, model, develop, costs* *Variety, level, decisions, platform, inventory*	Balancing product variety and commonality with NPD decisions about modular design to achieve organizational performance	Product-production system
3: *Manufacturing, supply chain, and customization* *N* = 16 Years = 1965–2007 Ø Year = 2001 (yellow)	*Journal of Operations Management, Harvard Business Review, IEEE, International Journal of Production Economics*	OM [37%] MGT [26%] TIM [21%]	Salvador et al. (2002), Worren et al. (2002), Pine et al. (1993), Fixson (2005), Mikkola and Gassmann (2003)	*Modular, architecture, custom, design, component* *Mass, strategy, flexible, supply, chain*	Impact on manufacturing, processes, and supply chain networks, subject to (mass) customization	Production system
4: *Organizational effects of modular (product) architectures* *N* = 32 Years = 1962–2012 Ø Year = 1997 (green)	*Strategic Management Journal, Academy of Management, Research Policy, Industrial Corporation Change, Organization Science*	MGT [47%] ORG [25%] TIM [9%]	Sanchez and Mahoney (1996), Baldwin and Clark (2000), Schilling (2000), Henderson and Clark (1990), Simon (1962)	*Firm, modular, design, innovation, system* *Knowledge, organization, technology, network, competition*	Effects on organizations and industries concerning innovation, knowledge, organizational design, flexibility, and collaboration	Organizational system
5: *Fundamentals, including product and service architecture* *N* = 11 Years = 1989–2008 Ø Year = 2001 (purple)	*Research Policy, Journal of Product Innovation Management, IEEE, R&D Management*	MGT [50%] TIM [25%] OM [13%]	Ulrich (1995), Baldwin and Clark (1997), Eisenhardt (1989), Campagnolo and Camuffo (2010), Mikkola (2006)	*Modular, architecture, design, develop, process* *Service, empirical, degree, case, interface*	Increasing modularity of product, service, production, and organizational architectures	Fundamental cluster

We label Cluster 1 as the product system perspective. This perspective is dominated by ED and concerns the design and development of modular and platform-based product families, while elaborating and improving methods of product modularization. Overall, the perspective considers product modularization as a process to design modularity into a product system.

Cluster 2 incorporates both the product and production systems perspectives, denoted as the product-production system. It is dominated by MGT and dedicated to product variety management. Costs and decisions play a crucial role. As a result, the cluster discusses product modularization as a process to manage variety through modular designs in products and production environments and can therefore be related both to the product and production systems perspectives.

Cluster 3 is classified as the production system perspective. It includes terms such as "*mass customization*," "*manufacturing*," and "*supply chain*," and its key publications consider how product modularization shapes processes, production, and supply chains. The OM discipline is most prominent in this cluster, closely followed by MGT and TIM. This composition documents an interdisciplinary view, and the cluster investigates production systems also beyond manufacturing.

Cluster 4 is labeled as the organizational system perspective. It attends to the organizational effects of modular product architectures emanating from product modularizations. The discussions specifically concern the effects on knowledge, coordination, collaboration, and innovation. Importantly, ORG studies are uniquely prevalent in this cluster, offering confirmation for its label.

Cluster 5 contains fundamental publications. It is highly intertwined with the network and views product modularization through a wide lens, employing product and service architectures as basic concepts, complemented with the architectures of production, organization, and systems (Baldwin & Clark, 2000; Campagnolo & Camuffo, 2010). The key publications emphasize product architectures (Baldwin & Clark, 1997; Mikkola, 2006; Ulrich, 1995) and service architectures (Bask et al., 2010; Voss & Hsuan, 2009), complemented by references to the case study method (Eisenhardt, 1989). The cluster's disciplinary composition is diverse, indicating an interdisciplinary view in the center.

5 | DISCUSSION

5.1 | Dynamics

The use of focal research perspectives as a stylized framework helps us to analyze and discuss the field's dynamics. By creating a co-citation network for each of the four periods, we trace the development of the research perspectives over time and identify peculiarities when comparing later and earlier periods. To display the network, we set a threshold of 17 citations for publications and again require 10 co-citations for a link to appear in the networks. We keep both thresholds constant throughout all phases to ensure comparability. As an in-depth discussion of each focal research perspective is beyond the scope and length of this paper, we focus on tracking critical variations in each period, while retaining our integrative orientation. Figure 5 depicts the four co-citation networks, revealing the dynamics at the level of both individual publications and research perspectives.

5.1.1 | Emergence 1990–2006

The network of the earliest period has 34 publications. It includes the most central publications of the overall co-citation network (Baldwin & Clark, 2000; Henderson & Clark, 1990; Sanchez & Mahoney, 1996; Schilling, 2000; Ulrich, 1995) and three focal research perspectives—the product system, the organizational system, and a mixed perspective of the product and production systems. The first two systems are very close. The basic theoretical papers discuss modularity in systems (Schilling, 2000; Simon, 1962) and design theory (Suh & Sekimoto, 1990). The MGT and TIM disciplines dominate. Discussions in this phase focus on product modularization as a product-family strategy during NPD (Meyer & Lehnerd, 1997; Simpson et al., 2001), the creation of modular product architectures (Ulrich, 1995), and the enhancement of loose couplings between components. Such modular designs offer opportunities for mass customization (Feitzinger & Lee, 1997; Pine et al., 1993), increasing profitability due to improved inventory management (Baker et al., 1986), strategic flexibility, and knowledge coordination (Sanchez, 1995; Sanchez & Mahoney, 1996).

5.1.2 | Fermentation 2007–2012

In the second period, the network grew from 34 to 95 publications, still featuring the three clusters from the previous period. The corresponding focal research perspectives move to the center and have more links, indicating a more comprehensive discussion and understanding of product modularization. ED becomes much more prominent, with a large share in the product system, while MGT decreases and TIM remains constant. This shift in the product system is accompanied by

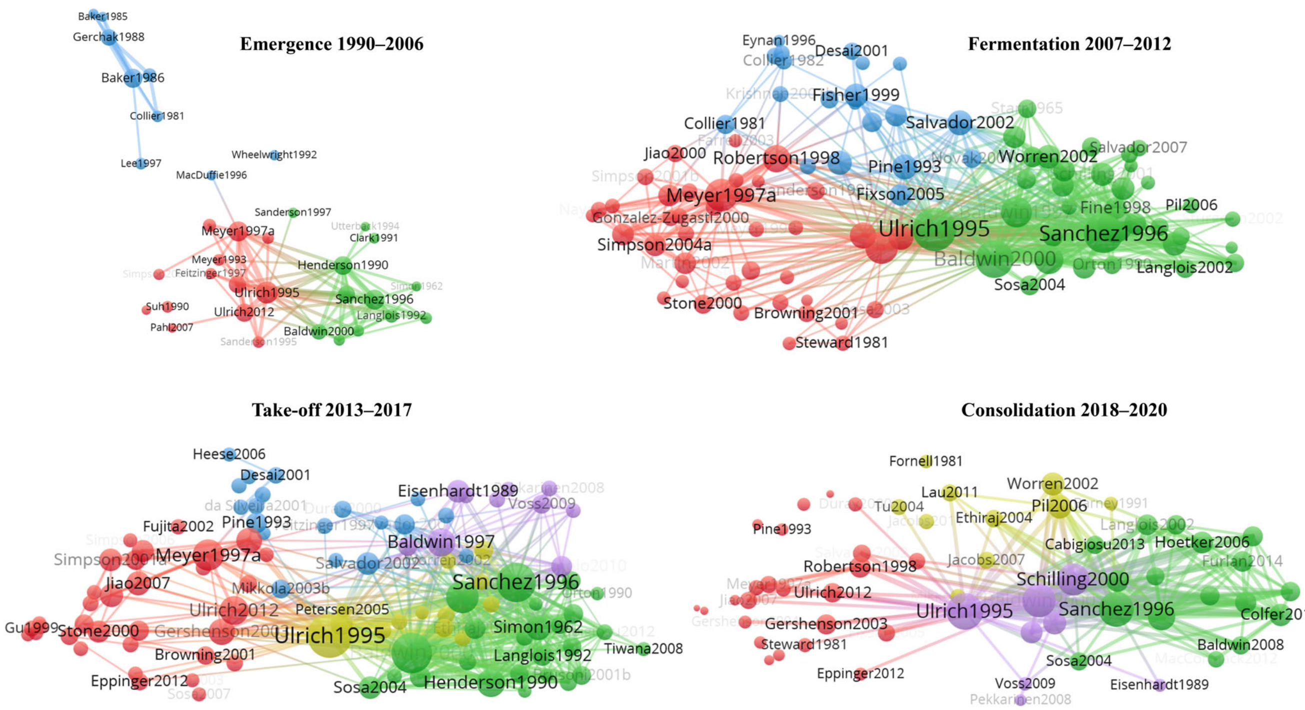

FIGURE 5 Co-citation networks over the periods. The graphic representation is again based on the VOS viewer, using the VOS technique for cluster identification. To account for the lower number of citations per period, we use a citation threshold of ≥17. Red = product system; blue = product-production system; green = organizational system; yellow = production system; purple = fundamental cluster.

methods and practical cases of product modularization to manage an increasing variety of products (Martin & Ishii, 2002; Simpson, 2004). Specifically, product life cycles (Ericsson & Erixon, 1999; Gu & Sosale, 1999) are regarded as critical for efficient modular product architectures (Dahmus et al., 2001; Du et al., 2001). The mixture of product and production system emphasizes the interdependence of products and production (Fixson, 2005; Krishnan & Ulrich, 2001) and attends to deliberate decisions on variety and differentiation (Desai et al., 2001; Ramdas, 2003). Similarly, the organizational system focuses on the interdependence of organizational and product designs (Brusoni & Prencipe, 2001; Sosa et al., 2004). It discusses the impact of modular product architectures on innovation (Ethiraj et al., 2008; Ethiraj & Levinthal, 2004; Henderson & Clark, 1990; Pil & Cohen, 2006). In this period, the field was enriched by theories such as transaction cost economics (Williamson, 1981) and the resource-based view (Barney, 1991).

5.1.3 | Take-off 2013–2017

This period includes 100 publications and five clusters. The two new clusters reflect the pure production system perspective and fundamental cluster and "redefine" the field's intellectual structure. The share of MGT decreases, while those of ED and TIM remain stable, but OM's share increases. The new perspectives capture central publications, for example, the production system (Ulrich, 1995) and the fundamental cluster (Baldwin & Clark, 1997). The latter places a broader scope on product modularization. For example, Campagnolo and Camuffo (2010) provide a review encompassing products, production, and organizations. This view is supported by new research foci on the interdependencies of modular product architectures and the supply chain (Novak & Eppinger, 2001; Pero et al., 2010; Ülkü & Schmidt, 2011) or modular product architectures and industries (Staudenmayer et al., 2005; Sturgeon, 2002; Tiwana, 2008). Interdependencies in particular seem to require new theoretical approaches (Nelson & Winter, 1982; Parnas, 1972). The product-production system initiates the (well-known) product variety management (Heese & Swaminathan, 2006; Lee & Tang, 1997), while the fundamental cluster highlights service architecture (Bask et al., 2010). The product system accentuates product modularization methods and sustainability (Tseng et al., 2008), and elaborates on a conceptual formalism in design structure modeling (Eppinger & Browning, 2012; Steward, 1981).

5.1.4 | Consolidation 2018–2020

In this period, the number of publications declines to 59. The mixed perspective of product-production system vanishes completely, but its publications diffuse to other perspectives, mainly the product and production systems. The perspectives of the organizational system, production system, and fundamental cluster are still integrated in this period, but the product system does not display the same behavior. Interestingly, the disciplinary composition of the field also changes as the share of ED declines and that of ORG increases. In this regard, the mirroring hypothesis becomes central in the organizational system (Cabigiosu & Camuffo, 2012; Colfer & Baldwin, 2016; Furlan et al., 2014). In contrast, the product system focuses on product-process development. The relatively recent contributions of Furlan et al. (2014) and Hoetker (2006) are central in this final period. They also converge, in that both conclude that modular product and organizational architectures will affect neighboring systems, manifesting in the trajectory of the mirror hypothesis. The production system therefore entails the concept of innovativeness, relating to the debate over whether or not modular product architecture empirically facilitates innovation (Langlois, 2002; Lau et al., 2011; Pil & Cohen, 2006). Furthermore, the topic of modularity measurement is more salient (Jacobs et al., 2007; Mikkola & Gassmann, 2003; Tu et al., 2004). In this period, the data suggest that the central publications of earlier periods changed considerably, marking a shift in the discussion of product modularization.

The strong shift of publications in the final period emphasizes mirroring hypotheses and a broader scope embedded in the concept of system architectures. The closeness centrality of several new and frequently cited publications (e.g., Colfer and Baldwin (2016)) escalates, compared with overall centrality (Table 2) and to previous centralities in the dynamics (Table 5), revealing the mirroring hypothesis as a key mechanism. In one of the emerging and highly cited publications, MacDuffie (2013, p. 8) accordingly defines modularization as "*a process that affects those designs* [designs of architectures of products and organizations] *while also shaping firm boundaries and industry landscapes*."

Furthermore, the increasing share of ORG (Table 5) alludes to new discussions on organizational topics. In addition, Table 5 specifies the increasing scope and documents the accumulating interdependencies between product architecture and organizations, supply chain networks, industries, and systems. In detail, studies investigated the architecture of services (Voss & Hsuan, 2009), teams (Sosa et al., 2003), organizational structures (Sosa et al., 2004), knowledge (Brusoni & Prencipe, 2001), buyers, customers, suppliers, design parameters (Hsuan, 1999; Jiao et al., 2007), processes (Worren et al., 2002), technology (Langlois, 2002), competition (Sanchez, 1995), product families (Salvador et al., 2002), technical (Colfer & Baldwin, 2016), platforms (Baldwin & Woodard, 2009; Gawer, 2014), organizations (Cabigiosu & Camuffo, 2012; Maccormack et al., 2012), supply chains (Fixson, 2005; Jacobs et al., 2011; Sanchez, 1999; Vickery et al., 2016), and industries (Furlan et al., 2014). To capture this broad scope and connect the related studies, the concept of *system architecture* is used (Baldwin & Woodard, 2009; Gawer, 2014; Sanchez, 1999).

Summarizing our analysis of the dynamics, Table 6 depicts the identified research foci, methods, and theories that characterized the intellectual structure over the four periods. In addition, we partially repeat the procedure used in our results section by showing discipline shares and the five publications with the highest increases of closeness centrality in each period.

5.2 | Key developments in the field of product modularization

Our results, particularly the comparison of the networks over the different periods, enable us to elaborate on the field's key developments and to develop a current, integrative understanding of the discussion on product modularization. We identify three research trajectories, which we discuss below.

5.2.1 | The differentiation of the field over time and the decreased integration of the product system

The comparison of the four periods yields an observable differentiation of several research perspectives, seen specifically in the product, production, and organizational systems. This specialization is reflected in more dedicated key publications in the respective clusters, as well as in the split of publications in the formerly mixed product-production system cluster during the final period. Such a differentiation of perspectives represents a typical pattern in the maturation of fields (Hauke et al., 2017). Still, this process is accompanied by a gradual decrease in product system integration. While the product system and the organizational system were close and had many links in the first period, the product system later grew more distant from the organizational system (see the overall network and Period 4). In addition, the dynamics indicate that the product system did not incorporate many new

TABLE 6 Summary of key characteristics of the field for the four periods

Period	1990–2006	2007–2012	2013–2017	2018–2020
Disciplines	MGT [41%]; TIM [18%]; OM [6%]; ED [3%]	MGT [33%]; ED [21%]; TIM [18%]; OM [11%]; ORG [4%]	MGT [26%]; OM [22%]; TIM [18%]; ED [16%]; ORG [6%]	MGT [31%]; OM [20%]; TIM [19%]; ORG [8%]; ED [8%]
Publications with top five increases of closeness centrality	Henderson and Clark (1990) Ulrich (1995) Sanchez and Mahoney (1996) Meyer and Lehnerd (1997) Pine et al. (1993)	Fisher et al. (1999) Gershenson et al. (2003) Salvador et al. (2002) Simpson (2004) Martin and Ishii (2002)	Campagnolo and Camuffo (2010) Fixson and Park (2008) Jacobs et al. (2007) Cabigiosu and Camuffo (2012) MacDuffie (2013)	Colfer and Baldwin (2016) Furlan et al. (2014) Cabigiosu et al. (2013) MacCormack et al. (2012) Lau et al. (2011)
Focal research perspectives	Product system Organizational system Product-production system	Product system Organizational system Product-production system	Product system Organizational system Product-production system Production system Fundamental cluster	Product system Organizational system Production system Fundamental cluster
Key research foci across the research perspectives	Modular NPD and product family design [1] Mass customization [1] Modular designs for strategy, organization, management [2] Operational performance [3] Inventory management [3]	Product modularization methods [1] Modular product architecture [1] Product life cycle view [1] Product-organizational system interdependence [2] Product architecture and innovation [2] Decision making on variety [3] Product-production system interdependence [3]	Sustainability [1] Design structure modeling [2] Product-organization-industry interdependence [2] Product variety management [3] Product-supply chain interdependence [4] Service architecture [5]	New product-process development [1] Mirroring hypothesis [2] Modularity measurement [4] Innovativeness [4] Foundations [5]
Methods	Conceptual Modeling/Analytical Field experiments	Conceptual Case studies Modeling/Analytical Surveys	Case studies Qualitative analysis Interviews Surveys	Case studies Surveys Qualitative analysis
Theories/concepts	Complex systems Modular systems theory Design theory	Transaction cost economics Loose coupling Resource-based view	Evolutionary theory of the firm Design structure modeling	Mirroring hypothesis
Focus of product modularization	Internal product (family) view	Firm-centric view (i.e., product, production, organizational system)	Firm-network view (i.e., suppliers, competitors, and industries)	System view (i.e., mirroring, interdependencies, system architecture, complex system)

Note: This table is an aggregation of four individual tables that cover each period. The Appendix S1 contains details. A key research focus is characterized by at least three close publications that address a similar topic. We use them to spot specific discussions within the research perspectives and provide the number of the corresponding research perspective in brackets. 1 = product system; 2 = organizational system; 3 = product-production system; 4 = production system; 5 = fundamental cluster.

publications, as we only found two new publications in the last period (Elmaraghy et al., 2013; Simpson et al., 2014), while the product system's remaining publications became less central in the field (see Appendix S1). The share of ED, the major discipline of the product system, likewise declined over the last two periods (Table 5).

While a differentiation of perspectives allows for a cognitive division of labor and fosters specialization, the potential dangers of fragmentation must be kept in mind. As the product system loses track in the field, knowledge on modularizing products by using certain methods and research foci of product life cycles, sustainability, and modularity measurement might recede into the background of other perspectives. Since the organizational system employs modular product architectures as a primitive unit, it may not sufficiently integrate the relevant processual characteristics. The findings imply that the field paid more attention to the interdependence of process and organizationally relevant outcomes in earlier times, but this waned as the periods succeeded one another. As a result, firms and scholars might underestimate the importance of process characteristics when trying to figure out and scrutinize the later effects of modular product architectures.

5.2.2 | Increasing scope of product modularization in combination with an emerging center of gravity of fundamental publications

While the field differentiates, we also find an increasing scope of product modularization over time. Simultaneously, we see an emerging cluster of fundamental publications and the use of the concept of system architecture. The fundamental publications include Schilling (2000), Baldwin and Clark (2000), Baldwin & Clark, 1997), which were also documented as the most central publications in the field (Table 4). Interestingly, the most central publication, Ulrich (1995), also appears in this cluster, which has been part of other research perspectives before. This emergence of a fundamental cluster appears in the overall co-citation network and over the last two periods, but is not explicitly documented in the literature to date. We welcome this trajectory, as it underscores the integrative efforts of this review toward a more cohesive scientific field. Note that the development of such a core is not standard for a research field, especially one involving interdisciplinary discourse. For instance, Van Eck and Waltman (2010) document a clear separation of publications in the economics and business disciplines. Similarly, the co-citation networks show increasing interweaving between the fundamental cluster and organizational systems (Figures 4 and 5), and the fundamental cluster connects the different research perspectives with each other, especially in the latest period.

Notably, product modularization initiates changes in the product architectures that diffuse to other architectures, reflected in a more general system architecture. System architectures have become prominent during the last period (Baldwin & Woodard, 2009; Gawer & Cusumano, 2014). Hence, it seems a helpful concept to combine different architectures across perspectives and disciplines. However, a comprehensive understanding of the concept is not entirely clear. For example, in the product system, Jiao et al. (2007) delineate a system architecture by customers, products, functions, design parameters, processes, and supply chains. By contrast, the organizational system relates teams, tasks, knowledge, department structures, supply chains, and industry networks in a system architecture, in combination with technical architectures (Brusoni & Prencipe, 2011). As a result, the product system does not cover the organizational system, and the organizational system does not entirely employ the product system.[16] These two systems' distinct disciplinary backgrounds impair mutual understanding, but the remaining ambiguity over the meaning of a system architecture can hamper interdisciplinary progress. Further, stakeholders in firms do not necessarily employ a similar view of system architectures, given distinct perceptions.

Our study indicates that product modularization shapes system architecture by affecting the modularity of several architectures. The observations in the discussion of the dynamics (see the consolidation period and publications exemplifying the scope of architectures) provide a snapshot of a novel understanding of product modularization and characterizes its outcomes as a broader change in the system architecture beyond product architectures. It implies that the structural choices of product modularization apply to several technical and organizational architectures, resulting in a complex system, and that more attention should be paid to its interdependencies. This compels firms and scholars to think about design changes beyond the scope of product architectures based on the concept of system architecture, especially when planning product modularization.

In sum, our review suggests that the (product) modularization process develops toward a system architectural view with a broader scope that encompasses

[16]We provide an area-based co-citation analysis in the Appendix S1 that shows that the management area does not entirely capture the product system, while the engineering area does not fully reflect the organizational system.

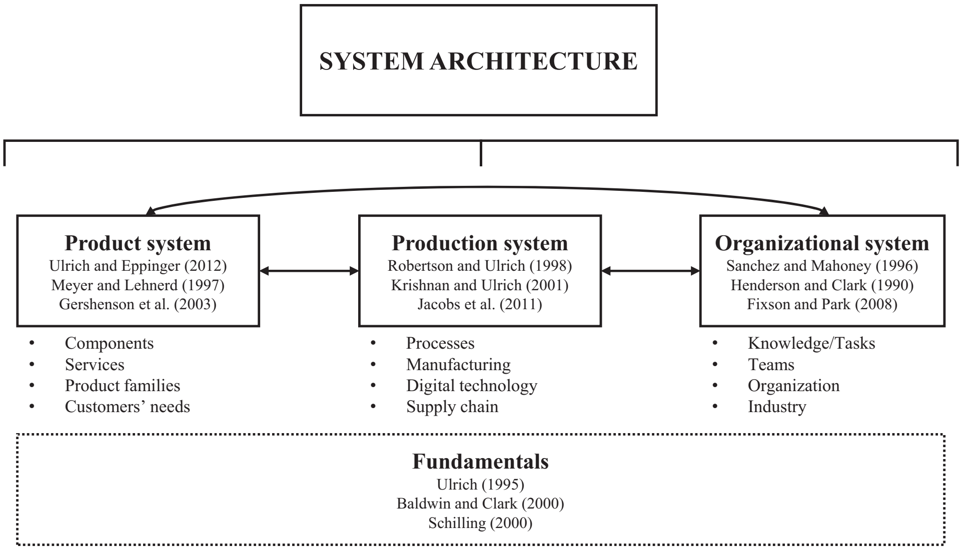

FIGURE 6 Increasing scope of product modularization and concept of system architecture. The figure illustrates the scope of system architecture in the literature. It is based on a stylized representation of the intellectual structure we identified for the field of product modularization. The three systems refer to the three basic research perspectives documented in the overall citation network. The unit lists below the perspectives are based on publications in these perspectives.

interdependent architectures and can be related to the three key research perspectives identified. Figure 6 depicts this view of system architecture indicated by the co-citation network, embodying the wider scope of product modularization as a structural process typically rearranging components of the product, production and organizational systems (e.g., components, processes, or tasks/knowledge) to create modular architectures.

5.2.3 | Substantial change within the constant research perspectives of production and organizational systems

Our study identified the product, production, and organizational systems that persist over the four periods, while partly changing in respect of underlying publications. Figure 5 documents dynamism in the publications and research foci within the constant research perspectives of production and organizational systems. While the product system is characterized by fewer changes (see above), the production and organizational systems changed rapidly in publications during the two most recent periods. In terms of this general development, we identify two noteworthy trajectories.

First, the research focus of innovation in the organizational system received a lot of attention in the first period, including the classical categories of incremental and radical innovations (Henderson & Clark, 1990). This declined during later periods, being diffused over various research perspectives—even though "*innovation*" is still among the most frequent keywords in the overall list (Table 2). In the most recent period (Period 4), several publications conceptually address innovation in the production system (Ethiraj & Levinthal, 2004; Lau et al., 2011; Pil & Cohen, 2006), creating a new research focus. This focus considers when and whether product modularizations facilitate innovation, which empirical studies have yet to explore.

Second, we find no intermediate results in our analyses that point to an increasing emphasis on digitalization and collaboration. Although these global trends affect firms and are increasingly discussed, no cluster has yet appeared. This could be because co-citation analysis suffers from a time lag, but we still expect digitalization to emerge, because modularization is a standard concept in software projects and programming. Similarly, product modularization can affect collaboration, such as in supply chains (Tee, 2019). To overcome limitations due to time lag, we considered recent citing publications in our data set. Here we find nascent discussions of digitalization, involving digital innovation and design (Nambisan, 2018; Nambisan et al., 2017) and of collaboration research (Jacobides et al., 2016; Tiwana et al., 2010).

6 | FUTURE RESEARCH AGENDA

Based on the discussion of our results, we present future research opportunities in the field of product modularization in Table 7. The previously identified developments are used as a framework to identify research

TABLE 7 Future research agenda

Research trajectories	Research opportunities	Potential research questions	Potential methods and data sources	Research foci, helpful theories, and concepts
[1] The differentiation of the field and the decreased integration of the product system	*Modularity measurements*	• How do technical measures compare with survey-based constructs of modularity? • Do and should measures differ when going beyond products (e.g., the supply chain or organization)? • What is a suitable level of decomposition to measure modularity? • How and to what extent can firms use the resulting knowledge of modularity in their decisions (e.g., to increase flexibility, to reduce costs and complexity, and to simplify processes)? • Which measurements perform best in predicting the effects of interest (e.g., costs, flexibility, and differentiation) on variables?	Computational methods to comparatively assess sensitivity and peculiarities of measures (Cabigiosu & Camuffo, 2016), data of firms about design of products, supply chain and organization Proprietary data of firms concerning modularity measures and performance (Hackl et al., 2020)	Production system (Period 4)—Modularity measurements Modularity measurements (Cabigiosu & Camuffo, 2016; Collier, 1981; Jacobs et al., 2007; Kota et al., 2000) Complexity measurements (Efatmaneshnik & Ryan, 2016) and network measures (Bonacich, 1987; Scott, 1988) Decomposition and granularity (Algeddawy & Elmaraghy, 2013; Browning, 2016)
	Product life cycle	• What is the role of product life cycles in product modularization, especially concerning interdependencies with production and organizational systems? • How and to what extent do other life cycles in firms (e.g., technology of production programs) affect modularity, and vice versa? • How can information from product life cycle management support product modularization?	Longitudinal studies in firms with proprietary data (Meyer et al., 2018)	Product system (Period 2)—Product life cycle Product life cycles (Gu & Sosale, 1999; Hackl et al., 2020; Martin & Ishii, 2002; Otto et al., 2016) Product life cycle management (He et al., 2019; Lim et al., 2020; Micheli et al., 2019)
	Sustainability	• How can we measure the impact of product modularization to sustainability, and vice versa? How does this relate to product life cycles? • To what extent do trade-offs between performance and sustainability exist in the context of product modularization? • What role does a modular design play in the circular economy?	Case-based research	Product system (Period 3)—Sustainability Design for sustainability (Kim & Moon, 2019; Marion et al., 2015; Sonego et al., 2018) Circular economy (Geissdoerfer et al., 2017; Stahel, 2016; Tukker, 2015)

TABLE 7 (Continued)

Research trajectories	Research opportunities	Potential research questions	Potential methods and data sources	Research foci, helpful theories, and concepts
[2] Increasing scope of product modularization in combination with an emerging center of gravity of fundamental publications	*System architecture*	• How can the differences in scope of the disciplines concerning system architecture be reconciled? • Does managerial decision making already reflect this increasing scope, and which best practices can be identified? • What is a suitable level of decomposition for architectures (e.g., a trade-off between information overload and abstraction)? • What are the most relevant architectures to manage modular change (e.g., focus only on technical architecture or combined with organizational architecture)? • Does concept generation involve more than product architectures (relevance of considering other architectures such as production or organizational architecture)? • What is the role of design structure modeling, axiomatic design, and design science in designing system architecture?	Explorative and conceptual research on different architectures and their interdependencies (Schilling, 2000) Data of product, production, and organizational architectures to test interdependencies between systems (Colfer & Baldwin, 2016)	Fundamental cluster Period 3—Service architecture Organizational system Period 4—Mirroring hypothesis System architecture (Baldwin et al., 2014; Engler et al., 2017) NPD concept generation (Cooper, 2019; Evanschitzky et al., 2012; Markham, 2013; Mertens et al., 2021) Design structure modeling and axiomatic design (Eppinger & Browning, 2012; Suh, 2001)
	Process	• To what extent is product modularization a deliberate and actively managed or emergent process in firms? • To what extent is product modularization incorporated in strategic processes? • What is the appropriate time horizon to study the outcomes of product modularizations? • Is the allowance or prevention of mirroring a managerial decision?	Interviews of top-level management or modularization professionals (Halman et al., 2003), participating observation during product modularizations, and case study research	Deliberate vs. emergent strategy (Mintzberg & Waters, 1985) Resource-based and knowledge-based views (Barney, 1991; Kogut & Zander, 1992) Case study research (Eisenhardt, 1989; Yin, 2011) Organizational change management (By, 2007)
	Platforms	• What is the role of product modularizations in creating supply chain and industry platforms? • What are the differences between the concepts of product modularization, platform-based development, and platform creation? • What is the relationship between the concepts of dominant design and platforms? Do dominant designs foster the creation of supply chain and industry platforms?	Explorative research with panel, archival, or web-based data	Fundamental cluster Period 4—Cluster Platform economics (De Reuver et al., 2018; Gawer, 2014) Dominant design (Murmann & Frenken, 2006; Srinivasan et al., 2006)

(Continues)

TABLE 7 (Continued)

Research trajectories	Research opportunities	Potential research questions	Potential methods and data sources	Research foci, helpful theories, and concepts
[3] Substantial change within the constant research perspectives of production and organizational systems	*Innovation*	• What is the role of product modularization in creating innovations? • Is there empirical evidence for a potential trade-off between innovation and imitation resulting from product modularization? • What is the interplay between user innovation and product modularization? • To what extent do internal or external search processes during product modularization influence outcomes (e.g., marketing information about costumer segmentation vs. cost information in the supply chain)?	Surveys using modularity constructs measuring modularity in systems and its impact on innovation (Jacobs et al., 2011) Multi-method case studies involving various data sources (e.g., patent data, interviews, and proprietary data) (Marion & Fixson, 2020; Pesch et al., 2021)	Production system Period 4—Innovativeness Knowledge-based view (Eisenhardt & Santos, 2006; Kogut & Zander, 1992) Organizing, decomposition, and coupling of knowledge (Phelps et al., 2012; Yayavaram & Ahuja, 2008) Search processes and idea generation (Ehls et al., 2020; Van den Ende et al., 2015)
	Digitalization	• What is the influence of digital tools and Artificial Intelligence on developing the next generation of design methods for modularity? • To what extent can product modularization facilitate digitalization? • How will digital technologies change the (business) innovation process, and what is the role of modularity? • How can we integrate the design methods for modular products into the virtual design process? • How can model-based (system) engineering support design methods for modular products?	Longitudinal case studies with qualitative and quantitative data (Marion & Fixson, 2020)	Fundamental cluster Period 4—Service architecture Business model innovation (Afuah & Tucci, 2001; Nambisan, 2018) Digitalization, digital design, and digital tools (Appio et al., 2021; Marion et al., 2015; Marion & Fixson, 2020; Pesch et al., 2021)
	Collaboration	• How does modularity structure ecosystems and collaboration among firms? For example, how powerful are individual firms (OEM or supplier)? • What is the impact of product modularization on global wealth chains? • How can modularity foster collaboration like co-creation? • Can design thinking principles benefit the process of product modularization?	Online and laboratory experiments to identify causal relationships between modular designs and collaboration Trade statistics, panel data	Platform ecosystems (Gawer & Cusumano, 2014; Jacobides et al., 2018) International economics and trade theory (Seabrooke & Wigan, 2017) Co-creation (Gemser & Perks, 2015; Jacobides et al., 2016; Perks et al., 2012) Design thinking (Auernhammer & Roth, 2021; Carlgren et al., 2016; Verganti et al., 2021)

opportunities and pose questions that researchers could address in future. Whenever applicable, we complement them with supportive research foci, theories, and concepts detected in our review.

6.1 | Research trajectory 1: The differentiation of the field and the decreased integration of the product system

Variation in different scholarly perspectives and fragmentation point to areas where the field can profit from knowledge exchange and integration.

6.1.1 | Modularity measurements

So far, studies within the different perspectives have developed specific measures to assess the degree of product modularity. The product system employs comprehensive technical measures (Gershenson et al., 2004; Kota et al., 2000; Martin & Ishii, 2002), while organizational studies typically use measures such as the number of components, functions, and interfaces (Cabigiosu & Camuffo, 2016). Remarkably, the production system has developed survey instruments to question stakeholders about modularity (Jacobs et al., 2007; Jacobs et al., 2011; Tu et al., 2004; Worren et al., 2002). Although Cabigiosu and Camuffo (2016) discussed differences between engineering and management measures of modularity, these measures did not—at the time—include questionnaire constructs imported from the production system. Because the theory of complex systems is so prominent in product modularization, research could also consider applying diverse complexity-related constructs (Efatmaneshnik & Ryan, 2016) and network measures (Bonacich, 1987; Scott, 1988). Furthermore, there is little discussion on the right level of decomposition of measures in terms of granularity, although studies emphasize its relevance (Algeddawy & Elmaraghy, 2013; Voss & Hsuan, 2009). In addition, little is known about the performance of different measures in terms of predicting key modularization outcomes. Collectively, these research opportunities extend a concerted call to increase the integration of measurements.

6.1.2 | Product life cycle

The product system addresses the topic of product life cycles and discusses the implications of design decisions for products, production, distribution, reuse, recycling, and disposal (Gu & Sosale, 1999). Surprisingly, we find that this issue has been neglected by the research perspectives of production and organizational systems, despite earlier claims that it is relevant (Campagnolo & Camuffo, 2010). Specifically, how do other life cycles of technological change—such as the increasing use of advanced manufacturing or digital technology—affect previously designed modular product architectures? Which other systems must be considered from the viewpoint of the product life cycle? In this regard, practice advances by leveraging information obtained from product life cycle management (Lim et al., 2020)—a process that scholars can join, for example, by longitudinal studies with proprietary data from firms.

6.1.3 | Sustainability

While sustainability is evident as a goal of product modularization in the product system discussion (Period 3), it has not yet received much attention across the field. As sustainability seems to be a key source of competitive advantage in future markets, the lack of coverage in the overall network suggests that it should receive more attention. In particular, recent literature reviews call for a better understanding of the relationship between modularity and sustainability (Sonego et al., 2018), and this raises several unanswered questions. Since there might be trade-offs between different product modularization goals, what are the implications of increased sustainability for other goals, such as firms' financial performance? How do modular designs relate to sustainable design (Geissdoerfer et al., 2017; Stahel, 2016)? While sustainable designs theoretically support circularity, we need more empirical investigations.

6.2 | Research trajectory 2: Increasing scope of product modularization in combination with an emerging center of gravity of fundamental publications

The study's second documented development is that increasing modularity through product modularization often affects various other systems and their architectures.

6.2.1 | System architecture

This widening scope compels scholars to adopt a broader view of the relationships between different systems—of larger system architectures. Although the concept of system architecture appears in seminal publications (Baldwin & Clark, 2000; Simon, 1962) and more recent ones (Brusoni & Prencipe, 2001; Brusoni & Prencipe, 2011; Engler et al., 2017), research with this explicit focus is marginal. Our study reveals differences in the understanding of system architecture.

While the product system pertains to technical aspects and excludes the organizational system, the organizational system reduces technical architectures mostly to products. Our study argues for a broader scope and pinpoints toward various components (e.g., product families, processes, teams, or knowledge) from different systems (e.g., product, production, or organizational systems) and their relationships. To achieve a comprehensive view, one must balance the scope and the right level of decomposition. For instance, which architectures and components are necessary to consider, and does increasing the scope imply a change in the way modularization is conducted? With respect to firms, the question arises to which extent managerial decision making reflects this increasing scope and which best practices can be identified. Since a larger scope should give decision-makers more information to process, firms will have to find the right level of decomposition in system component hierarchies that provides the right level of complexity (Algeddawy & Elmaraghy, 2013; Suh, 2005). They must also find the right scope when applying product modularization and decide what to include during early concept generation (Cooper, 2019; Mertens, 2020; Mertens et al., 2021). Given our review and an increased scope, fundamental publications, formalisms such as design structure modeling, and exchange between research perspectives could support scholarly activities (Eppinger & Browning, 2012; Steward, 1981; Suh, 2001).

6.2.2 | Process

The increased scope of product modularization also offers opportunities to revisit its processes. How far is product modularization a deliberate choice or an emergent strategy (Mintzberg & Waters, 1985) and how much could it be so? An example could be interviews with top-level management or modularization professionals. Product modularization received attention as a new strategic approach at the dawn of the field (Sanchez, 1995; Sanchez & Mahoney, 1996; Worren et al., 2002). Meyer and Lehnerd (1997), conceptually, discussed how to gain competitive advantage via different strategies of product modularization. Since then, there has been a noticeable drop in in-depth discussions of the benefits of increased flexibility, coordination, and other firm performance measures at the strategic level. With a few exceptions (e.g., Halman et al., 2003; Piran et al., 2016), empirical studies of product modularization in the context of strategy and corresponding high-level organizational processes remain relatively scarce. The mirroring hypothesis is of interest here, because it sheds light on potentially strong linkages between modular architectures. Under which circumstances would it be beneficial to allow or prevent mirroring (Colfer & Baldwin, 2016)? To what extent is this a managerial choice? Given these issues, theories drawn from strategic management provide an appropriate starting point (Barney, 1991; Jarzabkowski & Paul Spee, 2009; Kogut & Zander, 1992).

6.2.3 | Platforms

The broader scope of product modularization is also linked to the discussion of platforms (Gawer, 2014; Gawer & Cusumano, 2014). Specifically, the product modularization can be considered as a deliberate strategy to create a platform for organizations (Simpson, 2004), supply chain networks (Van den Broeke et al., 2015), or ecosystems (Gawer & Cusumano, 2014), providing numerous research opportunities. Initial steps can reconcile differences and identify similarities between platform creation (Khanagha et al., 2020), platform-based product development (Chai et al., 2012; Meyer et al., 2018), and product modularization. Even though the concept of dominant design is an explanation for supply chain and industrial changes (Murmann & Frenken, 2006), analyses between dominant design and platform creation remain scarce. Murmann and Frenken (2006) define it as a "*complex system perspective*" with "*stable core components that can be stable interfaces*" (p. 925). This view can be similar to that of platforms, because Gawer (2014) denotes platforms as "*stable system architectures with stable interfaces*" (p. 1243). Research with panel, archival, or web-based data could further explore their relationship.

6.3 | Research trajectory 3: Substantial change within the constant research perspectives of production and organizational systems

As a third development, we recently noted active discussions and substantial changes in the field, even as the research perspectives remained constant. Against this backdrop, we note three future research opportunities. One research perspective—the production system—already addresses one of these (i.e., innovation). In addition, we propose two others—digitalization and collaboration—that represent important trends that are only reflected in our citing publications.[17]

6.3.1 | Innovation

Regarding innovation, modularity is potentially a double-edged sword. Modular designs are characterized by higher levels of standardization and combinability (Baldwin & Clark, 2000) and present an opportunity for extensive technology exploitation (Chesbrough & Prencipe, 2008). Hence, one possible intention of modularity is to support innovation, as discussed early in the product system and subsequently in the production system (Ethiraj & Levinthal, 2004; Henderson & Clark, 1990; Langlois & Robertson, 1992). Modularity can, however, also facilitate imitation (Ethiraj et al., 2008; Pil & Cohen, 2006). As only a few empirical studies address the potential trade-off between innovation and imitation, its exact circumstances and underlying mechanisms unfortunately remain ambiguous. Innovation-oriented firms may shy away from modularity because low-cost labor countries could easily imitate their designs at lower rates. However, the very factors that raise the threat of imitation—such as accessible designs and interfaces—could be beneficial in other ways. If modular designs are made easier to share, they can improve user accessibility and facilitate user innovation (Piller & Walcher, 2006; Von Hippel & Katz, 2002). To ease this tension, firms could benefit from a better understanding of whether and when their modular designs facilitate (user) innovation while preventing imitation by competitors. Research can apply empirical studies as surveys with modularity constructs or multimethod case studies to fill this gap.

Notably, product modularization provides different settings for future innovation search in which search processes could play a vital role (Ehls et al., 2020). Specifically, how should firms conduct search processes during product modularization to identify and develop platforms and modules? To what extent should firms rely on external and internal search processes? What are the implications of these search processes? In this regard, does product modularization benefit from greater diversity across domains and provide new value (Felin & Hesterly, 2007)? The answers will help firms understand when and under what circumstances modularity and innovation harmonize or counteract.

6.3.2 | Digitalization

Our study reports little attention to digitalization, even though recent studies deem the relationship between modularity and digital technologies to be underdeveloped (Nambisan, 2018; Nambisan et al., 2017). Scholarly opportunity arises because of increasingly powerful digital technologies that are transforming innovation processes (Appio et al., 2021; Marion & Fixson, 2020) and potentially also product modularization. Current topics are model-based (system) engineering or virtual design processes for modular product families (Lim et al., 2020). In contrast, little is known about whether and how product modularization facilitates the implementation of digital technologies through increasing standardization, for example with respect to new interfaces. Does greater modularity prepare firms' portfolios for digitalization? Furthermore, do these settings support digital innovations and are they starting points for business-model innovations (Kroh et al., 2018)? Although these questions were not identified in the review, they were found in the citing publications (Cenamor et al., 2017; Marion et al., 2015).

6.3.3 | Collaboration

Because modularity increases flexibility and coordination (Sanchez & Mahoney, 1996), product modularization can facilitate collaboration. Here, the emerging topic of platform ecosystems asks how product modularization can shape collaborations among firms and how this affects the power relationships between them (Jacobides et al., 2016). Research can scrutinize the effects of modules and platforms on global wealth chains by identifying broader societal impacts (e.g., Seabrooke & Wigan, 2017). Finally, an emerging topic regarding collaboration is value co-creation (Tiwana et al., 2010). Co-creation refers to the interplay between agents in interactive environments (Ramaswamy & Ozcan, 2018; Wang et al., 2016) that provide new value, such as innovation. Similar contexts are evident in NPD departments, supply chains, and user networks, and citing publications in the data set already call on scholars to investigate co-creation in these settings (Brax et al., 2017; Ulkuniemi & Pekkarinen, 2011), facilitated by modularity. Accordingly, design thinking, which is known to foster collaboration, may be relevant. For example, product modularization can potentially benefit from its new ways

[17]The choice of these two areas is substantiated by our data set of citing publications already including a discussion of collaboration (Jacobides et al., 2016) and digitalization (Nambisan, 2018). The use of bibliographic coupling (see Appendix S1) reveals additional publications on digitalization (Yin et al., 2017) and collaboration (Tiwana et al., 2010) that can be related to the production and organizational systems as well as to the fundamental cluster.

of multi-stakeholder collaboration and the combined use of engineering design and innovation management methods (Auernhammer & Roth, 2021; Verganti et al., 2021). Questions of co-creation and design thinking may particularly profit from online and laboratory experiments to identify causal relationships between modular designs and collaboration.

7 | CONCLUSIONS AND LIMITATIONS

This study provides an integrative literature review of the field of product modularization, aiming to unravel the field's intellectual structure and indicate future research opportunities.

First, our use of a bibliometric analysis provides an up-to-date synthesis that complements existing narrative studies by crossing disciplinary boundaries and taking a global view of the field's intellectual structure. This allows us to isolate focal research perspectives with distinct disciplines, research foci, concepts, and trends. The resulting stylized framework synthesizes latent knowledge about the intellectual structure of product modularization (Campagnolo & Camuffo, 2010; Fixson, 2007) and reduces conceptual ambiguity and the experienced distance between perspectives and disciplines.

Second, we provide an overview of the evolution of the field in terms of three key developments that are still undocumented. While we observe a disintegration of the product system and the related discipline of *Engineering Design*, the broadening scope of system architectures that we document charts a path toward an integrative, cross-disciplinary understanding that will help make the field more cohesive. This enriches our understanding of product modularization as something that affects the architecture of other systems beyond product architecture. The results have implications for firms and managers. When managers are only responsible for a single department and function—such as NPD, marketing, operations, finance, or procurement—they can fall into a “silo” mentality. While the stylized framework gives a first indication of the most relevant departments, the widening scope compels firms to think more expansively about the extent of product modularization, and how to cross functional and disciplinary boundaries. The concept of system architecture could therefore improve the management and efficacy of product modularizations by and for firms.

Third, the future research agenda points toward new topics and outcomes of product modularization for firms. While cost-efficacy and flexibility are well-known, new aspects include sustainability, innovation, digital technology, and collaboration. Likewise, there are other opportunities for knowledge diffusion and integration between research perspectives, for example concerning modularity measurements.

Although we concentrated on offering a thorough, integrative review of product modularization, our study has limitations. First, although our use of WoS was beneficial, it did exclude certain publications as well as proceedings and restricted us to works written in English. Another issue that restricts citation studies is the time lag between publications appearing and being cited. To ensure robustness, in anticipation of future developments, we performed a bibliographic coupling and found a similar structure of research perspectives. Although our data covers most current trajectories, it can only be used to extrapolate to future trajectories. Third, even though the derivations of results are transparently backed by data, a certain degree of subjectivity prevails. To counter this limitation, we discussed the interpretations with the members of our interdisciplinary research team and with other experts. Overall, we are confident that we present a comprehensive and integrative review of the multidisciplinary field of product modularization.

ACKNOWLEDGMENTS

The authors would like to thank the editor Jelena Spanjol, the associate editor, and three anonymous reviewers for their detailed feedback and comments helping us to improve the article. We also gratefully acknowledge helpful discussions at the International Conference on Engineering Design (ICED) 2021 and multidisciplinary workshops at the Hamburg University of Technology. We would like to thank Loet Leydesdorff for his advice on analyses concerning interdisciplinary research and Ludo Waltman for his methodological feedback on the normalization method and cluster identification algorithm. Open Access funding enabled and organized by Projekt DEAL.

ORCID

Kai G. Mertens https://orcid.org/0000-0002-3335-2462
Christoph Rennpferdt https://orcid.org/0000-0001-5596-9773
Erik Greve https://orcid.org/0000-0001-5341-4600
Dieter Krause https://orcid.org/0000-0002-1253-1699
Matthias Meyer https://orcid.org/0000-0003-2980-4670

REFERENCES

Afuah, A., and C. L. Tucci. 2001. *Internet Business Models and Strategies*, Vol 2. New York: McGrawHill.

Algeddawy, T., and H. Elmaraghy. 2013. “Optimum Granularity Level of Modular Product Design Architecture.” *CIRP Annals* 62(1): 151–4. https://doi.org/10.1016/j.cirp.2013.03.118.

Appio, F. P., F. Frattini, A. M. Petruzzelli, and P. Neirotti. 2021. "Digital Transformation and Innovation Management: A Synthesis of Existing Research and an Agenda for Future Studies." *Journal of Product Innovation Management* 38(1): 4–20. https://doi.org/10.1111/jpim.12562.

Auernhammer, J., and B. Roth. 2021. "The Origin and Evolution of Stanford University's Design Thinking: From Product Design to Design Thinking in Innovation Management." *Journal of Product Innovation Management* 38(6): 623–44. https://doi.org/10.1111/jpim.12594.

Baker, K. R., M. J. Magazine, and H. L. W. Nuttle. 1986. "The Effect of Commonality on Safety Stock in a Simple Inventory Model." *Management Science* 32(8): 982–8. https://doi.org/10.1287/mnsc.32.8.982.

Baldwin, C. Y., and K. B. Clark. 1997. "Managing in an Age of Modularity." *Harvard Business Review* 75(5): 84–93.

Baldwin, C. Y., and K. B. Clark. 2000. *Design Rules: The Power of Modularity*, Vol 1. Cambridge: The MIT Press.

Baldwin, C. Y., and C. J. Woodard. 2009. "The Architecture of Platforms: A Unified View." In *Platforms, Markets and Innovation*, edited by Annabelle Gawer, 19–44. Northhamption: Edward Elgar Publishing.

Baldwin, C., A. MacCormack, and J. Rusnak. 2014. "Hidden Structure: Using Network Methods to Map System Architecture." *Research Policy* 43(8): 1381–97. https://doi.org/10.1016/j.respol.2014.05.004.

Barney, J. 1991. "Firm Resources and Sustained Competitive Advantage." *Journal of Management* 17(1): 99–120. https://doi.org/10.1177/014920639101700108.

Bask, A., M. Leseure, M. Lipponen, M. Rajahonka, and M. Tinnilä. 2010. "The Concept of Modularity: Diffusion from Manufacturing to Service Production." *Journal of Manufacturing Technology Management* 21(3): 355–75. https://doi.org/10.1108/17410381011024331.

Birnbaum, P. H. 1981. "Contingencies for Interdisciplinary Research: Matching Research Questions with Research Organizations." *Management Science* 27(11): 1279–93. https://doi.org/10.1287/mnsc.27.11.1279.

Bonacich, P. 1987. "Power and Centrality: A Family of Measures." *American Journal of Sociology* 92(5): 1170–82.

Bonvoisin, J., F. Halstenberg, T. Buchert, and R. Stark. 2016. "A Systematic Literature Review on Modular Product Design." *Journal of Engineering Design* 27(7): 488–514. https://doi.org/10.1080/09544828.2016.1166482.

Boyack, K. W., and R. Klavans. 2010. "Co-Citation Analysis, Bibliographic Coupling, and Direct Citation: Which Citation Approach Represents the Research Front most Accurately?" *Journal of the American Society for Information Science and Technology* 61(12): 2389–404. https://doi.org/10.1002/asi.21419.

Brax, S. A., A. Bask, J. Hsuan, and C. Voss. 2017. "Service Modularity and Architecture: An Overview and Research Agenda." *International Journal of Operations & Production Management* 37(6): 686–702. https://doi.org/10.1108/ijopm-03-2017-0191.

Browning, T. R. 2016. "Design Structure Matrix Extensions and Innovations: A Survey and New Opportunities." *IEEE Transactions on Engineering Management* 63(1): 27–52. https://doi.org/10.1109/TEM.2015.2491283.

Brusoni, S., and A. Prencipe. 2001. "Unpacking the Black Box of Modularity: Technologies, Products and Organizations." *Industrial and Corporate Change* 10(1): 179–205. https://doi.org/10.1093/icc/10.1.179.

Brusoni, S., and A. Prencipe. 2011. "Patterns of Modularization: The Dynamics of Product Architecture in Complex Systems." *European Management Review* 8(2): 67–80. https://doi.org/10.1111/j.1740-4762.2011.01010.x.

By, R. T. 2007. "Organisational Change Management: A Critical Review." *Journal of Change Management* 5(4): 369–80. https://doi.org/10.1080/14697010500359250.

Cabigiosu, A., and A. Camuffo. 2012. "Beyond the "Mirroring" Hypothesis: Product Modularity and Interorganizational Relations in the Air Conditioning Industry." *Organization Science* 23(3): 686–703. https://doi.org/10.1287/orsc.1110.0655.

Cabigiosu, A., and A. Camuffo. 2016. "Measuring Modularity: Engineering and Management Effects of Different Approaches." *IEEE Transactions on Engineering Management* 64(1): 103–14. https://doi.org/10.1109/TEM.2016.2614881.

Cabigiosu, A., F. Zirpoli, and A. Camuffo. 2013. "Modularity, Interfaces Definition and the Integration of External Sources of Innovation in the Automotive Industry." *Research Policy* 42(3): 662–75. https://doi.org/10.1016/j.respol.2012.09.002.

Campagnolo, D., and A. Camuffo. 2010. "The Concept of Modularity in Management Studies: A Literature Review." *International Journal of Management Reviews* 12(3): 259–83. https://doi.org/10.1111/j.1468-2370.2009.00260.x.

Carlgren, L., I. Rauth, and M. Elmquist. 2016. "Framing Design Thinking: The Concept in Idea and Enactment." *Creativity and Innovation Management* 25(1): 38–57. https://doi.org/10.1111/caim.12153.

Cash-Gibson, L., D. F. Rojas-Gualdron, J. M. Pericas, and J. Benach. 2018. "Inequalities in Global Health Inequalities Research: A 50-Year Bibliometric Analysis (1966-2015)." *PLoS One* 13(1): 1–22. https://doi.org/10.1371/journal.pone.0191901.

Cenamor, J., D. Rönnberg Sjödin, and V. Parida. 2017. "Adopting a Platform Approach in Servitization: Leveraging the Value of Digitalization." *International Journal of Production Economics* 192: 54–65. https://doi.org/10.1016/j.ijpe.2016.12.033.

Chai, K.-H., Q. Wang, M. Song, J. I. M. Halman, and A. C. Brombacher. 2012. "Understanding Competencies in Platform-Based Product Development: Antecedents and Outcomes." *Journal of Product Innovation Management* 29(3): 452–72. https://doi.org/10.1111/j.1540-5885.2012.00917.x.

Chen, C., and M. Song. 2019. "Visualizing a Field of Research: A Methodology of Systematic Scientometric Reviews." *PLoS One* 14(10): 1–25. https://doi.org/10.1371/journal.pone.0223994.

Chen, K., Y. Zhang, and X. Fu. 2019. "International Research Collaboration: An Emerging Domain of Innovation Studies?" *Research Policy* 48(1): 149–68. https://doi.org/10.1016/j.respol.2018.08.005.

Chesbrough, H., and A. Prencipe. 2008. "Networks of Innovation and Modularity: A Dynamic Perspective." *International Journal of Technology Management* 42(4): 414–25. https://doi.org/10.1504/ijtm.2008.019383.

Clark, K. B., and T. Fujimoto. 1990. "The Power of Product Integrity." *Harvard Business Press* 68(6): 107–18.

Cobo, M. J., A. G. López-Herrera, E. Herrera-Viedma, and F. Herrera. 2011. "Science Mapping Software Tools: Review, Analysis, and Cooperative Study Among Tools." *Journal of the Association for Information Science and Technology* 62(7): 1382–402. https://doi.org/10.1002/ASI.21525.

Colfer, L. J., and C. Y. Baldwin. 2016. "The Mirroring Hypothesis: Theory, Evidence, and Exceptions." *Industrial and Corporate Change* 25(5): 709–38. https://doi.org/10.1093/icc/dtw027.

Collier, D. A. 1981. "The Measurement and Operating Benefits of Component Part Commonality." *Decision Sciences* 12(1): 85–96. https://doi.org/10.1111/j.1540-5915.1981.tb00063.x.

Cooper, R. G. 2019. "The Drivers of Success in New-Product Development." *Industrial Marketing Management* 76: 36–47. https://doi.org/10.1016/j.indmarman.2018.07.005.

Dahmus, J. B., J. P. Gonzalez-Zugasti, and K. N. Otto. 2001. "Modular Product Architecture." *Design Studies* 22(5): 409–24. https://doi.org/10.1016/S0142-694X(01)00004-7.

De Reuver, M., C. Sørensen, and R. C. Basole. 2018. "The Digital Platform: A Research Agenda." *Journal of Information Technology* 33(2): 124–35. https://doi.org/10.1057/s41265-016-0033-3.

Desai, P., S. Kekre, S. Radhakrishnan, and K. Srinivasan. 2001. "Product Differentiation and Commonality in Design: Balancing Revenue and Cost Drivers." *Management Science* 47(1): 37–51. https://doi.org/10.1287/mnsc.47.1.37.10672.

Du, X., J. R. Jiao, and M. M. Tseng. 2001. "Architecture of Product Family: Fundamentals and Methodology." *Concurrent Engineering: Research and Application* 9(4): 309–25. https://doi.org/10.1177/1063293X0100900407.

Efatmaneshnik, M., and M. J. Ryan. 2016. "General Framework for Measuring System Complexity." *Complexity* 21(S1): 533–46. https://doi.org/10.1002/cplx.21767.

Ehls, D., S. Polier, and C. Herstatt. 2020. "Reviewing the Field of External Knowledge Search for Innovation: Theoretical Underpinnings and Future (Re-)Search Directions*." *Journal of Product Innovation Management* 37(5): 405–30. https://doi.org/10.1111/jpim.12549.

Eisenhardt, K. M. 1989. "Building Theories from Case Study Research." *The Academy of Management Review* 14(4): 532–50. https://doi.org/10.2307/258557.

Eisenhardt, K. M., and F. M. Santos. 2006. "Knowledge-Based View: A New Theory of Strategy?" In *Handbook of Strategy and Management*, edited by Andrew Pettigrew, 139–64. https://doi.org/10.4135/9781848608313.n7.

Elmaraghy, H., G. Schuh, W. Elmaraghy, F. Piller, P. Schönsleben, M. Tseng, and A. Bernard. 2013. "Product Variety Management." *CIRP Annals* 62(2): 629–52. https://doi.org/10.1016/j.cirp.2013.05.007.

Emmons, S., S. Kobourov, M. Gallant, and K. Borner. 2016. "Analysis of Network Clustering Algorithms and Cluster Quality Metrics at Scale." *PLoS One* 11(7): 159–61. https://doi.org/10.1371/journal.pone.0159161.

Engler, D., R. Lecuona, C. Baldwin, A. Camuffo, G. Hoetker, and M. G. Jacobides. 2017. "The Evolution of System Architectures: Products, Organizations, and Industries." *Academy of Management Proceedings* 2017(1): 12910. https://doi.org/10.5465/AMBPP.2017.12910symposium.

Eppinger, S. D., and T. R. Browning. 2012. *Design Structure Matrix Methods and Applications*. Cambridge: MIT Press.

Ericsson, A., and G. Erixon. 1999. *Controlling Design Variants: Modular Product Platforms*. New York: ASME.

Ethiraj, S. K., and D. Levinthal. 2004. "Modularity and Innovation in Complex Systems." *Management Science* 50(2): 159–73. https://doi.org/10.1287/mnsc.1030.0145.

Ethiraj, S. K., D. Levinthal, and R. R. Roy. 2008. "The Dual Role of Modularity: Innovation and Imitation." *Management Science* 54(5): 939–55. https://doi.org/10.1287/mnsc.1070.0775.

Evanschitzky, H., M. Eisend, R. J. Calantone, and Y. Jiang. 2012. "Success Factors of Product Innovation: An Updated Meta-Analysis." *Journal of Product Innovation Management* 29: 21–37. https://doi.org/10.1111/j.1540-5885.2012.00964.x.

Feitzinger, E., and H. L. Lee. 1997. "Mass Customization at Hewlett-Packard: The Power of Postponement." *Harvard Business Review* 75: 116–23.

Felin, T., and W. S. Hesterly. 2007. "The Knowledge-Based View, Nested Heterogeneity, and New Value Creation: Philosophical Considerations on the Locus of Knowledge." *Academy of Management Review* 32(1): 195–218. https://doi.org/10.5465/amr.2007.23464020.

Fisher, M., K. Ramdas, and K. Ulrich. 1999. "Component Sharing in the Management of Product Variety: A Study of Automotive Braking Systems." *Management Science* 45(3): 297–315. https://doi.org/10.1287/mnsc.45.3.297.

Fixson, S. K. 2005. "Product Architecture Assessment: A Tool to Link Product, Process, and Supply Chain Design Decisions." *Journal of Operations Management* 23(3–4): 345–69. https://doi.org/10.1016/j.jom.2004.08.006.

Fixson, S. K. 2007. "Modularity and Commonality Research: Past Developments and Future Opportunities." *Concurrent Engineering: Research and Applications* 15(2): 85–111. https://doi.org/10.1177/1063293x07078935.

Fixson, S. K., and J.-K. Park. 2008. "The Power of Integrality: Linkages between Product Architecture, Innovation, and Industry Structure." *Research Policy* 37(8): 1296–316. https://doi.org/10.1016/j.respol.2008.04.026.

Frandsen, T. 2017. "Evolution of Modularity Literature: A 25-Year Bibliometric Analysis." *International Journal of Operations & Production Management* 37(6): 703–47. https://doi.org/10.1108/ijopm-06-2015-0366.

Furlan, A., A. Cabigiosu, and A. Camuffo. 2014. "When the Mirror Gets Misted Up: Modularity and Technological Change." *Strategic Management Journal* 35(6): 789–807. https://doi.org/10.1002/smj.2138.

Garud, R., and A. Kumaraswamy. 1995. "Technological and Organizational Designs for Realizing Economies of Substitution." *Strategic Management Journal* 16(S1): 93–109. https://doi.org/10.1002/smj.4250160919.

Gawer, A. 2014. "Bridging Differing Perspectives on Technological Platforms: Toward an Integrative Framework." *Research Policy* 43(7): 1239–49. https://doi.org/10.1016/j.respol.2014.03.006.

Gawer, A., and M. A. Cusumano. 2014. "Industry Platforms and Ecosystem Innovation." *Journal of Product Innovation Management* 31(3): 417–33. https://doi.org/10.1111/jpim.12105.

Geissdoerfer, M., P. Savaget, N. M. P. Bocken, and E. J. Hultink. 2017. "The Circular Economy—A New Sustainability Paradigm?" *Journal of Cleaner Production* 143: 757–68. https://doi.org/10.1016/j.jclepro.2016.12.048.

Gemser, G., and H. Perks. 2015. "Co-Creation with Customers: An Evolving Innovation Research Field." *Journal of Product*

Innovation Management 32(5): 660–5. https://doi.org/10.1111/jpim.12279.

Gerchak, Y., M. J. Magazine, and A. B. Gamble. 1988. "Component Commonality with Service Level Requirements." *Management Science* 34(6): 753–60. https://doi.org/10.1287/mnsc.34.6.753.

Gershenson, J. K., G. J. Prasad, and Y. Z. Zhang. 2003. "Product Modularity: Definitions and Benefits." *Journal of Engineering Design* 14(3): 295–313. https://doi.org/10.1080/0954482031000091068.

Gershenson, J. K., G. J. Prasad, and Y. Z. Zhang. 2004. "Product Modularity: Measures and Design Methods." *Journal of Engineering Design* 15(1): 33–51. https://doi.org/10.1080/0954482032000101731.

Gmür, M. 2003. "Co-Citation Analysis and the Search for Invisible Colleges: A Methodological Evaluation." *Scientometrics* 57(1): 27–57.

Gu, P., and S. Sosale. 1999. "Product Modularization for Life Cycle Engineering." *Robotics and Computer-Integrated Manufacturing* 15(5): 387–401. https://doi.org/10.1016/s0736-5845(99)00049-6.

Hackl, J., D. Krause, K. Otto, M. Windheim, S. K. Moon, N. Bursac, and R. Lachmayer. 2020. "Impact of Modularity Decisions on a Firm's Economic Objectives." *Journal of Mechanical Design* 142(4): 1–41. https://doi.org/10.1115/1.4044914.

Halman, J. I. M., A. P. Hofer, and W. van Vuuren. 2003. "Platform-Driven Development of Product Families: Linking Theory with Practice." *Journal of Product Innovation Management* 20(2): 149–62. https://doi.org/10.1111/1540-5885.2002007.

Hauke, J., I. Lorscheid, and M. Meyer. 2017. "Recent Development of Social Simulation as Reflected in Jasss between 2008 and 2014: A Citation and Co-Citation Analysis." *Journal of Artificial Societies and Social Simulation* 20(1). https://doi.org/10.18564/jasss.3238.

He, B., T. Luo, and S. Huang. 2019. "Product Sustainability Assessment for Product Life Cycle." *Journal of Cleaner Production* 206: 238–50. https://doi.org/10.1016/j.jclepro.2018.09.097.

Heese, H. S., and J. M. Swaminathan. 2006. "Product Line Design with Component Commonality and Cost-Reduction Effort." *Manufacturing & Service Operations Management* 8(2): 206–19. https://doi.org/10.1287/msom.1060.0103.

Henderson, R. M., and K. B. Clark. 1990. "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms." *Administrative Science Quarterly* 35(1): 9–30. https://doi.org/10.2307/2393549.

Hoetker, G. 2006. "Do Modular Products Lead to Modular Organizations?" *Strategic Management Journal* 27(6): 501–18. https://doi.org/10.1002/smj.528.

Hopp, C., D. Antons, J. Kaminski, and T. O. Salge. 2018. "The Topic Landscape of Disruption Research—A Call for Consolidation, Reconciliation, and Generalization." *Journal of Product Innovation Management* 35(3): 458–87. https://doi.org/10.1111/jpim.12440.

Hsuan, J. 1999. "Impacts of Supplier-Buyer Relationships on Modularization in New Product Development." *European Journal of Purchasing & Supply Management* 5(3-4): 197–209. https://doi.org/10.1016/S0969-7012(99)00026-X.

Jacobides, M. G., C. Cennamo, and A. Gawer. 2018. "Towards a Theory of Ecosystems." *Strategic Management Journal* 39(8): 2255–76. https://doi.org/10.1002/smj.2904.

Jacobides, M. G., J. P. Macduffie, and C. J. Tae. 2016. "Agency, Structure, and the Dominance of Oems: Change and Stability in the Automotive Sector." *Strategic Management Journal* 37(9): 1942–67. https://doi.org/10.1002/smj.2426.

Jacobs, M., C. Droge, S. K. Vickery, and R. Calantone. 2011. "Product and Process Modularity's Effects on Manufacturing Agility and Firm Growth Performance." *Journal of Product Innovation Management* 28(1): 123–37. https://doi.org/10.1111/j.1540-5885.2010.00785.x.

Jacobs, M., S. K. Vickery, and C. Droge. 2007. "The Effects of Product Modularity on Competitive Performance." *International Journal of Operations & Production Management* 27(10): 1046–68. https://doi.org/10.1108/01443570710820620.

Jarzabkowski, P., and A. Paul Spee. 2009. "Strategy-as-Practice: A Review and Future Directions for the Field." *International Journal of Management Reviews* 11(1): 69–95. https://doi.org/10.1111/j.1468-2370.2008.00250.x.

Jiao, J., T. W. Simpson, and Z. Siddique. 2007. "Product Family Design and Platform-Based Product Development: A State-of-the-Art Review." *Journal of Intelligent Manufacturing* 18(1): 5–29. https://doi.org/10.1007/s10845-007-0003-2.

Kekre, S., and K. Srinivasan. 1990. "Broader Product Line: A Necessity to Achieve Success?" *Management Science* 36(10): 1216–32. https://doi.org/10.1287/mnsc.36.10.1216.

Khanagha, S., S. Ansari, S. Paroutis, and L. Oviedo. 2020. "Mutualism and the Dynamics of New Platform Creation: A Study of Cisco and Fog Computing." *Strategic Management Journal* 43(3): 476–506. https://doi.org/10.1002/smj.3147.

Kim, S., and S. K. Moon. 2019. "Eco-Modular Product Architecture Identification and Assessment for Product Recovery." *Journal of Intelligent Manufacturing* 30(1): 383–403. https://doi.org/10.1007/s10845-016-1253-7.

Kogut, B., and U. Zander. 1992. "Knowledge of the Firm, Combinative Capabilities, and the Replication of Technology." *Organization Science* 3(3): 383–97. https://doi.org/10.1287/orsc.3.3.383.

Kota, S., K. Sethuraman, and R. Miller. 2000. "A Metric for Evaluating Design Commonality in Product Families." *Journal of Mechanical Design* 122(4): 403–10. https://doi.org/10.1115/1.1320820.

Krishnan, V., and K. T. Ulrich. 2001. "Product Development Decisions: A Review of the Literature." *Management Science* 47(1): 1–21. https://doi.org/10.1287/mnsc.47.1.1.10668.

Kroh, J., H. Luetjen, D. Globocnik, and C. Schultz. 2018. "Use and Efficacy of Information Technology in Innovation Processes: The Specific Role of Servitization." *Journal of Product Innovation Management* 35(5): 720–41. https://doi.org/10.1111/jpim.12445.

Langlois, R. N. 2002. "Modularity in Technology and Organization." *Journal of Economic Behavior & Organization* 49(1): 19–37. https://doi.org/10.1016/S0167-2681(02)00056-2.

Langlois, R. N., and P. L. Robertson. 1992. "Networks and Innovation in a Modular System: Lessons from the Microcomputer and Stereo Component Industries." *Research Policy* 21(4): 297–313. https://doi.org/10.1016/0048-7333(92)90030-8.

Lau, A. K. W., R. C. M. Yam, and E. Tang. 2007. "The Impacts of Product Modularity on Competitive Capabilities and Performance: An Empirical Study." *International Journal of Production Economics* 105(1): 1–20. https://doi.org/10.1016/j.ijpe.2006.02.002.

Lau, A. K. W., R. C. M. Yam, and E. Tang. 2011. "The Impact of Product Modularity on New Product Performance: Mediation by Product Innovativeness." *Journal of Product Innovation Management* 28(2): 270–84. https://doi.org/10.1111/j.1540-5885.2011.00796.x.

Lee, H. L., and C. S. Tang. 1997. "Modelling the Costs and Benefits of Delayed Product Differentiation." *Management Science* 43(1): 40–53. https://doi.org/10.1287/mnsc.43.1.40.

Lim, K. Y. H., P. Zheng, and C.-H. Chen. 2020. "A State-of-the-Art Survey of Digital Twin: Techniques, Engineering Product Lifecycle Management and Business Innovation Perspectives." *Journal of Intelligent Manufacturing* 31(6): 1313–37. https://doi.org/10.1007/s10845-019-01512-w.

Maccormack, A., C. Y. Baldwin, and J. Rusnak. 2012. "Exploring the Duality between Product and Organizational Architectures: A Test of the "Mirroring" Hypothesis." *Research Policy* 41(8): 1309–24. https://doi.org/10.1016/j.respol.2012.04.011.

MacDuffie, J. P. 2013. "Modularity-as-Property, Modularization-as-Process, and 'Modularity'-as-Frame: Lessons from Product Architecture Initiatives in the Global Automotive Industry." *Global Strategy Journal* 3(1): 8–40. https://doi.org/10.1111/j.2042-5805.2012.01048.x.

Magnusson, M., and M. Pasche. 2014. "A Contingency-Based Approach to the Use of Product Platforms and Modules in New Product Development." *Journal of Product Innovation Management* 31(3): 434–50. https://doi.org/10.1111/jpim.12106.

Marion, T. J., and S. K. Fixson. 2020. "The Transformation of the Innovation Process: How Digital Tools Are Changing Work, Collaboration, and Organizations in New Product Development." *Journal of Product Innovation Management* 38(1): 192–215. https://doi.org/10.1111/jpim.12547.

Marion, T. J., M. H. Meyer, and G. Barczak. 2015. "The Influence of Digital Design and it on Modular Product Architecture." *Journal of Product Innovation Management* 32(1): 98–110. https://doi.org/10.1111/jpim.12240.

Markham, S. K. 2013. "The Impact of Front-End Innovation Activities on Product Performance." *Journal of Product Innovation Management* 30: 77–92. https://doi.org/10.1111/jpim.12065.

Martin, B. R., P. Nightingale, and A. Yegros-Yegros. 2012. "Science and Technology Studies: Exploring the Knowledge Base." *Research Policy* 41(7): 1182–204. https://doi.org/10.1016/j.respol.2012.03.010.

Martin, M. V., and K. Ishii. 2002. "Design for Variety: Developing Standardized and Modularized Product Platform Architectures." *Research in Engineering Design* 13(4): 213–35. https://doi.org/10.1007/s00163-002-0020-2.

Martín-Martín, A., E. Orduna-Malea, M. Thelwall, and E. Delgado López-Cózar. 2018. "Google Scholar, Web of Science, and Scopus: A Systematic Comparison of Citations in 252 Subject Categories." *Journal of Informetrics* 12(4): 1160–77. https://doi.org/10.1016/j.joi.2018.09.002.

Mertens, K. G. 2020. *Measure and Manage your Products Costs Right – Using an Extended Axiomatic Design for Measuring and Managing the Costs of Products*. Hamburg: Hamburg University of Technology.

Mertens, K. G., M. Schmidt, T. Yildiz, and M. Meyer. 2021. "Introducing a Framework to Generate and Evaluate the Cost Effects of Product (Family) Concepts." *Proceedings of the Design Society* 1: 1907–16. https://doi.org/10.1017/pds.2021.452.

Meyer, M., M. Zaggl, and K. M. Carley. 2011. "Measuring CMOT'S Intellectual Structure and its Development." *Computational and Mathematical Organization Theory* 17(1): 1–34. https://doi.org/10.1007/s10588-010-9076-0.

Meyer, M. H., and A. P. Lehnerd. 1997. *The Power of Product Platforms: Building Value and Cost Leadership*. New York: The Free Press.

Meyer, M. H., O. Osiyevskyy, D. Libaers, and M. van Hugten. 2018. "Does Product Platforming Pay Off?" *Journal of Product Innovation Management* 35(1): 66–87. https://doi.org/10.1111/jpim.12378.

Meyer, M. H., P. Tertzakian, and J. M. Utterback. 1997. "Metrics for Managing Research and Development in the Context of the Product Family." *Management Science* 43(1): 88–111. https://doi.org/10.1287/mnsc.43.1.88.

Micheli, G. J. L., P. Trucco, Y. Sabri, and M. Mancini. 2019. "Modularization as a System Life Cycle Management Strategy: Drivers, Barriers, Mechanisms and Impacts." *International Journal of Engineering Business Management* 11: 1–23. https://doi.org/10.1177/1847979018825041.

Mikkola, J. H. 2006. "Capturing the Degree of Modularity Embedded in Product Architectures." *Journal of Product Innovation Management* 23(2): 128–46. https://doi.org/10.1111/j.1540-5885.2006.00188.x.

Mikkola, J. H. 2007. "Management of Product Architecture Modularity for Mass Customization: Modeling and Theoretical Considerations." *IEEE Transactions on Engineering Management* 54(1): 57–69. https://doi.org/10.1109/TEM.2006.889067.

Mikkola, J. H., and O. Gassmann. 2003. "Managing Modularity of Product Architectures: Toward an Integrated Theory." *IEEE Transactions on Engineering Management* 50(2): 204–18. https://doi.org/10.1109/tem.2003.810826.

Mintzberg, H., and J. A. Waters. 1985. "Of Strategies, Deliberate and Emergent." *Strategic Management Journal* 6(3): 257–72. https://doi.org/10.1002/smj.4250060306.

Muffatto, M. 1999. "Introducing a Platform Strategy in Product Development." *International Journal of Production Economics* 60-61: 145–53. https://doi.org/10.1016/s0925-5273(98)00173-x.

Murmann, J. P., and K. Frenken. 2006. "Toward a Systematic Framework for Research on Dominant Designs, Technological Innovations, and Industrial Change." *Research Policy* 35(7): 925–52. https://doi.org/10.1016/j.respol.2006.04.011.

Nambisan, S. 2018. "Digital Entrepreneurship: Toward a Digital Technology Perspective of Entrepreneurship." *Entrepreneurship Theory and Practice* 41(6): 1029–55. https://doi.org/10.1111/etap.12254.

Nambisan, S., K. Lyytinen, A. Majchrzak, and M. Song. 2017. "Digital Innovation Management: Reinventing Innovation Management Research in a Digital World." *MIS Quarterly* 41(1): 223–38. https://doi.org/10.25300/MISQ/2017/41:1.03.

Nelson, R. R., and S. G. Winter. 1982. *An Evolutionary Theory of Economic Change*. Cambridge: Belknap Press of Harvard University Press.

Newman, M. E. J. 2006. "Modularity and Community Structure in Networks." *Proceedings of the National Academy of Sciences of the United States of America* 103(23): 8577–82. https://doi.org/10.1073/pnas.0601602103.

Newman, M. E. J., and M. Girvan. 2004. "Finding and Evaluating Community Structure in Networks." *Physical Review E* 69(2): 026113. https://doi.org/10.1103/PhysRevE.69.026113.

Novak, S., and S. D. Eppinger. 2001. "Sourcing by Design: Product Complexity and the Supply Chain." *Management Science* 47(1): 189–204. https://doi.org/10.1287/mnsc.47.1.189.10662.

Otto, K., K. Holtta-Otto, T. W. Simpson, D. Krause, S. Ripperda, and S. K. Moon. 2016. "Global Views on Modular Design Research: Linking Alternative Methods to Support Modular Product Family Concept Development." *Journal of Mechanical Design* 138(7): 16. https://doi.org/10.1115/1.4033654.

Parnas, D. L. 1972. "On the Criteria to Be Used in Decomposing Systems into Modules." *Communications of the ACM* 15(12): 479–98. https://doi.org/10.1145/361598.361623.

Parolo, P. D. B., R. K. Pan, R. Ghosh, B. A. Huberman, K. Kaski, and S. Fortunato. 2015. "Attention Decay in Science." *Journal of Informetrics* 9(4): 734–45. https://doi.org/10.1016/j.joi.2015.07.006.

Perks, H., T. Gruber, and B. Edvardsson. 2012. "Co-Creation in Radical Service Innovation: A Systematic Analysis of Micro-level Processes." *Journal of Product Innovation Management* 29(6): 935–51. https://doi.org/10.1111/j.1540-5885.2012.00971.x.

Pero, M., N. Abdelkafi, A. Sianesi, and T. Blecker. 2010. "A Framework for the Alignment of New Product Development and Supply Chains." *Supply Chain Management* 15(2): 115–28. https://doi.org/10.1108/13598541011028723.

Pesch, R., H. Endres, and R. B. Bouncken. 2021. "Digital Product Innovation Management: Balancing Stability and Fluidity Through Formalization." *Journal of Product Innovation Management* 38(6): 726–44. https://doi.org/10.1111/jpim.12609.

Phelps, C., R. Heidl, and A. Wadhwa. 2012. "Knowledge, Networks, and Knowledge Networks: A Review and Research Agenda." *Journal of Management* 38(4): 1115–66.

Pil, F. K., and S. K. Cohen. 2006. "Modularity: Implications for Imitation, Innovation, and Sustained Advantage." *Academy of Management Review* 31(4): 995–1011. https://doi.org/10.5465/amr.2006.22528166.

Piller, F. T., and D. Walcher. 2006. "Toolkits for Idea Competitions: A Novel Method to Integrate Users in New Product Development." *R&D Management* 36(3): 307–18. https://doi.org/10.1111/j.1467-9310.2006.00432.x.

Pine, B. J., V. Bart, and A. C. Boynton. 1993. "Making Mass Customization Work." *Harvard Business Review* 71(5): 108–10.

Piran, F. a. S., D. P. Lacerda, L. F. R. Camargo, C. F. Viero, A. Dresch, and P. A. Cauchick-Miguel. 2016. "Product Modularization and Effects on Efficiency: An Analysis of a Bus Manufacturer Using Data Envelopment Analysis (DEA)." *International Journal of Production Economics* 182: 1–13. https://doi.org/10.1016/j.ijpe.2016.08.008.

Raasch, C., V. Lee, S. Spaeth, and C. Herstatt. 2013. "The Rise and Fall of Interdisciplinary Research: The Case of Open Source Innovation." *Research Policy* 42(5): 1138–51. https://doi.org/10.1016/j.respol.2013.01.010.

Rafols, I. 2014. "Knowledge Integration and Diffusion: Measures and Mapping of Diversity and Coherence." In *Measuring Scholarly Impact*, edited by Y. Ding, Ronald Rousseau, and D. Wolfram, 169–90. Switzerland, Cham: Springer.

Ramaswamy, V., and K. Ozcan. 2018. "What is Co-Creation? An Interactional Creation Framework and its Implications for Value Creation." *Journal of Business Research* 84: 196–205. https://doi.org/10.1016/j.jbusres.2017.11.027.

Ramdas, K. 2003. "Managing Product Variety: An Integrative Review and Research Directions." *Production and Operations Management* 12(1): 79–101.

Randhawa, K., R. Wilden, and J. Hohberger. 2016. "A Bibliometric Review of Open Innovation: Setting a Research Agenda." *Journal of Product Innovation Management* 33(6): 750–72. https://doi.org/10.1111/jpim.12312.

Ravasi, D., and I. Stigliani. 2012. "Product Design: A Review and Research Agenda for Management Studies." *International Journal of Management Reviews* 14(4): 464–88. https://doi.org/10.1111/j.1468-2370.2012.00330.x.

Robertson, D., and K. Ulrich. 1998. "Planning for Product Platforms." *Sloan Management Review* 39(4): 19–31.

Ronda-Pupo, G. A., and J. S. Katz. 2017. "The Scaling Relationship Between Citation-Based Performance and Coauthorship Patterns in Natural Sciences." *Journal of the Association for Information Science and Technology* 68(5): 1257–65. https://doi.org/10.1002/asi.23759

Rousseau, R., L. Zhang, and X. Hu. 2019. "Knowledge Integration: Its Meaning and Measurement." In *Handbook of Science and Technology Indicators*, edited by Wolfgang Glänzel, Henk F. Moed, Ulrich Schmoch, and Mike Thelwall. Switzerland, Cham: Springer.

Salvador, F. 2007. "Toward a Product System Modularity Construct: Literature Review and Reconceptualization." *IEEE Transactions on Engineering Management* 54(2): 219–40. https://doi.org/10.1109/tem.2007.893996.

Salvador, F., C. Forza, and M. Rungtusanatham. 2002. "Modularity, Product Variety, Production Volume, and Component Sourcing: Theorizing beyond Generic Prescriptions." *Journal of Operations Management* 20(5): 549–75. https://doi.org/10.1016/S0272-6963(02)00027-X.

Sanchez, R. 1995. "Strategic Flexibility in Product Competition." *Strategic Management Journal* 16(S1): 135–59. https://doi.org/10.1002/smj.4250160921.

Sanchez, R. 1999. "Modular Architectures in the Marketing Process." *Journal of Marketing* 63: 92–111. https://doi.org/10.2307/1252104.

Sanchez, R., and J. T. Mahoney. 1996. "Modularity, Flexibility, and Knowledge Management in Product and Organization Design." *Strategic Management Journal* 17(S2): 63–76. https://doi.org/10.1002/smj.4250171107.

Sarin, S., C. Haon, and M. Belkhouja. 2018. "A Twenty-Year Citation Analysis of the Knowledge Outflow and Inflow Patterns from the Journal of Product Innovation Management." *Journal of Product Innovation Management* 35(6): 854–63. https://doi.org/10.1111/jpim.12469.

Schilling, M. A. 2000. "Toward a General Modular Systems Theory and its Application to Interfirm Product Modularity." *Academy of Management Review* 25(2): 312–34. https://doi.org/10.5465/amr.2000.3312918.

Schilling, M. A., and H. K. Steensma. 2001. "The Use of Modular Organizational Forms: An Industry-Level Analysis." *Academy of Management Journal* 44(6): 1149–68. https://doi.org/10.2307/3069394.

Scott, J. 1988. "Social Network Analysis." *Sociology* 22(1): 109–27.

Seabrooke, L., and D. Wigan. 2017. "The Governance of Global Wealth Chains." *Review of International Political Economy* 24(1): 1–29. https://doi.org/10.1080/09692290.2016.1268189.

Shaw, J. D., S. Tangirala, B. Vissa, and J. B. Rodell. 2018. "New Ways of Seeing: Theory Integration across Disciplines." *Academy of Management Journal* 61(1): 1–4. https://doi.org/10.5465/amj.2018.4001.

Simon, H. A. 1962. "The Architecture of Complexity." *Proceedings of the American Philosophical Society* 106(6): 467–82. https://doi.org/10.1007/978-1-4899-0718-9_31.

Simpson, T. W. 2004. "Product Platform Design and Customization: Status and Promise." *Artificial Intelligence for Engineering Design, analysis and Manufacturing* 18(1): 3–20. https://doi.org/10.1017/S0890060404040028.

Simpson, T. W., J. Jiao, Z. Siddique, and K. Hölttä-Otto. 2014. *Advances in Product Family and Product Platform Design*. New York: Springer.

Simpson, T. W., J. R. Maier, and F. Mistree. 2001. "Product Platform Design: Method and Application." *Research in Engineering Design* 13(1): 2–22. https://doi.org/10.1007/s001630100002.

Small, H., and E. Sweeney. 1985. "Clustering the Science Citation Index® Using Co-Citations." *Scientometrics* 7(3): 391–409. https://doi.org/10.1007/BF02017157.

Sonego, M., M. E. S. Echeveste, and H. Galvan Debarba. 2018. "The Role of Modularity in Sustainable Design: A Systematic Review." *Journal of Cleaner Production* 176: 196–209. https://doi.org/10.1016/j.jclepro.2017.12.106.

Sosa, M. E., S. D. Eppinger, and C. M. Rowles. 2003. "Identifying Modular and Integrative Systems and their Impact on Design Team Interactions." *Journal of Mechanical Design* 125(2): 240–52. https://doi.org/10.1115/1.1564074.

Sosa, M. E., S. D. Eppinger, and C. M. Rowles. 2004. "The Misalignment of Product Architecture and Organizational Structure in Complex Product Development." *Management Science* 50(12): 1674–89. https://doi.org/10.1287/mnsc.1040.0289.

Srinivasan, R., G. L. Lilien, and A. Rangaswamy. 2006. "The Emergence of Dominant Designs." *Journal of Marketing* 70(2): 1–17. https://doi.org/10.1509/jmkg.70.2.001.

Stahel, W. R. 2016. "The Circular Economy." *Nature* 531(7595): 435–8. https://doi.org/10.1038/531435a.

Staudenmayer, N., M. Tripsas, and C. L. Tucci. 2005. "Interfirm Modularity and its Implications for Product Development." *Journal of Product Innovation Management* 22(4): 303–21.

Steward, D. V. 1981. "The Design Structure System: A Method for Managing the Design of Complex Systems." *IEEE Transactions on Engineering Management* EM-28(3): 71–4. https://doi.org/10.1109/tem.1981.6448589.

Sturgeon, T. J. 2002. "Modular Production Networks: A New American Model of Industrial Organization." *Industrial and Corporate Change* 11(3): 451–96. https://doi.org/10.1093/icc/11.3.451.

Suh, N. P. 2001. *Axiomatic Design. Advances and Applications, the Oxford Series on Advanced Manufacturing*. New York: Oxford University Press.

Suh, N. P. 2005. "Complexity: Theory and Application." In *Mit Series in Mechanical Engineering*, edited by Rohean C. Abeyaratne and Nam Pyo Suh. New York: Oxford University Press.

Suh, N. P., and S. Sekimoto. 1990. "Design of Thinking Design Machine." *CIRP Annals* 39(1): 145–8. https://doi.org/10.1016/S0007-8506(07)61022-1.

Tee, R. 2019. "Benefiting from Modularity within and across Firm Boundaries." *Industrial and Corporate Change* 28(5): 1011–28. https://doi.org/10.1093/icc/dtz007.

Teece, D. J., G. Pisano, and A. Shuen. 1997. "Dynamic Capabilities and Strategic Management." *Strategic Management Journal* 18(7): 509–33. https://doi.org/10.1002/(sici)1097-0266(199708)18:7.

Tiwana, A. 2008. "Does Technological Modularity Substitute for Control? A Study of Alliance Performance in Software Outsourcing." *Strategic Management Journal* 29(7): 769–80. https://doi.org/10.1002/smj.673.

Tiwana, A., B. Konsynski, and A. A. Bush. 2010. "Research Commentary—Platform Evolution: Coevolution of Platform Architecture, Governance, and Environmental Dynamics." *Information Systems Research* 21(4): 675–87. https://doi.org/10.1287/isre.1100.0323.

Torraco, R. J. 2005. "Writing Integrative Literature Reviews: Guidelines and Examples." *Human Resource Development Review* 4(3): 356–67. https://doi.org/10.1177/1534484305278283.

Tranfield, D., D. Denyer, and P. Smart. 2003. "Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review." *British Journal of Management* 14(3): 207–22. https://doi.org/10.1111/1467-8551.00375.

Tseng, H., C. Chang, and J. Li. 2008. "Modular Design to Support Green Life-Cycle Engineering." *Expert Systems with Applications* 34(4): 2524–37. https://doi.org/10.1016/j.eswa.2007.04.018.

Tu, Q., M. A. Vonderembse, T. S. Ragu-Nathan, and B. Ragu-Nathan. 2004. "Measuring Modularity-Based Manufacturing Practices and their Impact on Mass Customization Capability: A Customer-Driven Perspective." *Decision Sciences* 35(2): 147–68. https://doi.org/10.1111/j.00117315.2004.02663.x.

Tukker, A. 2015. "Product Services for a Resource-Efficient and Circular Economy – A Review." *Journal of Cleaner Production* 97: 76–91. https://doi.org/10.1016/j.jclepro.2013.11.049.

Ülkü, S., and G. M. Schmidt. 2011. "Matching Product Architecture and Supply Chain Configuration." *Production and Operations Management* 20(1): 16–31. https://doi.org/10.1111/j.1937-5956.2010.01136.x.

Ulkuniemi, P., and S. Pekkarinen. 2011. "Creating Value for the Business Service Buyer through Modularity." *International Journal of Services and Operations Management* 8(2): 127–41.

Ulrich, K. 1995. "The Role of Product Architecture in the Manufacturing Firm." *Research Policy* 24(3): 419–40. https://doi.org/10.1016/0048-7333(94)00775-3.

Ulrich, K., and S. D. Eppinger. 2012. *Product Design and Development*, Vol 5. New York: McGraw-Hill.

Van den Broeke, M., R. Boute, and B. Samii. 2015. "Evaluation of Product-Platform Decisions Based on Total Supply Chain Costs." *International Journal of Production Research* 53(18): 5545–63. https://doi.org/10.1080/00207543.2015.1034329.

Van den Ende, J., L. Frederiksen, and A. Prencipe. 2015. "The Front End of Innovation: Organizing Search for Ideas." *Journal of Product Innovation Management* 32(4): 482–7. https://doi.org/10.1111/jpim.12213.

Van der Have, R. P., and L. Rubalcaba. 2016. "Social Innovation Research: An Emerging Area of Innovation Studies?" *Research Policy* 45(9): 1923–35. https://doi.org/10.1016/j.respol.2016.06.010.

Van Eck, N. J., and L. Waltman. 2017. "Citation-Based Clustering of Publications Using Citnetexplorer and Vosviewer."

Scientometrics 111(2): 1053–70. https://doi.org/10.1007/s11192-017-2300-7.

Van Eck, N. J. V., and L. Waltman. 2009. "How to Normalize Cooccurrence Data? An Analysis of some Well-Known Similarity Measures." *Journal of the American Society for Information Science and Technology* 60(8): 1635–51. https://doi.org/10.1002/asi.21075.

Van Eck, N. J. V., and L. Waltman. 2010. "Software Survey: Vosviewer, a Computer Program for Bibliometric Mapping." *Scientometrics* 84(2): 523–38. https://doi.org/10.1007/s11192-009-0146-3.

Verganti, R., C. Dell'era, and K. S. Swan. 2021. "Design Thinking: Critical Analysis and Future Evolution." *Journal of Product Innovation Management* 38(6): 603–22. https://doi.org/10.1111/jpim.12610.

Vickery, S. K., X. Koufteros, C. Dröge, and R. Calantone. 2016. "Product Modularity, Process Modularity, and New Product Introduction Performance: Does Complexity Matter?" *Production and Operations Management* 25(4): 751–70. https://doi.org/10.1111/poms.12495.

Von Hippel, E., and R. Katz. 2002. "Shifting Innovation to Users Via Toolkits." *Management Science* 48(7): 821–33. https://doi.org/10.1287/mnsc.48.7.821.2817.

Voss, C. A., and J. Hsuan. 2009. "Service Architecture and Modularity." *Decision Sciences* 40(3): 541–69. https://doi.org/10.1111/j.1540-5915.2009.00241.x.

Waltman, L., and N. J. van Eck. 2013. "A Smart Local Moving Algorithm for Large-Scale Modularity-Based Community Detection." *European Physical Journal B* 86(11): 1–14. https://doi.org/10.1140/epjb/e2013-40829-0.

Wang, J. J., J. J. Li, and J. Chang. 2016. "Product Co-Development in An Emerging Market: The Role of Buyer-Supplier Compatibility and Institutional Environment." *Journal of Operations Management* 46(1): 69–83. https://doi.org/10.1016/j.jom.2016.07.002.

Williamson, O. E. 1981. "The Economics of Organization: The Transaction Cost Approach." *American Journal of Sociology* 87(3): 548–77.

Worren, N., K. Moore, and P. Cardona. 2002. "Modularity, Strategic Flexibility, and Firm Performance: A Study of the Home Appliance Industry." *Strategic Management Journal* 23(12): 1123–40. https://doi.org/10.1002/smj.276.

Yan, E., and Y. Ding. 2012. "Scholarly Network Similarities: How Bibliographic Coupling Networks, Citation Networks, Cocitation Networks, Topical Networks, Coauthorship Networks, and Coword Networks Relate to each Other." *Journal of the American Society for Information Science and Technology* 63(7): 1313–26. https://doi.org/10.1002/asi.22680.

Yayavaram, S., and G. Ahuja. 2008. "Decomposability in Knowledge Structures and its Impact on the Usefulness of Inventions and Knowledge-Base Malleability." *Administrative Science Quarterly* 53(2): 333–62. https://doi.org/10.2189/asqu.53.2.333.

Yin, R. K. 2011. *Case Study Research and Applications: Design and Methods*. Los Angeles: Sage.

Yin, Y., K. E. Stecke, and D. Li. 2017. "The Evolution of Production Systems from Industry 2.0 through Industry 4.0." *International Journal of Production Research* 56(1-2): 848–61. https://doi.org/10.1080/00207543.2017.1403664.

AUTHOR BIOGRAPHIES

Kai G. Mertens is a postdoctoral researcher at the Institute for Management Accounting and Simulation at Hamburg University of Technology (TUHH), Germany. He received his Ph.D. in management engineering from the Hamburg University of Technology. He holds a B.Sc. in environmental engineering from the Hamburg University of Applied Science and a M.Sc. in industrial engineering from the Hamburg University of Technology. Dr. Mertens worked as a quality and measurement engineer at a large forklift manufacturer. His research interests are technology and innovation management, management accounting, artificial intelligence, simulation, and data science.

Christoph Rennpferdt is a research fellow at the Institute of Product Development and Mechanical Engineering Design at the Hamburg University of Technology (TUHH). He holds a B.Sc. and M.Sc. degree in product development from the Hamburg University of Technology. His research interest is the development of modular product families with a focus on product-service systems.

Erik Greve is a research fellow in the field of modular product families at the Institute of Product Development and Mechanical Engineering Design at the Hamburg University of Technology (TUHH). He holds the degree of B.Sc. and M.Sc. in product development from the Hamburg University of Technology. His research interest is the development of modular product families with a focus on future robustness.

Dieter Krause is a full professor and head of the Institute of Product Development and Mechanical Engineering Design at the Hamburg University of Technology (TUHH). He studied mechanical engineering and received his doctorate in product development from the Friedrich-Alexander-University Erlangen-Nuernberg. This was followed by leading positions as head of engineering design, technical director, and managing director in mechanical and plant engineering. Prof. Krause is a board member of the Scientific Society for Product Development (WiGeP) and on the Advisory Board of the Design Society. His research interests are the development of modular product families, structural analysis, and testing.

Matthias Meyer is full professor and head of the Institute for Management Accounting and Simulation at Hamburg University of Technology (TUHH). Previously he was associate and assistant professor of

management control and accounting at the WHU – Otto Beisheim School of Management in Vallendar, Germany. He holds a Habilitation degree (Dr. oec. publ. habil.) from WHU – Otto Beisheim School of Management and a PhD (Dr. oec. publ.) in business economics from Ludwig Maximilians University Munich. He is alumnus from Catholic University of Eichstätt-Ingolstadt and the London School of Economics and Political Science and had visiting positions at Carnegie Mellon University and Venice International University. His research and teaching interests include management accounting and control, product costing, risk management, simulation modeling, and philosophy of science.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Mertens, Kai G., Christoph Rennpferdt, Erik Greve, Dieter Krause, and Matthias Meyer. 2022. "Reviewing the Intellectual Structure of Product Modularization: Toward a Common View and Future Research Agenda." *Journal of Product Innovation Management* 1–34. https://doi.org/10.1111/jpim.12642