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Abstract

Purpose – The purpose of this paper is to review and analyze the modularity literature to identify the established and emerging perspectives.
Design/methodology/approach – A systematic literature search and review was conducted through the use of bibliometrics and network analysis. The analysis identified structure within the literature, which revealed how the research area evolved between 1990 and 2015. Based on this search, the paper establishes the basis for analyzing the structure of modularity literature.
Findings – Factors were identified within the literature, demonstrating how it has evolved from a primary focus on the modularity of products to a broader view of the applicability of modularity. Within the last decade, numerous research areas have emerged within the broader area of modularity. Through core-periphery analysis, eight emerging sub-research areas are identified, of which one is the study of modularity in the context of services.
Research limitations/implications – Although bibliographic methods are limited as they are based on common citations within the field, they enable systematic analysis and the identification of structure within an emergent field of research. Such analysis has implications by for a growing and inter-disciplinary field like modularity by providing overview and suggesting future directions.
Originality/value – This paper contributes by conducting a systematic review based on the citation structure within modularity and identifies the established and emerging areas of research on modularity.

Keywords Service, Bibliometrics, Architecture, Modularity

Paper type Literature review

1. Introduction

Managers are faced with the challenge of navigating an increasingly complex world, in which customers with individual needs and preferences expect providers to customize their solutions. Moreover, the boundaries between products and services are blurring and business models are changing rapidly, which both impact the complexity and dynamics of delivery systems even further. In this changing context, the concept of modularity increasingly finds application within and across organizations. The literature has grown significantly and the multifaceted nature of the concept of modularity is becoming ever more clearer. There appears to be a need to establish an overview of this growing literature and identify its future directions. In other fields of research, bibliometric analysis has proved to be a strong technique for providing such an overview in a systematic and objective manner and one which has uncovered latent structures and identified emerging areas (i.e. Pilkington and Chai, 2008).

This paper surveys the extant modularity literature from a managerial perspective and seeks to identify its intellectual structure and developments. Several researchers have contributed to the field by reviewing different aspects of the modularity literature, with several reviews taking the perspective of modularity in management studies (Campagnolo and Camuffo, 2010), product modularity (Salvador, 2007), modularity research themes (Bask *et al.*, 2010), service decomposition and modularizing services (Eissens-van der Laan *et al.*, 2016), concurrent engineering (Fixson, 2007), and dominant design (Murmann and Frenken, 2006).

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Other studies have focused on particular aspects of modularity, such as manufacturing operations (Doran and Hill, 2009), supply chain management (Gunasekaran and Ngai, 2005; Reichhart and Holweg, 2007), interface definitions (Parslov and Mortensen, 2015), product platforms (Zhang, 2015; Chen and Liu, 2005), manufacturing scheduling systems (Framinan and Ruiz, 2010), product architecture and supply chain design (Pashaei and Olhager, 2015; Yassine and Wissmann, 2007), and research and development outsourcing (Hsuan and Mahnke, 2011).

To a varying degree, these literature reviews were based on a delimited search strategy; identifying relevant literature, selecting and coding articles based on perceived relevance and content, and analyzing and synthesizing based on a reading of the selected articles in light of the authors' knowledge of the field. A strength of these studies is that they provide an overview of a field of research and point to its evolution and future research areas. The weakness lies in the reliance on interpretation and coding to identify structures in the literature. An alternative approach is the one taken in this study, in which bibliometric analysis is used as the basis for identifying the structure of the citation patterns, instead of the subjective coding of content. Although this type of analysis has been conducted in related fields within operations management (Pilkington and Fitzgerald, 2006; Pilkington and Meredith, 2009), no co-citation-based analysis of modularity has been identified. As modularity has become an increasingly interdisciplinary field, as suggested in the previous reviews, the notion is discussed from many perspectives and at different levels. Given that co-citation patterns have repeatedly been shown to systematically identify structures within fields of literature, it is curious that this has not been applied to the widening modularity literature. The purpose of this paper, therefore, is to review the management literature on modularity in an attempt to identify the central positions, based on a systematic analysis of citation patterns. Through the use of bibliographic information, this paper advances our understanding by applying network analysis to systematically identify the intellectual structures and development of the literature. Specifically, this paper has four aims: first, to identify the structure within the modularity literature by highlighting seminal contributions, as well as to emphasize the apparent structure of the way in which articles on modularity co-cited; second, to show how the field has evolved from 1990 to 2015; third, to systematically identify emerging research areas within the modularity literature; and fourth, to locate the emerging field of service modularity in the wider modularity literature.

To achieve these aims, this paper identifies and systematically analyzes and reviews the modularity literature produced during the period 1990-2015. The paper employs co-citation analysis to identify structures and the evolution of the literature, whilst the network analytical technique of core-periphery analysis is used to identify emerging research areas. The review reveals how this area has developed during recent years and how it is receiving increasing attention. New topics within modularity have emerged, including the study of service modularity (Voss and Hsuan, 2009; Bask *et al.*, 2010; Pekkarinen and Ulkuniemi, 2008).

Section 2 discusses the notion of modularity and provides an explanation. In Section 3, the research methodology is presented, while Section 4 presents the findings from the analysis. Section 5 provides conclusions and points to future directions for research on modularity, in general and specifically by reference to service modularity.

2. Modularity and its meaning: an explanation

2.1 Defining modularity

Modularity is a method of designing a structure to reduce its complexity. Although complexity is clearly related to the number of different elements of a structure, the nature of the interdependencies between those elements and the way in which they interface has profound implications for structural complexity. This complexity may be handled by reducing the number of units and by grouping these units into subsystems. The primary driver is to reduce the interdependencies between elements across subsystems (Langlois, 2002).

Thus, modularity can be defined by referring to relations between the module's elements and the relations of those elements with elements of other modules. The word "module" has been used variously but is suggested in *Webster's Revised Unabridged Dictionary* to originate from the Latin word *modulus*, which means "a small measure." A contemporary meaning, which is consistent with the *Webster* characterization, can be found in Wiktionary: a "module" is "a self-contained component of a system, often interchangeable, which has a well-defined interface to the other components."

Modularity has been studied in a wide range of disciplines, from mathematics to psychology. With the aim of studying modularity in relation to management, this paper follows Baldwin and Clark (2000) in defining modularity. A module is consequently characterized by an interdependence between the elements of the modules and a high degree of independence across the modules (Baldwin and Clark, 2000). The loose coupling of components occurs by defining an architecture that specifies the interfaces between the components of the architecture (Sanchez and Mahoney, 1996). Thus, the degree of modularity depends on the components used, their interfaces, the character of the coupling, and the opportunity for replacement (Mikkola, 2006).

Modularity provides numerous design advantages (Ethiraj and Levinthal, 2004b; Sanchez and Mahoney, 1996; Baldwin and Clark, 2000). Modular construction improves opportunities for rapid changes through splitting and substituting modules (Baldwin and Clark, 2000). Modular product architectures and the opportunity to "mix and match" modules can lead to strategic flexibility, with the opportunity for greater product variation, as well as a higher and more frequent number of product introductions (Sanchez and Mahoney, 1996; Worren *et al.*, 2002). Moreover, reusing the same module in several structures provides scale benefits (Baldwin and Clark, 2000) and the economic advantage of substitution (Garud and Kumaraswamy, 1995). Product modularity is closely related to product configuration strategies such as mass customization and postponement (Mikkola and Skjøtt-Larsen, 2004). Reducing the interdependence between modules can reduce asset specificity (Baldwin, 2008), increase the opportunity for outsourcing (Schilling and Steensma, 2001), and, in general, reduce the cost of coordination between components (Langlois, 2002). In addition, modular constructions are more robust to changes in the environment (Pil and Cohen, 2006).

Modularity research has been undertaken from multiple perspectives, as can be seen in Table AI, which lists the 20 articles on modularity most frequently cited by other papers on modularity. Modularity is relevant not only to product design but also to processes and organizations (Sanchez and Mahoney, 1996; Baldwin and Clark, 2000) and, increasingly, to services (Voss and Hsuan, 2009; De Blok *et al.*, 2010). MacCormack *et al.* (2001) argue that in turbulent environments, the development process must be flexible, so that it may respond to "new or changing information during a development project" (p. 134). Turbulence requires a modular design that can be adapted not only after its development but also during its design (Buganza and Verganti, 2006). Regarding service design, Verganti and Buganza (2005) point to a modular technological architecture as one factor that can increase the life-cycle flexibility of services. However, modularity is not an either/or choice and should be seen as a trade-off between the advantages and the disadvantages in the specific context (Ethiraj and Levinthal, 2004b) in which modularity is associated, with the cost of achieving a modular design over an integrated design (Langlois, 2002). Pursuing modularity too far may even be associated with a penalty (Ethiraj and Levinthal, 2004b).

2.2 Theoretical underpinnings of modularity research

Although modularity has recently gained substantial attention, the topic has been discussed in the literature for many years, and modular principles have been applied since the building of the Pyramids (Starr, 2010). However, since the mid-twentieth century, many seminal

contributions have considered different aspects of modularity in various contexts. Starr (1965) made an early contribution within operations management, proposing modular production to increase the variety of product offerings in order to meet market requirements without sacrificing efficiency in production. Whereas Starr specifically addressed manufacturing operations, Simon (1962) turned to complex systems in general. He conceptualized architectures as hierarchical systems and argued that the ability to decompose systems hierarchically is the primary means of managing complexity. Within design, Alexander (1964), in his "notes on the synthesis of form," explains how the challenge of design is not usually optimizing a set of individual requirements but designing interdependent subsystems that simultaneously meet requirements and create a functioning whole (the synthesis of form), a more complex task. Thompson (1967), an organizational theorist who realized the importance of uncertainty and the need for adaptability in organizational systems early, pointed to the nature of interdependencies and how they differ within and across organizations. Although Thompson did not explicitly discuss modularity, he proposed that organizational design is crucially related to the grouping of components by referring to the nature of their interdependencies with other components within the organization. He distinguished between pooled, sequential, and reciprocal interdependencies and argued that there are different ways of achieving coordination, the appropriateness depending on the nature of the interdependencies (Thompson, 1967). Building on Thompson's insight that organizations simultaneously attempt to operate as closed systems in some ways and as open systems in others, Weick (1976) proposed loose coupling as a method for capturing the nuances of organizations that are not caught by "words like connection, link, or interdependence" (p. 3). Similar to Simon's notion of nearly decomposable systems, loose coupling embraces the idea that most systems are neither entirely decoupled nor fully coupled and instead are nearly decomposable or hierarchical. In the software engineering literature, Parnas (1972) offered early insights into the value of information hiding, by suggesting that a module should be "characterized by its information of a design decision which it hides from all others. Its interface or definition was chosen to reveal as little as possible about its inner workings" (p. 1056). Furthermore, in relation to processes, Parnas suggested that when software systems are designed, the basis for decomposition into modules should be by reference to design decisions instead of steps in the process. Looking at task problem-solving interdependencies, von Hippel proposed that they can be managed in two ways: by partitioning the tasks to reduce interdependencies between them or by reducing the cost of problem solving across task boundaries. Partitioning tasks has three requirements: the tasks most likely to be sources of new information must be anticipated, which other tasks will be affected by such information must be predicted, and these insights should be incorporated into the tasks' specification (Von Hippel, 1990).

Although the growing academic interest in modularity is increasingly specific about the empirical objects of modularity and theoretical understandings of causal mechanisms, several seminal contributions are typically drawn upon for the key principles that underpin discussions of modularity. These principles, summarized in Table I, are related to different areas of research and bring the principle of modularity into different domains that are relevant to management. Once primarily related to physical systems such as products, modularity is now discussed in relation to organizations, information systems, innovation, and, importantly, service architectures. This discussion has important implications in the present study for the search criteria used to source articles on modularity. Modularity is a multifaceted concept with managerial implications in multiple fields. The search criteria used in this paper were designed to capture the literature that addresses these managerial concerns, while avoiding an excessive number of irrelevant source articles.

Author	Research area	Key principle	Implication
Simon (1962)	General systems theory	Near decomposable systems	Decomposing systems hierarchically is the primary method by which designers can reduce complexity
Alexander (1964)	Design	Decomposition of systems	Suggests a program of functional decomposition, based on identifying the requirement variables and their interdependencies, as the key to solving design problems
Starr (1965)	Operations management	Modular production	Proposes modular production as a method for increasing flexibility in manufacturing systems
Thompson (1967)	Organizational studies	Interdependencies of components	Complex organizations are natural systems subject to rationality norms, which, at the same time, attempt to adapt to environment change and reduce uncertainty
Parnas (1972)	Information systems	Information hiding	Modules should be characterized by the knowledge of key design decisions, and this should be hidden from others
Weick (1976)	Organizational studies	Loose coupling	Suggests a dialectic interpretation of loose coupling as systems in which responsiveness and distinctiveness are simultaneously present
Von Hippel (1990)	Innovation process research	Task partitioning	Suggests that the way tasks are partitioned in innovation projects has important effects on innovation efficiency and effectiveness

Table I.
Key principles on which the modularity literature draws

3. Methodology and data for bibliographic analysis

In this section, an extensive review of the modularity literature is provided, followed by a detailed examination, in Section 4, of the findings. The selection criteria are described and the methodology for analyzing the literature using bibliographic data is presented.

3.1 Inclusion and exclusion criteria for the literature search

To establish a base population of items within modularity, a search was performed on the ISI Web of Science using the Science Citation Index and the Social Science Citation Index. To identify the current state of the research on modularity, as well as to uncover developments in the literature, the period from 1990 to 2015 was chosen. Although scholars made seminal contributions to complexity and decomposition before this period (c.f. Simon, 1962; Alexander, 1964; Starr, 1965), the 1990s marked the formation of a stream of modularity literature. Furthermore, generally fewer articles were published and/or indexed in the Web of Science prior to 1990, which led to fewer available data. When the specified search criteria were used for pre-1990 literature, 18 records were returned, of which only two contain cited references and abstracts.

The Web of Science field "topic" was chosen as an inclusion criterion as it evaluates not only the title or author-supplied keywords of an article but also abstracts and keyword plus. The search was performed using the Boolean search terms "modularity," "modular AND design," and "modular AND architecture." To narrow the search to items focused on modularity and management, the Web of Science field "subject area" was used as an exclusion criterion, and items not classified within one or more of the subject areas "management," "operations research and management science," "economics," and "business" were omitted. The search was narrowed by the field "type" to include only "articles," "proceedings papers," and "reviews". In total, 888 source articles were identified, which are specified in Table II.

Based on a reading of the abstracts, titles, and keywords of these articles, those that were not relevant and those in which modularity was treated only peripherally were excluded. Articles were mainly excluded because modularity was mentioned as a characteristic of a developed model or in relation to mathematical algorithms. The abstract screening resulted in 636 articles.

3.2 Limitations of the search criteria

Identifying the group of articles that best reflects the topic under investigation is critical to any literature review, and different strategies can be chosen. However, any search, whether subjective or mechanical, runs the risk of excluding articles that should have been included and conversely including articles that are not relevant. Thus, the search strategy and screening process have limitations and may be problematic. First, the Web of Science contains only selected journals, which implies that the inclusion criteria may result in the omission of journals including relevant articles. Second, the terms chosen to perform the search may have unintended consequences; for instance, using the broad term "modul*" resulted in numerous irrelevant items. However, the terms used widened the search without considerably increasing the number of irrelevant items.

To mitigate the shortcomings of the mechanical nature of the search, many choices were made. First, using "topic" as the main search criterion will return results including item titles and the criteria within the "abstract," "author supplied keywords," and the "keyword plus." "Keyword plus" identifies articles that touch upon modularity without a specific reference in the title, abstract, or keyword. Keyword plus indexes are based on the titles of an article's cited references. Articles that are relevant to the search that do not use any of the search terms may, therefore, still be included, provided that the references include articles with the search terms in their titles. As shown in Table II, 159 articles were identified, based on one of the three combinations of search terms, which would not have been identified otherwise.

3.3 Improvements to data quality

Based on this literature search, a data set consisting of 636 relevant articles, along with 32,691 individual references (links between an article and the cited reference) was constructed. Each reference was treated as an edge between two vertices (the citing article and the cited article, respectively). To identify the individual vertices in the data set, unique reference identification was created. The data quality of the Web of Science is generally high, especially for items recently added to the index. However, several inconsistencies caused by errors in abbreviations of author names, page numbers, and journal names were identified. Inconsistencies imply that the same contribution is not identified as such but is represented as two vertices in the data set. To eliminate inconsistencies and accommodate redundancies, corrections were made by identifying similar, but not identical, items and evaluating whether the similarity was caused by an error in the data set. A total of 7,630 corrections were made to the data set, which eliminated redundancies among the most frequently cited references. Thus, the data set was suitable for bibliographic and network analysis. Bibliometric analysis has been critiqued for including negative citations and self-references (Pilkington and Meredith, 2009). The measures explained below do not express consensus among articles but rather topical proximity, which negative citations still indicate. However, extensive self-referencing can be a source of bias, particularly in citation analysis. Consequently, we have systematically identified 1,671 instances in which the first author of a cited reference is also an author of the citing article. Such self-references are excluded from the citation analysis, considered in Sub-section 4.1, in order to avoid

Table II. Source articles by search criteria

	In title, abstract or KW	Only in KW+	Total
Modularity	161	49	210
Modular and architecture	40	1	41
Modular and design	207	33	240
Multiple of criteria 1-3	321	76	397
Included in search	729	159	888

self-inflated citation counts. For bibliographic coupling and co-citation analysis, studies that "deliberately ignore self-citations are unfairly penalizing scholars who tend to publish in new or unfashionable fields in which few others are working, as well as those who have built careers through systematic exploration of a particular topic with which their name is associated" (Borgman and Furner, 2002, p. 16). The findings are not significantly impacted by self-referencing, but disregarding such references may penalize articles such as those of Sanchez and Mahoney (1996), which Borgman and Furner (2002) caution against.

3.4 Bibliographic coupling and co-citations

Bibliographic coupling of a directed network indicates the proximity of two vertices based on the number of other vertices to which the two vertices point toward. In a citation network, this method can indicate the proximity of two articles, as they share a similar reference pattern. A related proximity measure is co-citation, which measures the number of vertices that point toward both vertices i and j. In citation analysis, two articles that are similar to other articles typically cite both (Newman, 2010). Based on the citations data set, an asymmetric adjacency matrix A of references was constructed with A_{ij} 1, where article j cites article i, and 0 otherwise. As articles that have similar referencing patterns are likely to be related, this matrix was used to identify the structure in the group of articles. A bibliographic coupling matrix B was calculated as A^TA with B_{ij} being the number of references shared by articles i and j. Similarly, a bibliometric co-citation matrix C was calculated as AA^T with C_{ij} being the number of references citing both articles i and j. The metrics for bibliographic coupling can be calculated as either the number of identical references (Newman, 2010) or the Pearson correlation coefficients of the cited references (Pilkington and Meredith, 2009). A high number of identical references or a high correlation coefficient indicates the proximity of two articles, whereas low or no shared references or negative correlation coefficients indicate distance between the articles' content. To avoid negative values, the correlation coefficients were normalized to values between 0 and 1. Based on the correlation coefficients, a network graph can be drawn, as shown in Figure 3.

Figure 1 illustrates how the citation patterns of the contributions about modularity help identify two types of structures within the literature. The bibliographic coupling measure identifies the groupings of articles with similar citation patterns, which is used to indicate the proximity between the content of the articles. Gavetti *et al.* (2005) and Ethiraj and Levinthal (2004a) display tight bibliographic coupling, as they include numerous references to the literature on complex adaptive systems. Likewise, Salvador *et al.* (2002) and Jacobs *et al.* (2011) display tight coupling, due to the many common references to literature on production systems and mass customization. However, a high number of co-occurrences among cited references indicates proximity in the ideas of the articles. Thus, the same data set indicates that Kauffman (1993) and Levinthal (1997) are related as an element in the intellectual structure underpinning the modularity literature. Studying the content of these two contributions reveals that they are concerned with organizational search and adaptation in complex systems. The two measures thus provide indications of proximity, which can be used to identify a structure within the literature. A directed network graph based on a subset of the data set can illustrate the causes of these proximity measures.

The directed network graph in Figure 2 shows the referencing relationships between eight articles, which were found through the literature search and commonly referenced sources. As the figure illustrates, the articles have several references in common, notably Simon (1962), Baldwin and Clark (2000), Sanchez and Mahoney (1996), and Ulrich and Eppinger (1995). However, the figure also shows that the articles fall into two groups, each of which uses a distinct set of common references. Although the edges of the graph contain information only about the direction of the reference, these common references indicate that the articles in the two groups have conceptual proximity. Bibliographic coupling is used to

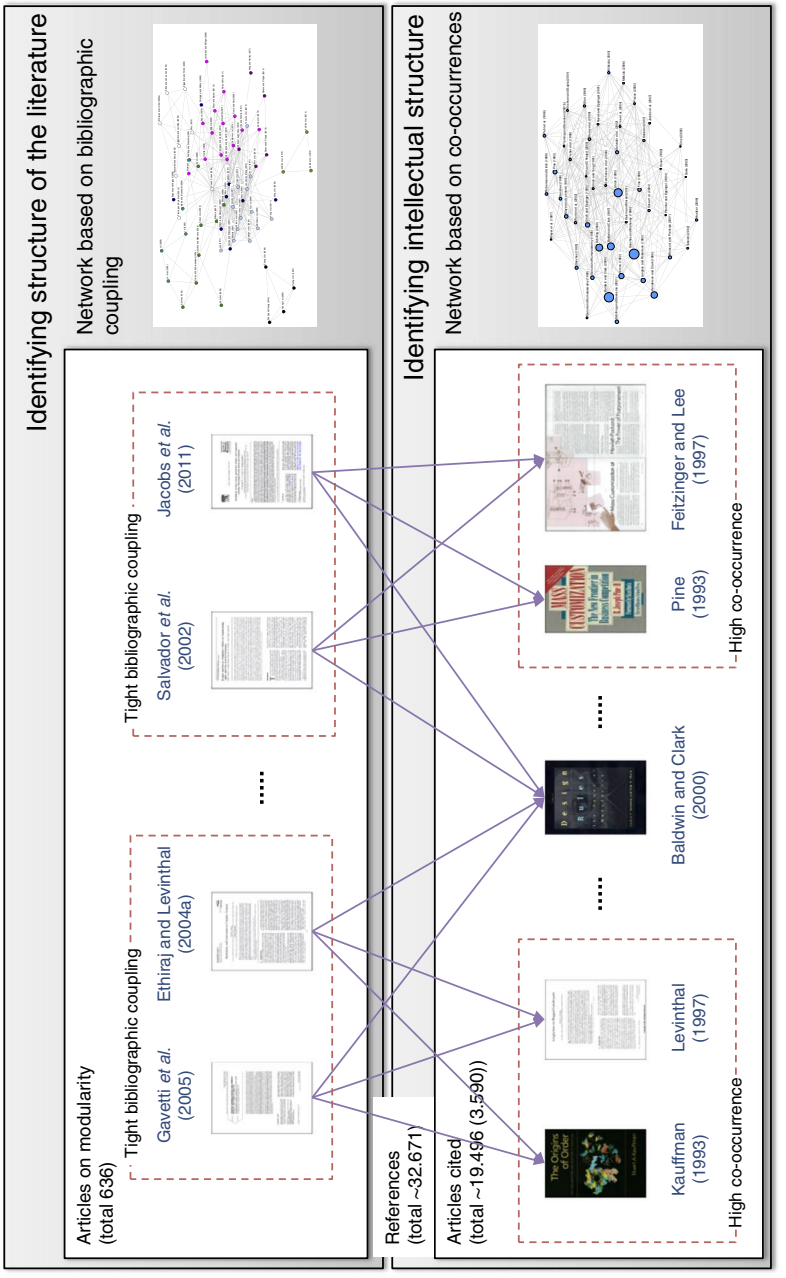

Figure 1.
Analytical approach to identifying the structure within the modularity literature

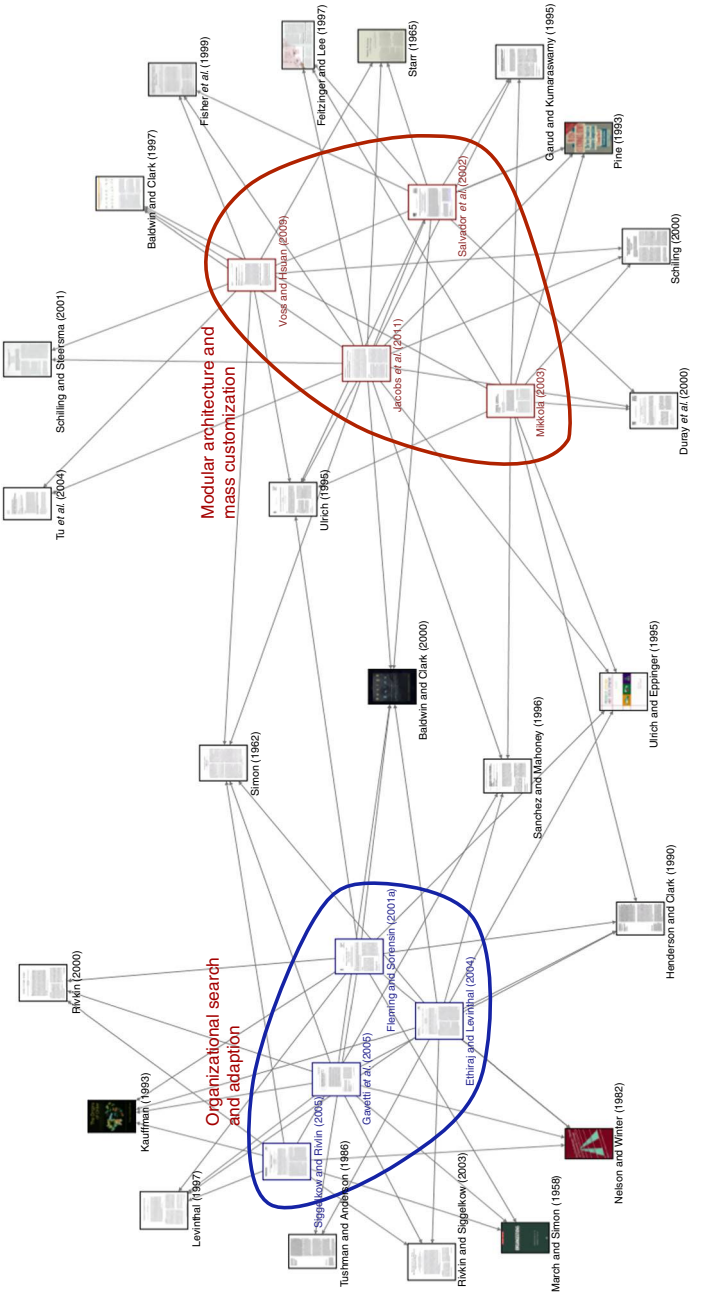

Figure 2.
Example of referencing from a subset of the modularity literature

estimate this proximity. Similar citation patterns in two articles thus result in a higher measure of bibliographic coupling. Based on this measure, the network graph in Figure 3 illustrates the relationships between the articles identified in the literature search. Links in this graph indicate bibliographic coupling between two articles; denser links indicate higher bibliographic coupling.

4. Findings

In the analysis of the bibliometric data from the modularity literature explained above, the source articles have been divided in three periods, corresponding first to the early period (the 1990s), then the formation period (the 2000s), and, finally, the recent period (2010-2015). This section provides a general overview of the modularity literature, its evolution and emerging research areas. Sub-section 4.1. present the findings which emerged from analyzing the journals cited by the modularity literature. Sub-section 4.2. identifies the structure of the modularity literature through an analysis based on bibliometric coupling. Sub-section 4.3 identifies the intellectual structure behind the modularity literature by undertaking co-citation analysis on the core literature. In Sub-section 4.4, the evolution of subfields within the modularity literature is mapped through the use of co-citation analysis on the periphery literature. Sub-section 4.5 explores, in more detail, the emerging field of service modularity identified in the previous section.

4.1 Identifying structure in the literature by seminal contributions and most cited journals

Citation analysis can be a useful way to identify the importance attributed to particular journals and individual contributions. Table III shows the journals most frequently cited by the reviewed papers on modularity, during the three periods and in total. The *Strategic Management Journal* (*SMJ*) is the most frequently cited journal for the entire period. Although 364 papers in *SMJ* are cited, approximately 29 percent of the citations made to this journal are to five of the 20 papers most frequently cited by other papers on modularity (Tables AI and AII). *Management Science* (5 percent of citations to Ethiraj and Levinthal, 2004b) and *Research Policy* (21 percent of citations to Ulrich, 1995) are second and third overall. Although there is some stability in the pattern of citations to journals throughout the period, the referencing patterns have changed. For example, the *Harvard Business Review* was the most frequently cited journal in the 1990s. However, many operations and innovation management journals entered the list in the 2000s and became more frequently cited during the recent period. Specifically, the 275 references made to articles in the *International Journal of Operations and Production Management* (*IJOPM*) make it the tenth most cited journal by articles on modularity published in the period 2010-2015. This change could reflect the observation, suggested in Figure 6 and Table III that modularity has entered several specific research domains and supplemented strategic management.

4.2 Identifying structure in the modularity literature through co-citing patterns

Bibliographic coupling is based on the premise that similarity in referencing patterns can be an indication of topical proximity between source articles and can be used to visualize and analyze structure within the referencing literature. This section explores the referencing patterns of the modularity literature using bibliographic coupling and factor analysis. Figure 3 shows a network visualization of the literature and indicates the factors identified. Nodes in the network represent citing articles, while edges represent bibliographic coupling, i.e. the number of references shared by two nodes.

Figure 3 was created using UciNet software (Borgatti *et al.*, 2002) for network analysis and was visualized using NetDraw (Borgatti, 2002). To identify structure within the modularity literature, it was necessary to reduce the density of the network diagram.

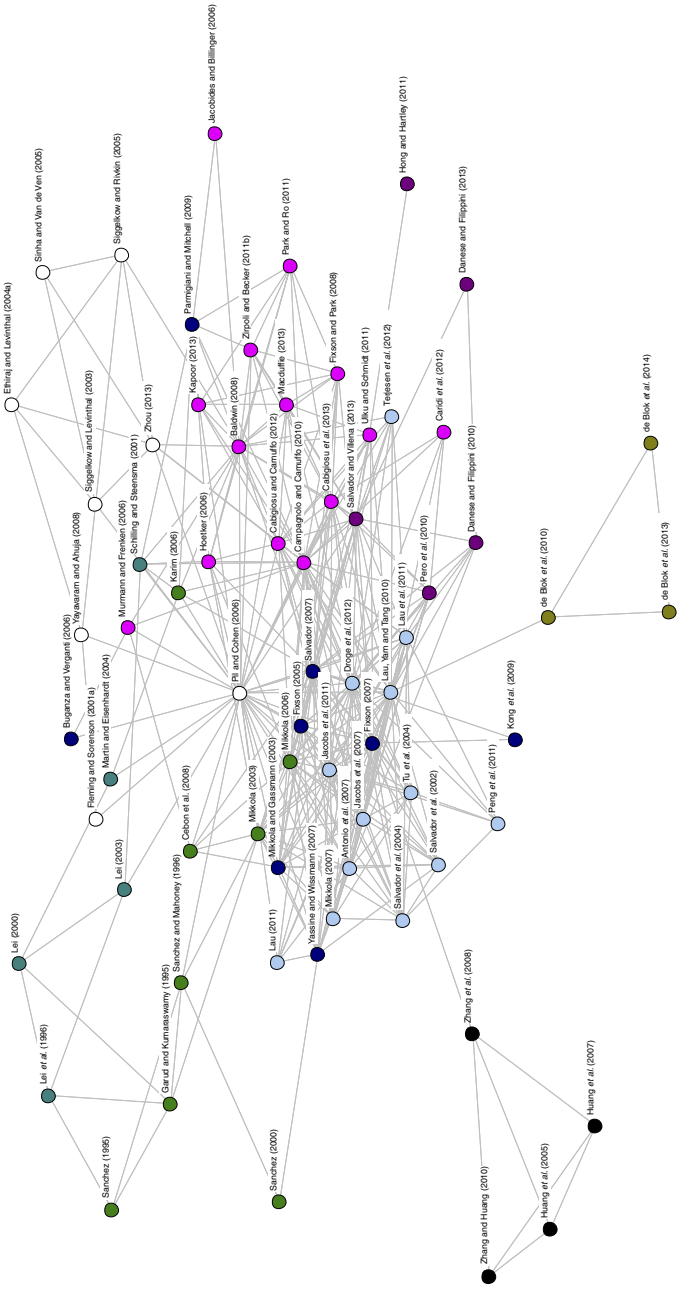

Figure 3.
Network visualization of the literature on modularity in relation to management

Table III.
Journals most frequently cited by papers on modularity

Early period: 1990-1999		%	Middle period: 2000-2009		%	Recent period: 2010-2015		%	Entire period: 1990-2015		%
Journal		citations	Journal		citations	Journal		citations	Journal		citations
Harvard Business Review	57	4.0	*Strategic Management Journal*	565	4.7	*Strategic Management Journal*	658	3.6	*Strategic Management Journal*	1,264	4.1
Strategic Management Journal	41	2.9	*Management Science*	459	4.0	*Management Science*	658	3.6	*Management Science*	1,144	3.7
Administrative Science Quarterly	29	2.0	*Research Policy*	366	3.2	*Journal of Operations Management*	463	2.6	*Research Policy*	781	2.5
Management Science	27	1.9	*Harvard Business Review*	344	2.5	*Organization Science*	411	2.3	*Harvard Business Review*	737	2.4
Research Policy	23	1.6	*Administrative Science Quarterly*	314	2.5	*Research Policy*	392	2.2	*Organization Science*	712	2.3
Communications of the ACM	21	1.5	*Organization Science*	286	2.3	*Academy of Management Review*	350	1.9	*Administrative Science Quarterly*	663	2.1
Academy of Management Review	20	1.4	*Academy of Management Review*	226	2.0	*Harvard Business Review*	336	1.9	*Journal of Operations Management*	626	2.0
IEEE Transactions on Software Engineering	17	1.2	*Academy of Management Journal*	168	1.5	*Administrative Science Quarterly*	320	1.8	*Academy of Management Review*	596	1.9
Organization Science	15	1.1	*Journal of Operations Management*	159	1.1	*Journal of Product Innovation Management*	277	1.5	*Academy of Management Journal*	428	1.4
International Journal of Production Research	14	1.0	*Industrial and Corporate Change*	130	1.0	*International Journal of Operations & Production Management*	275	1.5	*Journal of Product Innovation Management*	397	1.3
Sloan Management Review	13	0.9	*Journal of Product Innovation Management*	119	1.0	*International Journal of Production Economics*	250	1.4	*Industrial and Corporate Change*	376	1.2
Academy of Management Journal	13	0.9	*International Journal of Production Research*	107	0.9	*Academy of Management Journal*	247	1.4	*International Journal of Operations & Production Management*	366	1.2
California Management Review	13	0.9	*Sloan Management Review*	106	0.9	*Industrial and Corporate Change*	245	1.3	*International Journal of Production Research*	351	1.1

(*continued*)

Table III.

Early period: 1990-1999 Journal		% citations	Middle period: 2000-2009 Journal		% citations	Recent period: 2010-2015 Journal		% citations	Entire period: 1990-2015 Journal		% citations
Operations Research	10	0.7	*European Journal of Operational Research*	97	0.8	*International Journal of Production Research*	230	1.3	*International Journal of Production Economics*	339	1.1
Journal of Management Information Systems	9	0.6	*IEEE Transactions on Engineering Management*	88	0.8	*IEEE Transactions on Engineering Management*	187	1.0	*IEEE Transactions on Engineering Management*	283	0.9
IEEE Transactions on Engineering Management	8	0.6	*Journal of Marketing*	87	0.8	*European Journal of Operational Research*	122	0.7	*European Journal of Operational Research*	227	0.7
Mathematical Programming	8	0.6	*International Journal of Operations & Production Management*	87	0.8	*Decision Sciences*	121	0.7	*Sloan Management Review*	211	0.7
MIS Quarterly	8	0.6	*International Journal of Production Economics*	87	0.8	*MIS Quarterly*	119	0.7	*Journal of Marketing*	176	0.6
Artificial Intelligence	8	0.6	*California Management Review*	79	0.6	*Production and Operations Management*	106	0.6	*MIS Quarterly*	170	0.5
European Journal of Operational Research	8	0.6	*American Economic Review*	68	0.6	*Journal of Economic Behavior & Organization*	93	0.5	*California Management Review*	167	0.5
Total references	1,417		Total references	11,434		Total references	18,149		Total references	31,000	

Source: Citations to journals from source articles on modularity resulting from the literature search on modularity excluding self-references

Consequently, among the 636 source articles, only the 261 articles which have been cited at least once by other scholars have been included. Furthermore, we followed the procedure outlined by Vogel and Güttel (2013), in order to set a threshold for the number of shared references and the number of articles to which this applied. To achieve clarity without sacrificing detail, only the 68 articles sharing at least 14 references with at least two other source articles were included. Figure 3 shows that while there are similarities in referencing patterns, differences also exist, indicating that different views on modularity exist in the literature. To complement the network analysis and explore these differences, a factor analysis was conducted, using SPSS 22.0.

The factor analysis was performed as a principal component analysis using varimax rotation. The number of components was determined based on the evaluation of a scree plot, resulting in nine components, accounting for 37.7 percent of the variance explained. The factor analysis involved an analysis of the correlation matrix, based on the 68 source articles as outlined above. The analysis then identified factors among the source articles on modularity and resulted in an acceptable Kaiser-Meyer-Olkin measure of sampling adequacy of 0.768. Bartlett's test of sphericity was significant at a p-value of less than 0.001. These results indicate that the correlations in the data set are appropriate for factor analysis.

The rotated component matrix was inspected to identify the characteristics of each factor, based on the individual article in the component. To interpret these factors, the titles, abstracts, keywords, and content of the articles in each group were investigated to identify commonalities. Individual references in each group were used to identify the causes of the high bibliographical coupling of the articles. The labeling of factors was based on the interpretation of multiple researchers, following a process in which the authors were provided with initial labels, following which two researchers independently formulated labels for each of the factors and noted down the factors presenting difficulties. The labels were subsequently organized and are as set out in Table IV. Articles in different factors typically draw on different strands of research, and modularity tends to be defined and discussed in relation to different seminal articles on modularity. That is, the group organizational search and adaption tends to define modularity by reference to Simon (1962) on near decomposability and Baldwin and Clark (2000), whereas the group product architecture and platforms tend to define modularity by referring to Henderson and Clark (1990) and Ulrich (1995). The 68 source articles can be illustrated based on the groupings identified through the bibliographic analysis of the content. Modularity and its development are discussed in the following section.

Figure 4 shows the nine factors identified through factor analysis and the distribution of the 68 articles over time. Two factors were initiated in the 1990s, while most of the remaining factors were formed during the 2000s. Two of the factors only have references

Table IV. Factors identified through factor analysis

Factor	Interpretation	Articles	Eigenvalue	% of variance
1	Organizational integration and the boundaries of the firm	14	6.7	9.8
2	Modular production and mass customization	13	3.9	5.7
3	Component commonality	4	2.9	4.3
4	Organizational search and adaptation	8	2.6	3.8
5	Product architecture for flexibility and substitution	8	2.3	3.3
6	Service modularity the case of modular care provision	3	2.1	3.2
7	Product architecture and modularity	8	1.8	2.7
8	New product development	5	1.8	2.6
9	Organizational capabilities	5	1.5	2.3
Total		68		37.7

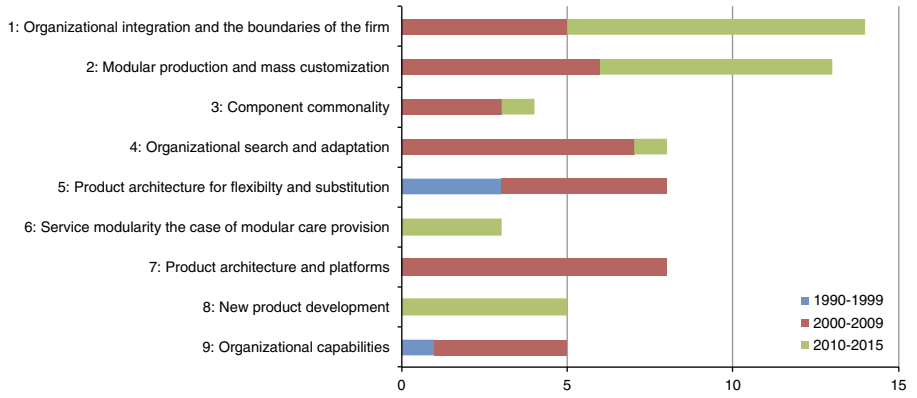

Figure 4. Factors and their development across time

published in the most recent period. A benefit of bibliometric coupling analysis is that it allows for the inclusion of recent articles. Consequently the analysis can suggest developments in the literature as seen above. Further consideration of emerging areas of research follows in Sub-section 4.4.

Figure 5 shows four snapshots of the modularity literature and indicates that research increases significantly toward the end of the middle period and during the beginning of the recent period. This growth seems to stem from a growing awareness of modularity and its relevance within different areas of research. In particular, modularity seems to be increasingly applied in domains other than product architecture, most notably service architecture and organizations.

4.3 Exploring the evolution of the field of modularity from 1990 to 2015

In co-citation analysis, proximity between referenced articles is estimated based on how frequently source articles cite two references. It can, therefore, be a way of identifying intellectual structures on which the field draws. By carrying out co-citation analysis for the entire period, as well as for separate periods within this study, it is possible to explore the evolution of the field. Figure 6 is based on a co-citation analysis of the bibliometric data for the 150 most frequently co-cited articles, showing only core references and lines represented by normalized Pearson correlation coefficients above 0.6. The figure reveals that the modularity literature draws on a range of sources. Distinct groupings of research with similar referencing patterns can also be identified.

As the figure shows, identifying distinct research areas in the core literature is difficult, in part perhaps because most of the source articles tend to define modularity by referring to the same group of seminal contributions. In Table AI, the 20 source articles that are most frequently cited by other source articles are listed. As Table AI suggests, there are nuances in the way modularity is defined in these seminal contributions, which stem from the different perspectives of the articles. Much of the modularity literature has focused on product architecture and how modular design is related to strategic outcomes. A key interest has been how modularity helps organizations achieve strategic flexibility and economics of substitution. Although part of the early literature focused on an organization's strategic advantages, another early interest was how modularity is related to the development of capabilities within organizations and, more recently, across organizations. Figures 7-9 show the developments in the core modularity literature, with Sanchez and Mahoney (1996), Baldwin and Clark (1997, 2000), and Ulrich (1995) becoming focal points of reference.

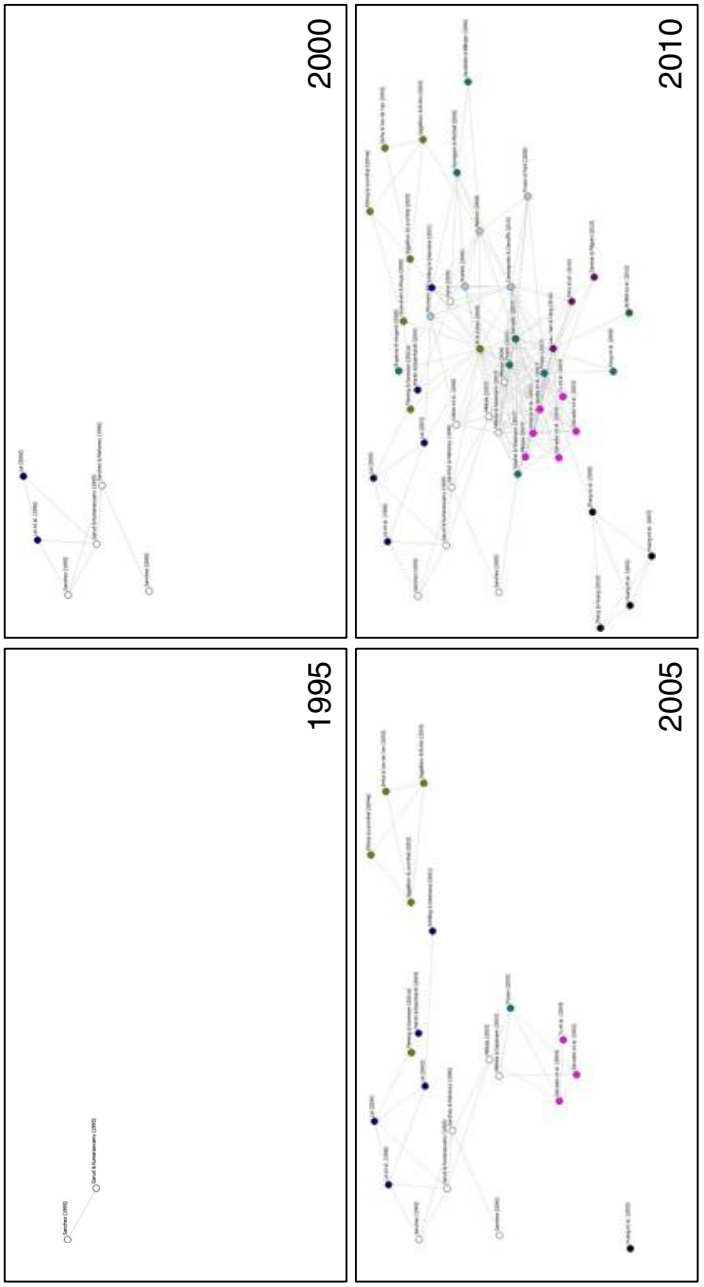

Figure 5.
Development of the modularity literature (1995-2010)

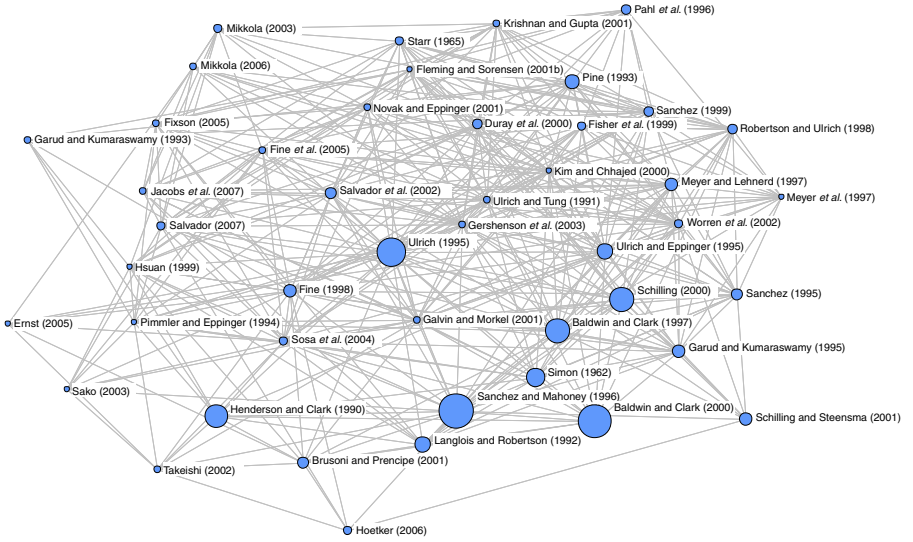

Figure 6.
Co-citation network for the core modularity literature in the period (1990-2015)

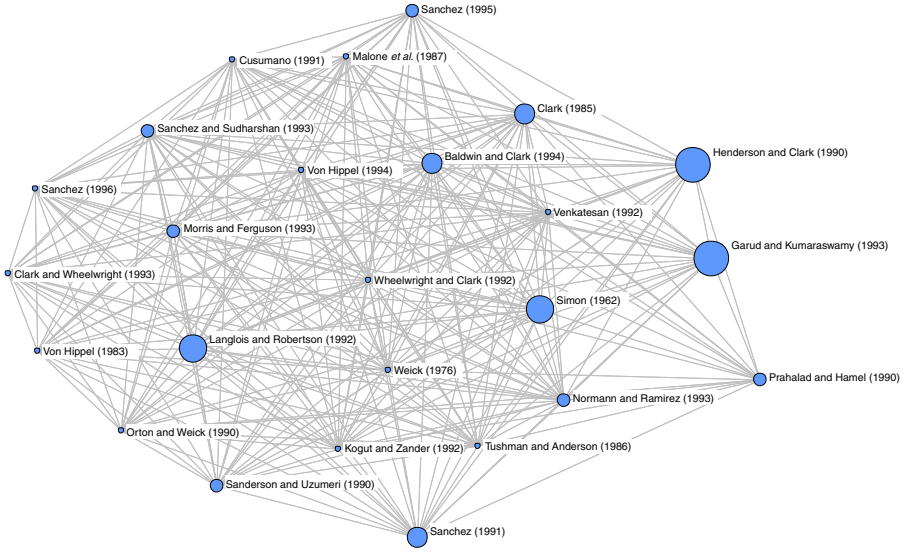

Figure 7.
Co-citation network for the core literature of the early period (1990-1999)

4.4 Identify emerging research areas within the modularity literature

As co-citation analysis is based on how frequently articles are co-cited, it generally gives more prominence to the frequently cited references. While it is beneficial to attribute prominence to highly cited papers when identifying the intellectual roots of a field, the time it takes to generate citations implies that emerging research may feature less prominently. Here, core-periphery analysis is beneficial, as it identifies and removes the dense core of co-citations illustrated in Figures 6-9, which represent the established mainstream references. Removing the core leaves the co-citation patterns that are still strong enough to reflect the commonality of thought but have not yet become part of the primary reference set.

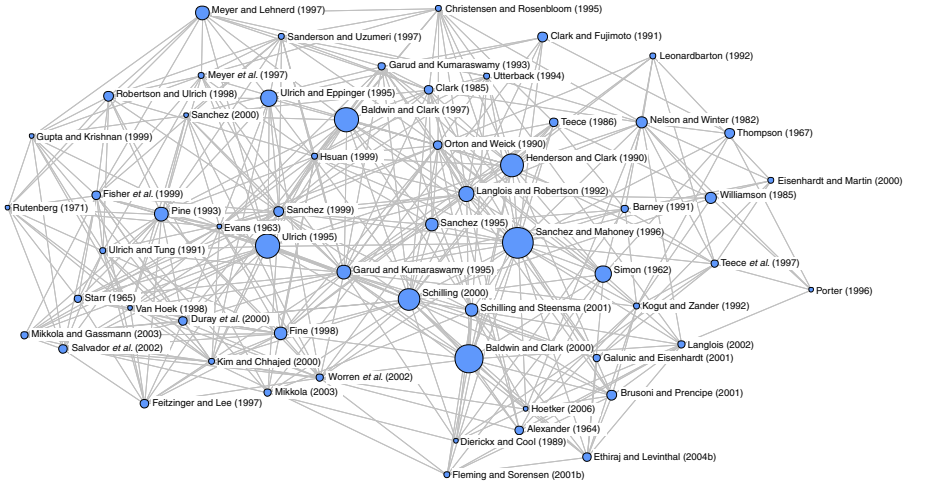

Figure 8.
Co-citation network for the core literature of the middle period (2000-2009)

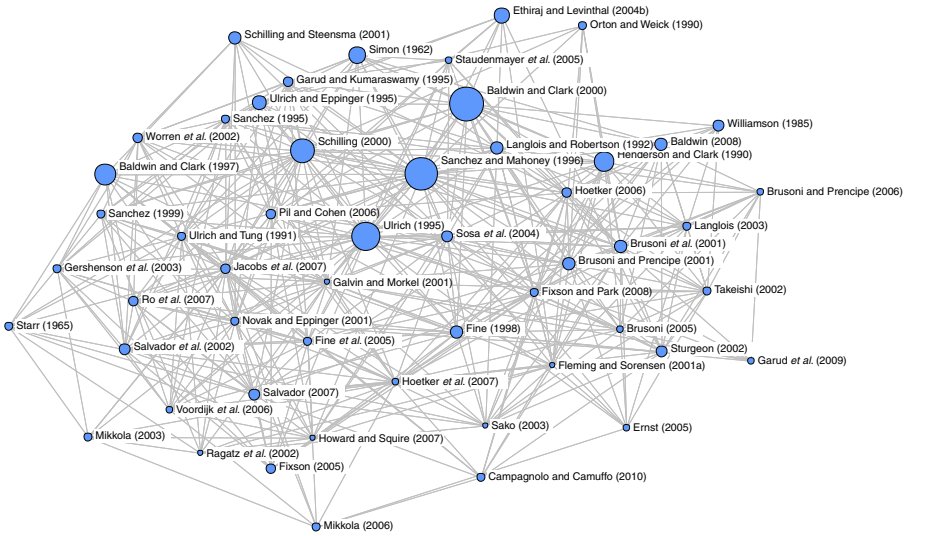

Figure 9.
Co-citation network for the core literature of the recent period (2010-2015)

Again, these peripheral citations are represented by lines based on normalized Pearson correlation coefficients, showing only lines with values above 0.75. The periphery network can identify potential emerging research areas (Pilkington and Chai, 2008). As suggested by Figures 10-13, the modularity literature has increasingly been linked to the study of organizations, in the sense that product and service modularity influences the structure of organizations, is a structural property of the organizations themselves, and affects decision making within organizations. Moreover, the literature seems to have evolved through the emergence of increasingly more specific knowledge domains, which have extended the study of modularity from product modularity to organizations and supply chains, as well as various levels of analysis from components to an architectural level.

Figure 13 suggests that there is a continuing opportunity for studies on modularity by identifying eight specific emerging areas of research. In addition to the use of

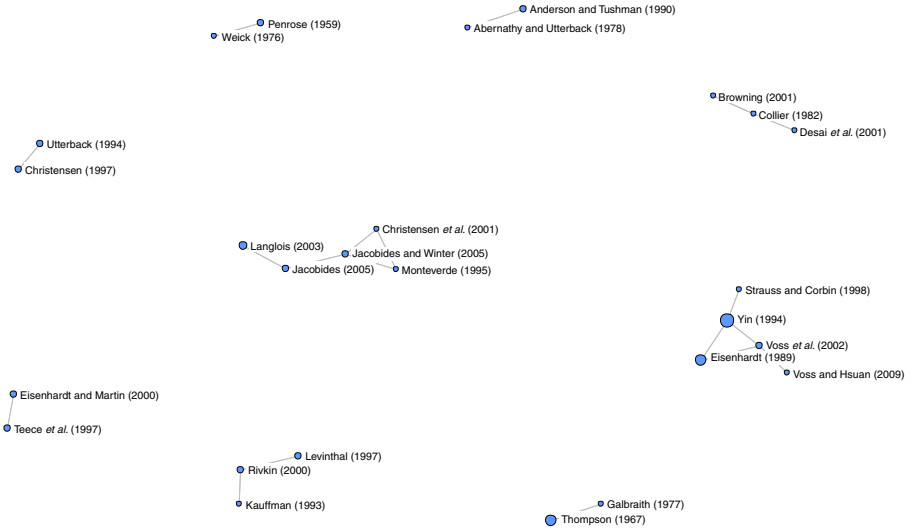

Figure 10.
Co-citation network for the periphery literature of the entire period (1990-2015)

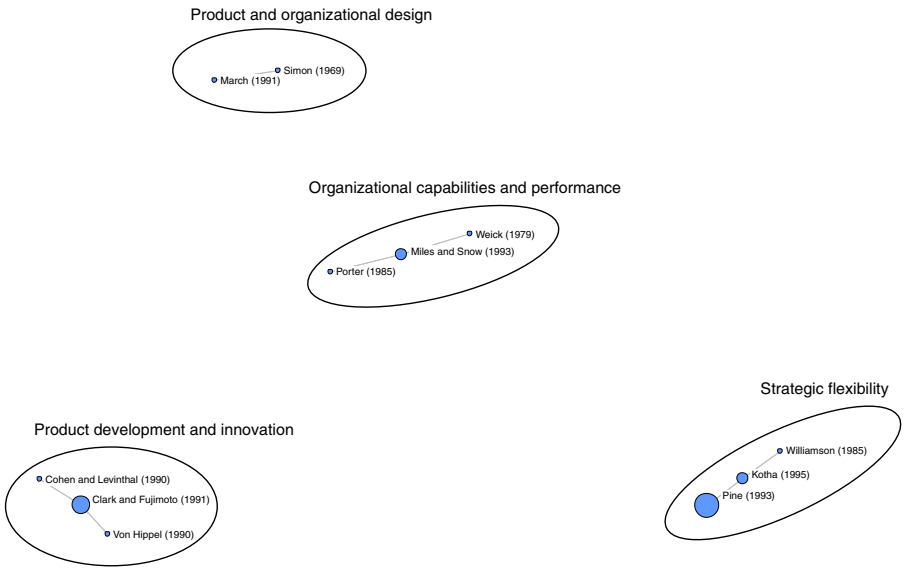

Figure 11.
Co-citation network for the periphery literature of the early period (1990-1999)

case-based research, these include studying the effects of modularity on organizations and supply chains (i.e. Cheng *et al.*, 2014) and reconfiguration and dynamic capabilities (i.e. Vickery *et al.*, 2015), as well as vertical integration and disintegration (i.e. Helfat, 2015). Similarly, the strong relation between modularity and innovation seems to suggest that modularity is finding a place in the literature on open innovation (i.e. Baldwin and von Hippel, 2011; Jaspers and Van den Ende, 2010), developing across boundaries (i.e. Hong and Hartley, 2011), and optimizing design of complex systems (i.e. Baldwin *et al.*, 2014). Interestingly, the three citations in the center of Figure 13 (Voss and Hsuan, 2009;

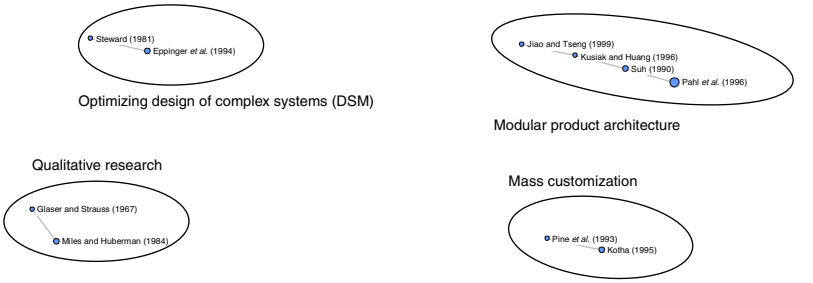

Figure 12.
Co-citation network for the periphery literature of the middle period (2000-2009)

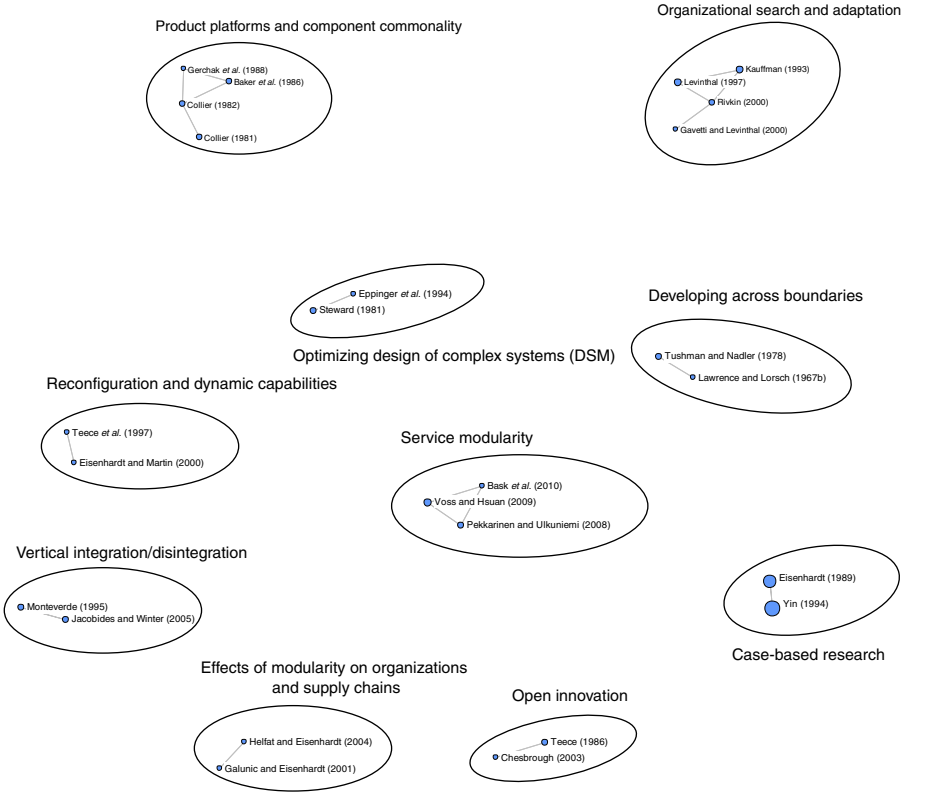

Figure 13.
Co-citation network for the periphery literature of the recent period (2010-2015)

Bask *et al.*, 2010; Pekkarinen and Ulkuniemi, 2008) all focus on the service modularity. Given the aim of this paper, this emerging area receives further attention in the following section.

4.5 Locating the emerging field of service modularity in the wider modularity literature

While service modularity has been identified as one of eight emerging research areas within the modularity literature, this section explores this subfield in more detail, in order to locate it within the wider modularity literature. Voss and Hsuan (2009) emphasize that service design must be considered from the perspective of service architecture, which implies a

concern with decomposition and understanding the nature of interfaces and components (Voss and Hsuan, 2009). Pekkarinen and Ulkuniemi (2008) suggest a platform-based approach for developing services, whereas Bask *et al.* (2010) propose, by reference to a logistic service provider case, a framework for understanding service modularity in relation to the business models and modular processes.

Table V sets out the 13 source articles whose co-citations cause service modularity to appear as an emerging research area in the periphery analysis of the recent period. They can be considered a starting point for understanding this emerging research area. De Blok *et al.* (2010) suggest that modularity has practical implications for service design and in designing services; modularity is a key aspect to consider. Within this literature, modularity has been studied in diverse contexts such as healthcare (De Blok *et al.*, 2010, 2013, 2014; Vähätalo and Kallio, 2015), logistic services (Rajahonka, 2013; Lin and Pekkarinen 2011; Cabigiosu *et al.*, 2015), and manufacturing (Carlborg and Kindström, 2014; Hellström, 2014). This development resonates well with the general realization of the growing economic importance of services, as well as the technological developments that fuse services in traditional manufacturing contexts (Carlborg and Kindström, 2014). Although most studies rely on case study research, Hofman and Meijerink (2015) employ a qualitative method to investigate platform thinking within services. The authors analyze human resource management (HRM) but address service modularity only indirectly, by classifying activities in terms of the service delivery mode, differentiation in needs, and HRM service value.

Reference	Title	Voss and Hsuan (2009)	Pekkarinen and Ulkuniemi (2008)	Bask *et al.* (2010)
Aas and Pedersen (2013)	The usefulness of componentization for specialized public service providers	1	1	1
Cabigiosu *et al.* (2015)	Modularity in KIBS: the case of third-party logistics service providers	1	1	1
De Blok *et al.* (2014)	Interfaces in service modularity: a typology developed in modular health care provision	1	1	1
Rajahonka (2013)	Views of logistics service providers on modularity in logistics services	1	1	1
Vähätalo and Kallio (2015)	Organising health services through modularity	1	1	1
Bask *et al.* (2011)	Framework for modularity and customization: service perspective		1	1
Bask *et al.* (2014)	Developing a modular service architecture for e-store supply chains: the small- and medium-sized enterprise perspective	1		1
Carlborg and Kindström (2014)	Service process modularization and modular strategies		1	1
De Blok *et al.* (2010)	Modular care and service packages for independently living elderly	1	1	
De Blok *et al.* (2013)	The human dimension of modular care provision: opportunities for personalization and customization	1	1	
Hellström (2014)	Solution business models based on functional modularity – the case of complex capital goods	1		1
Hofman and Meijerink (2015)	Platform thinking for services: the case of human resources	1	1	
Lin and Pekkarinen (2011)	QFD-based modular logistics service design	1	1	
Co-citations (total citations from modularity literature)		11 (17)	11 (15)	9 (9)

Source: Based on bibliographic data from the literature search on modularity

Table V.
Source articles in the recent period co-citing seminal service modularity papers

Table VI show the journals from which citations are made to the three key source articles. Although citations are made from dedicated service management journals, the majority are from within industrial marketing and operations management journals, and the *IJOPM* in particular. There may be several reasons, but the strong domain knowledge of product modularity, derived from decades of operations management research, seems to provide a strong foundation for understanding issues that are most important in service management. Product manufacturers have responded to customer requests for customization by modularizing product architectures and developing mass customization capabilities. In services, personalization has, possibly, been the preferred response to the same challenge. The advances in information technology and the growing scale of service operations imply that this response creates excessive complexity that service providers need to address, with modularity a strong candidate solution.

5. Discussion and future research directions

5.1 Summary of contributions

The modularity literature has grown significantly, and many approaches to studying modularity have emerged. Network analytical techniques based on bibliographic data have shown how this literature has developed into distinct research areas. Once primarily related to the strategic benefits of product modularity, the literature has increasingly turned to other aspects of modularity, including organizations, information technology, manufacturing capabilities, and innovation. The use of modularity as a key concept in different areas has resulted in the development of individual groupings that touch upon the different aspects of modularity and focus on its varying consequences. The original perception of modularity in terms of product architecture with strategic relevance has changed to operational capabilities and production strategies, innovation processes, organizational structure, and industry evolution.

Furthermore, the literature has evolved from predominantly theoretical frameworks and propositions to empirical investigations that use various research methods. Many studies

Table VI.
Journals with source articles in the recent period co-citing seminal service modularity papers

Reference	Voss and Hsuan (2009)	Pekkarinen and Ulkuniemi (2008)	Bask *et al.* (2010)	Total
Journal of Business & Industrial Marketing	1	5	2	8
International Journal of Operations & Production Management	4	2	1	7
Industry and Innovation	1	1	1	3
International Journal of Logistics-Research and Applications	1	1	1	3
Journal of Operations Management	1	1	1	3
Managing Service Quality	1	1	1	3
International Journal of Production Economics	1	1		2
Journal of Service Management	1		1	2
Service Industries Journal	1	1		2
Service Science	1		1	2
Concurrent Engineering-Research and Applications		1		1
Decision Sciences	1			1
International Journal of Production Research	1			1
R&D Management	1			1
Technological Forecasting and Social Change		1		1
Technovation	1			1
Total	17	15	9	41

Source: Based on bibliographic data from the literature search on modularity

have thus empirically tested the proposed relationships, while others have sought to understand modularization at the level of individual firms and their inter-organizational relationships. Using the network analytical approach to investigate the bibliographic data has proven to be a strong technique for revealing the development of research approaches on a topic of importance across disciplines. Although prior research applied similar techniques to the study of the development of research disciplines, this paper contributes by investigating the development of an increasingly noteworthy topic and demonstrating how the analytical approach can improve our understanding of the development of critical areas. This insight can aid research and practice and create an overview of the complexity of an evolving literature.

This paper seeks to add to the knowledge of the modularity literature gained through previous systematic literature reviews (Campagnolo and Camuffo, 2010; Salvador, 2007; Bask *et al.*, 2010; Fixson, 2007). While the observation that the modularity literature has expanded into several domains confirms those of previous studies, the findings from this paper contribute to the literature in a number of ways. First, the paper identifies distinct research groups within the modularity literature. Although they resonate with the previous reviews, these groups are based on the citation patterns in the literature, which are more objective than the subjective evaluations used to identify the similar structures in previous reviews. Second, the co-citation analysis of three specific time periods shows how the field has evolved from a primary emphasis on product modularity to address modularity in a range of other domains. Specifically, new sub-research of modularity in relation to topics such as organizational search and adaptation, mass customization, component commonality and the use of specific methods of conceptualizing modularity (such as the design structure matrix), whilst particular research methods, such as case study research, have emerged. Third, the paper identifies eight emerging sub-research areas (see Figure 13) based on a periphery analysis of the recent period (2010-2015), one of which is service modularity. Finally, by analyzing the source articles, which resulted in service modularity appearing as an emerging area, this paper discusses several potentially fruitful future directions for the modularity literature.

5.2 Future directions in modularity research

The findings suggest several avenues for future investigation. Modularity has become a diverse field of research, for which the objects of study have been widened and the levels of analysis extended. This broadened scope implies that modularity is now studied at the industry, supply chain, firm, platform, product/service, and component levels. Based on a periphery analysis of the recent period (2010-2015), eight sub-research areas were identified, suggesting emerging areas of modularity research. In addition to case research, these include studying modularity in relation to organizations and supply chains (i.e. Cheng *et al.*, 2014), dynamic capabilities (i.e. Vickery *et al.*, 2015), as well as vertical integration and disintegration (i.e. Helfat, 2015), open innovation (i.e. Baldwin and von Hippel, 2011), how modularity impacts development across boundaries (i.e. Hong and Hartley, 2011), and optimizing the design of complex systems (i.e. Baldwin *et al.*, 2014).

The final emerging research area is service modularity, which is identified in the analysis due to the frequent co-citations of Voss and Hsuan (2009), Bask *et al.* (2010), and Pekkarinen and Ulkuniemi (2008). This observation is in line with recent reviews suggesting that modularity seems to be growing in importance within the design and management of services (Bask *et al.*, 2010; Eissens-van der Laan *et al.*, 2016). It also resonates with the research priorities identified by Ostrom *et al.* (2015) through a survey of service researchers. For the area of service networks and systems, they point to "service architecture and modularization in the context of value networks" as an important research priority.

This paper contributes by systematically identifying service modularity as an emerging area through core-periphery analysis. By analyzing the same citation data used in the periphery analysis, the paper identifies the source articles whose co-citations are the basis for considering service modularity as an emerging area. The data suggest that these co-citing references are a starting point for understanding the evolution of this emerging area. A brief review of these source articles showed that numerous applications of service modularity have already been explored. However, given the early state of this area of research, the predominant research design has been exploratory, using qualitative research methods within either single or a few case contexts. An interesting exception is Hofman and Meijerink (2015), who employed a quantitative research method to study platform thinking in services. However, no direct operationalization of the service modularity construct as a scale for survey research was found in the literature. Consequently, there seems to be potential for future studies to synthesize and operationalize the knowledge gained through more exploratory studies, to further the understanding of service modularity. In addition to reviewing the source articles co-citing papers on service modularity, an analysis of the journals in which the papers are published reveals that service modularity primarily emanates from the operations management domain, with *IJOPM* being a journal that has devoted particular attention to service modularity.

Finally, the strong presence of service modularity within the industrial marketing and operations management journals may be a result of the growing importance of service modularity among manufacturing firms (Carlborg and Kindström, 2014; Hellström, 2014). An increasingly important emerging area within the wider service literature is servitization, which focuses on how manufacturers tackle the challenges of implementing service-based business models (Pilkington *et al.*, 2015). Service modularity is important in understanding how such firms can overcome the complexities of heterogeneous customer needs for advanced services, which would be a fruitful avenue for future research.

5.3 Limitations of the present study and suggestions for extending bibliometric analysis

While bibliometric analysis is a useful method for identifying structure within fields of research by using patterns of co-citation (Pilkington and Chai, 2008; Pilkington and Meredith, 2009), it also comes with its own limitations. Specifically, it is a retrospective form of analysis, entirely based on the co-citation patterns of already published research. As the publication process is often lengthy and takes months, sometimes years, the data collected from the ISI Web of Science and analyzed in this paper is, by its nature, lagging behind the most contemporary developments in the actual research settings. Furthermore, although bibliometric analysis relies on more objective data in the form of journal citations and replicable methods such as the co-citation analysis, it lacks the detailed understanding gained from systematically reading and interpreting the contributions within a field. Consequently, bibliometric analysis is not a substitute for systematic literature reviews and the interpretation of results still requires revisiting the literature to understand the meanings of the analysis. The use of bibliographic coupling has only recently gained attention in bibliometric studies within management. However as suggested by Zupic and Čater (2015), it has the benefit of including more recent publications in the analysis, thereby complementing co-citation analysis to enable timid identification of emerging areas of research. A potential area for future research could be to combine a systematic literature review of source articles, to add additional codes to the data. Such hybrid analysis would allow for a richer data set by reference to which refined bibliometric analysis along multiple dimensions could subsequently be performed. Such classifications could include the object of modularity, as well as the level of analysis and empirical methods employed.

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Appendix

Reference[a]	Cited[b]	Methodology	Theoretical perspective	Object of modularity
Sanchez and Mahoney (1996) Management in product modularity, flexibility, and knowledge organization design (*SMJ*)	204	Conceptual	Strategic management	Products and organization
Baldwin and Clark (1997) Managing in an age of modularity (*HBR*)	141	Conceptual with illustrative cases	Strategic management	Products and processes
Schilling (2000) Toward a general modular systems theory and its application to inter-firm product modularity (*AMR*)	140	General theory development	General theory of modular systems	Products and general systems
Schilling and Steensma (2001) The use of modular organizational forms: An industry-level analysis (*AMJ*)	64	Test of model using data from 330 manufacturing industries in the USA	General theory of modular systems	Organization
Ethiraj and Levinthal (2004a, b) Modularity and innovation in complex systems (*MS*)	60	Conceptual with NK simulation model	Complex adaptive systems	Decision variables
Garud and Kumaraswamy (1995) Technological and organizational designs for realizing economies of substitution (*SMJ*)	60	Conceptual	Strategic management	Technological systems
Langlois (2002) Modularity in technology and organization (*JEBO*)	57	Conceptual – developing a modularity theory of the firm	Organizational economic	Organization
Sanchez (1995) Strategic flexibility in product competition (*SMJ*)	52	Conceptual	Strategic management	Products
Salvador *et al.* (2002) Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions (*JOM*)	47	Multiple case studies (six product families)	Managerial/ engineering	Products
Duray *et al.* (2000) Approaches to mass customization: configurations and empirical validation (*JOM*)	42	Configuration model to classify mass customizers with empirical validation	Engineering	Products
Sanchez (1999) Modular architectures in the marketing process (*JM*)	40	Conceptual with reference to cases in the literature	Strategic/ marketing management	Product, processes, and knowledge
Mikkola and Gassmann (2003) Managing modularity of product architectures: toward an integrated theory (*IEEE TEM*)	40	Modeling (modularization function) with illustrative case (Schindler elevators)	Engineering/ management	Products
Worren *et al.* (2002) Modularity, strategic flexibility, and firm performance: a study of the home appliance industry (*SMJ*)	39	Conceptual model tested with SEM model (data from managers in home appliance comp.)	Management	Products
Baldwin (2008) Where do transactions come from? Modularity, transactions, and the boundaries of firms (*ICC*)	33	Develop theoretical framework	Economic	Organization

(*continued*)

Table AI. Seminal contributions within the modularity literature

Reference[a]	Cited[b]	Methodology	Theoretical perspective	Object of modularity
Hoetker (2006) Do modular products lead to modular organizations? (*SMJ*)	33	Causal model (empirical)	Economic	Products and organization
Sosa *et al.* (2004) The misalignment of product architecture and organizational structure in complex product development (*MS*)	33	Case study (large commercial aircraft engine development process)	Engineering/ organizational	Products and organization
Mikkola (2003) Modularity, component outsourcing, and inter-firm learning (*R&DM*)	31	Case study (Chrysler Jeep WIPER)	Engineering/ organizational	Products
Salvador (2007) Toward a product system modularity construct: Literature review and reconceptualization (*IEEE TEM*)	30	Literature review	Engineering/ management	Product
Pil and Cohen (2006) Modularity: Implications for imitation, innovation, and sustained advantage (*AMR*)	31	Develop theoretical framework	Management/ organizational	Products, processes, and design practices
Tu *et al.* (2004) Measuring modularity-based manufacturing practices and their impact on mass customization capability: a customer-driven perspective (*DS*)	28	Empirical survey ($n = 303$, LISREL to estimate structural relations)	Engineering/ organizational/ management	Products and manufacturing processes

Notes: [a]*AMJ*, *Academy of Management Journal*; *AMR*, *Academy of Management Review*; *DS*, *Decision Sciences*; *HBR*, *Harvard Business Review*; *IEEE TEM*, *IEEE Transactions on Engineering Management*; *JEBO*, *Journal of Economic Behavior and Organization*; *JM*, *Journal of Marketing*; *JOM*, *Journal of Operations Management*; *MS*, *Management Science*; *R&DM*, *R&D Management*; *RP*, *Research Policy*; *SMJ*, *Strategic Management Journal*; *ICC*, *Industrial and Corporate Change*; [b]number of citations from articles identified in the bibliographic search on modularity described in Section 3. Self references are excluded

Table AI.

Journal	Citations by modularity literature			Most cited reference in journal			Modularity literature in journal			Journal self-references (% of)	
	Citations	Articles	Average	Reference	Citations	% of all	Articles	References	To journal	Citations	References
Strategic Management Journal	1,264	364	3.5	Sanchez (1996), Vol.17, p. 63	204	16.1	16	1,076	119	9.4	11.1
Management Science	1,144	386	3.0	Ethiraj and Levinthal (2004b), Vol. 50, p. 159	60	5.2	19	798	76	6.6	9.5
Research Policy	781	204	3.8	Ulrich (1995), Vol. 24, p. 419	167	21.4	17	1,094	104	13.3	9.5
Harvard Business Review	737	250	2,9	Baldwin and Clark (1997), Vol. 75, p. 84	140	19.0	1	12	0	0.0	0.0
Organisation Science	712	284	2.5	Kogut and Zander (1992), Vol. 3, p. 383	25	3.5	18	1,363	95	13.3	7.0
Administrative Science Quarterly	663	161	4.1	Henderson and Clark (1990), Vol. 35, p. 9	135	20.4	2	124	13	2.0	10.5
Journal of Operations Management	626	252	2.5	Salvador *et al.* (2002) Vol. 20, p. 549	47	7.5	11	656	46	7.3	7.0
Academy of Management Review	596	183	3.3	Schilling (2000) Vol. 25, p. 312	140	23.5	4	393	24	4.0	6.1
Academy of Management Journal	428	204	2.1	Schilling and Steensma (2001), Vol. 44, p. 1149	64	15.0	1	98	0	0.0	0.0
Journal of Product Innovation Management	397	179	2.2	Mikkola (2006), Vol. 23, p. 128	26	6.5	15	922	55	13.9	6.0
Industrial and Corporate Change	376	107	3,5	Brusoni and Prencipe (2001) Vol. 10, p. 179	55	14.6	7	563	38	10.1	6.7
International Journal of Operations & Production Management	366	167	2.2	Jacobs *et al.* (2007), Vol. 27, p. 1046	22	6.0	51	1,896	136	37.2	7.2
International Journal of Production Research	351	288	1.2	Agard and Kusiak (2004), Vol. 42, p. 2955	5	1.4	51	1,830	175	49.9	9.6
International Journal of Production Economics	339	228	1.5	Muffatto (1999), Vol. 60-1, p. 145	12	3.5	30	1,853	139	41.0	7.5

(*continued*)

Table AII.
Seminal articles in journals most frequently cited by papers on modularity

Table AII.

Journal	Citations by modularity literature			Most cited reference in journal			Modularity literature in journal			Journal self-references (% of)	
	Citations	Articles	Average	Reference	Citations	% of all	Articles	References	To journal	Citations	References
IEEE Transactions on Engineering Management	283	105	2.7	Mikkola (2003), Vol. 50, p. 204	40	14.1	24	1,282	52	18.4	4.1
European Journal of Operational Research	227	160	1.4	Kim and Chhajed (2000), Vol. 125, p. 602	16	7.0	11	307	20	8.8	6.5
Sloan Management Review	211	77	2.7	Robertson and Ulrich (1998), Vol. 39, p. 19	45	21.3	1	10	0	0.0	0.0
Journal of Marketing	176	96	1.8	Sanchez (1999), Vol. 63, p. 92	40	22.7	1	23	0	0.0	0.0
MIS Quarterly	170	121	1.4	Rai *et al.* (2006), Vol. 30, p. 225	5	2.9	2	179	11	6.5	6.1
California Management Review	167	102	1.6	Thomke and Reinertsen (1998), Vol. 41, p. 8	9	5.4	6	220	14	8.4	6.4
Total	31.000	18.409	1.7				636	31.000	1.708	5.5	5.5

Source: Citations to journals from source articles on modularity resulting from the literature search on modularity excluding self-references

Table AIII. Factor loadings of references included in factor analysis

Component	Reference	Title	Loading on component
1. Organizational integration and the boundaries of the firm			
	MacDuffie (2013) *Global Strategy Journal*	Modularity-as-property, modularization-as-process, and "modularity"-as-frame: lessons from product architecture initiatives in the global automotive industry	0.604
	Campagnolo and Camuffo (2010) *International Journal of Management Review*	The concept of modularity in management studies: a literature review	0.59
	Kapoor (2013) *Organization Science*	Persistence of integration in the face of specialization: how firms navigated the winds of disintegration and shaped the architecture of the semiconductor industry	0.565
	Ülkü and Schmidt (2011) *Production Operations Management*	Matching product architecture and supply chain configuration	0.534
	Cabigiosu and Camuffo (2012) *Organization Science*	Beyond the "mirroring" hypothesis: product modularity and interorganizational relations in the air conditioning industry	0.526
	Baldwin (2008) *Industrial and Corporate Change*	Where do transactions come from? Modularity, transactions, and the boundaries of firms	0.526
	Fixson and Park (2008) *Research Policy*	The power of integrality: linkages between product architecture, innovation, and industry structure	0.515
	Park and Ro (2011) *Journal of Operations Management*	The impact of a firm's make, pseudo-make, or buy strategy on product performance	0.511
	Cabigiosu *et al.* (2013) *Research Policy*	Modularity, interfaces definition and the integration of external sources of innovation in the automotive industry	0.488
	Zirpoli and Becker (2011) *R&D Management*	The limits of design and engineering outsourcing: performance integration and the unfulfilled promises of modularity	0.421
	Hoetker (2006) *Strategic Management Journal*	Do modular products lead to modular organizations?	0.382
	Caridi *et al.* (2012) *International Journal of Production Economics*	Linking product modularity and innovativeness to supply chain management in the Italian furniture industry	0.355
	Jacobides and Billinger (2006) *Organization Science*	Designing the boundaries of the firm: From "make, buy, or ally" to the dynamic benefits of vertical architecture	0.347
	Murmann and Frenken (2006) *Research Policy*	Toward a systematic framework for research on dominant designs, technological innovations, and industrial change	0.293
2. Modular production and mass customization			
	Jacobs *et al.* (2011) *Journal of Product Innovation Management*	Product and process modularity's effects on manufacturing agility and firm growth performance	0.629

(*continued*)

Table AIII.

Component	Reference	Title	Loading on component
	Tu *et al.* (2004) *Decision Sciences*	Measuring modularity-based manufacturing practices and their impact on mass customization capability: a customer-driven perspective	0.627
	Jacobs *et al.* (2007) *International Journal of Operations & Production Management*	The effects of product modularity on competitive performance – Do integration strategies mediate the relationship?	0.566
	Droge *et al.* (2012) *International Journal of Production Economics*	Does supply chain integration mediate the relationships between product/process strategy and service performance? An empirical study	0.549
	Salvador *et al.* (2004) *Production Planning Control*	Supply-chain configurations for mass customization	0.491
	Peng *et al.* (2011) *International Journal of Operations & Production Management*	Impacts of information technology on mass customization capability of manufacturing plants	0.44
	Antonio *et al.* (2007) *International Journal of Production Economics*	The impacts of product modularity on competitive capabilities and performance: an empirical study	0.436
	Mikkola (2007) *IEEE Transactions of Engineering Management*	Management of product architecture modularity for mass customization: modeling and theoretical considerations	0.415
	Salvador *et al.* (2002) *Journal of Operations Management*	Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions	0.372
	Lau *et al.* (2010) *International Journal of Operations & Production Management*	Supply chain integration and product modularity: an empirical study of product performance for selected Hong Kong manufacturing industries	0.369
	Lau *et al.* (2011) *Journal of Product Innovation Management*	The impact of product modularity on new product performance: mediation by product innovativeness	0.346
	Lau (2011) Journal of Engineering and Technology Management	Critical success factors in managing modular production design: six company case studies in Hong Kong, China, and Singapore	0.283
	Terjesen *et al.* (2012) *Decision Sciences*	Managing differentiation-integration duality in supply chain integration	0.217
3. Component commonality			
	Zhang *et al.* (2008) *International Journal of Production Research*	Simultaneous configuration of platform products and manufacturing supply chains	0.844
	Zhang and Huang (2010) *International Journal of Production Economics*	Game-theoretic approach to simultaneous configuration of platform products and supply chains with one manufacturing firm and multiple cooperative suppliers	0.834
	Huang *et al.* (2007) *IEEE Transactions on Engineering Management*	Integrated configuration of platform products and supply chains for mass customization: a game-theoretic approach	0.825
	Huang *et al.* (2005) *Journal of Operations Management*	Towards integrated optimal configuration of platform products, manufacturing processes, and supply chains	0.817

(*continued*)

Component	Reference	Title	Loading on component
4. Organizational search and adaptation			
	Siggelkow and Rivkin (2005) *Organization Science*	Speed and search: designing organizations for turbulence and complexity	0.676
	Siggelkow and Levinthal (2003) *Organization Science*	Temporarily divide to conquer: centralized, decentralized, and reintegrated organizational approaches to exploration and adaptation	0.662
	Ethiraj and Levinthal (2004a) *Administrative Science Quarterly*	Bounded rationality and the search for organizational architecture: an evolutionary perspective on the design of organizations and their evolvability	0.558
	Sinha and Van de Ven (2005) *Organization Science*	Designing work within and between organizations	0.548
	Yayavaram and Ahuja (2008) *Administrative Science Quarterly*	Decomposability in knowledge structures and its impact on the usefulness of inventions and knowledge-base malleability	0.519
	Zhou (2013) *Organization Science*	Designing for complexity: using divisions and hierarchy to manage complex tasks	0.495
	Fleming and Sorenson (2001a) *Research Policy*	Technology as a complex adaptive system: evidence from patent data	0.404
	Pil and Cohen (2006) *Academy of Management Review*	Modularity: implications for imitation, innovation, and sustained advantage	0.351
5. Product architecture for flexibility and substitution			
	Sanchez and Mahoney (1996) *Strategic Management Journal*	Modularity, flexibility, and knowledge management in product and organization design	0.684
	Sanchez (2000) *International Journal of Technology Management*	Modular architectures, knowledge assets and organizational learning: new management processes for product creation	0.595
	Sanchez (1995) *Strategic Management Journal*	Strategic flexibility in product competition	0.542
	Garud and Kumaraswamy (1995) *Strategic Management Journal*	Technological and organizational designs for realizing economies of substitution	0.437
	Mikkola (2003) *R&D Management*	Modularity, component outsourcing, and inter-firm learning	0.417
	Mikkola (2006) *Journal of Product Innovation Management*	Capturing the degree of modularity embedded in product architectures	0.37
	Cebon *et al.* (2008) *International Journal of Technology Management*	Product modularity and the product life cycle: new dynamics in the interactions of product and process technologies	0.334
	Karim (2006) *Strategic Management Journal*	Modularity in organizational structure: the reconfiguration of internally developed and acquired business units	0.264

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Table AIII.

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Component	Reference	Title	Loading on component
6. Service modularity the case of modular care provision			
	De Blok *et al.* (2013) *International Journal of Production Economics*	The human dimension of modular care provision: opportunities for personalization and customization	0.872
	De Blok *et al.* (2010) *International Journal of Operations & Production Management*	Modular care and service packages for independently living elderly	0.824
	De Blok *et al.* (2014) *Journal of Operations Management*	Interfaces in service modularity: a typology developed in modular health care provision	0.801
7. Product architecture and platforms			
	Salvador (2007) *IEEE Transactions on Engineering Management*	Toward a product system modularity construct: Literature review and reconceptualization	0.464
	Kong *et al.* (2009) Concurrent Engineering: Research and Applications	On modular products development	0.463
	Fixson (2007) Concurrent Engineering: Research and Applications	Modularity and commonality research: past developments and future opportunities	0.458
	Parmigiani and Mitchell (2009) *Strategic Management Journal*	Complementarity, capabilities, and the boundaries of the firm: the impact of within-firm and interfirm expertise on concurrent sourcing of complementary components	0.422
	Mikkola and Gassmann (2003) *IEEE Transactions on Engineering Management*	Managing modularity of product architectures: Toward an integrated theory	0.405
	Yassine and Wissmann (2007) System Engineering	The implications of product architecture on the firm	0.394
	Fixson (2005) *Journal of Operations Management*	Product architecture assessment: a tool to link product, process, and supply chain design decisions	0.313
	Buganza and Verganti (2006) *Journal of Product Innovation Management*	Life-cycle flexibility: How to measure and improve the innovative capability in turbulent environments	0.248
8. New product development			
	Danese and Filippini (2010) *International Journal of Operations & Production Management*	Modularity and the impact on new product development time performance Investigating the moderating effects of supplier involvement and interfunctional integration	0.615
	Danese and Filippini (2013) *IEEE Transactions on Engineering Management*	Direct and mediated effects of product modularity on development time and product performance	0.609
	Salvador and Villena (2013) *Journal of Supply Chain Management*	Supplier integration and NPD outcomes: conditional moderation effects of modular design competence	0.506

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Table AIII.

Component	Reference	Title	Loading on component
	Hong and Hartley (2011) *Journal of Supply Chain Management*	Managing the supplier-supplier interface in product development: the moderating role of technological newness	0.414
	Pero *et al.* (2010) *Supply Chain Management*	A framework for the alignment of new product development and supply chains	0.335
9. Organizational capabilities			
	Lei (2000) *International Journal of Technology Management*	Industry evolution and competence development: the imperatives of technological convergence	0.792
	Lei (2003) *International Journal of Technology Management*	Competition, cooperation and learning: the new dynamics of strategy and organisation design for the innovation net	0.779
	Lei *et al.* (1996) *Organization Studies*	Advanced manufacturing technology: organizational design and strategic flexibility	0.545
	Martin and Eisenhardt (2004) *Advanced Strategic Management*	Coping with decline in dynamic markets: corporate entrepreneurship and the recombinative organizational form	0.287
	Schilling and Steensma (2001) *Academy of Management Journal*	The use of modular organizational forms: an industry-level analysis	0.287