CONCURRENT ENGINEERING: Research and Applications

Modularity and Commonality Research: Past Developments and Future Opportunities

Sebastian K. Fixson*

Sloan School of Management, Massachusetts Institute of Technology
Cambridge, MA 02138, USA

Abstract: Research on modularity and commonality has grown substantially over the past 15 years. Searching 36 journals over more than the past 35 years, over 160 references are identified in the engineering and management literature that focus on modularity or commonality in the product and process development context. Each of the references is analyzed along the dimensions *subject*, *effect*, and *research method*. The subjects of these studies have been products, processes, organizations, and even innovations, although the set of references shows a strong preference towards products. Similarly, a broad range of effects has been studied, albeit with the topic cost dominating all other effects. A variety of research methods has been applied to the study of modularity and commonality but the distribution of research methods differs substantially for modularity and commonality research. Despite the wealth of existing research, there are still significant opportunities for future research. In particular, studies that incorporate modularity and commonality's multiple effects on various players along the supply chain, that combine multiple research methods, and that follow systems over time appear very promising.

Key Words: modularity, commonality, innovation, multidisciplinary research.

1. Introduction

The underlying ideas for modularity and commonality are not really new. As early as 1914, an automotive engineer demanded the standardization of automobile subassemblies, such as axles, wheels, and fuel feeding mechanisms to facilitate a mix-and-matching of components and to reduce costs [161]. Nevertheless, the confluence of advancements in engineering and manufacturing technologies, of invention and diffusion of innovations such as computers, and of changes in the economic and demographic structure of consumer populations has only recently created a world in which customers expect to be able to purchase customized products for near mass production prizes. As a consequence, over the last 15 years research on the topics of modularity and commonality has surged in several research communities. In this study, the research that has been published in the engineering and management domains on modularity and commonality in the context of product and process development has been analyzed and interpreted. For this purpose, over 160 publications have been reviewed and analyzed along the dimensions *subject*, *effects*, and *methods*, and recommendations for future research have been developed.

What this study does not do is attempting to provide yet another, let alone final, definition for these terms. While the consensus of what constitutes commonality is fairly established, the picture concerning modularity is more complicated. Other reviews are referred to provide an overview of existing definitions [54,55]. This study rather acknowledges the variety of approaches used to measure, create, use, and test these concepts. In addition, related terms, such as product platform, product family, and standardization are part of the discussion where appropriate. The remainder of the study is structured as follows. The next section presents the reference selection process and its result. The analysis of all 168 references along subject, effect, and method follows in the third section. Section 4 identifies fruitful avenues for future research, and Section 5 concludes the study.

2. Data Set Construction

The data set for this analysis is the result of a search over 35 years in 36 journals in the ISI Web of Science database using the search terms 'modularity' and 'commonality.' With only a small overlap of $<8\%$ the

*E-mail: fixson@mit.edu
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search resulted in 194 references. After the removal of 38 references not relevant for product and process development, and the addition of 12 references widely known and cited in the research community, the final list contains 168 references. Of these 168 references, 75 are associated with the search term 'modularity,' 76 are associated with the search term 'commonality,' and 17 references are associated with both search terms. Table 1 details the search procedure. Figure 1 shows all references by publication year and search term association. It illustrates the significant increase of publications over the last 15 years. This increase in publication numbers occurs for both search terms relatively evenly. For more details on the search process, see the Appendix.

3. Looking Back: Mapping the Literature on Modularity and Commonality

To map the current understanding of modularity and commonality, in this section the ground is laid out that the 168 identified references cover along three dimensions: (i) the subjects in focus of these studies, (ii) the performance effects associated with modularity and commonality that the studies strove to understand, and (iii) the research methods applied in these studies. (The online appendix contains data tables with the details for each reference.) In Section 4, the findings are synthesized across the set of references to identify opportunities for future research.

3.1 Subjects of Modularity and Commonality Studies

Following the idea for this special issue, the analysis in this study strives to consider product, process, and organizational aspects of modularity and commonality. This subject list is extended for this analysis by a fourth aspect, innovation.

3.1.1 PRODUCT

Most articles in the data set focus on products while investigating the mechanics and effects of modularity and commonality. The types of products studied range from aircrafts [46] to wood working machines [53], from space station water tanks [164] to telecommunication switches [81]. The descriptions and definitions used to create, determine, measure, and test modularity and commonality of products come in a large variety. Sometimes the reasoning overlaps, for example the logic of component similarity across products can be found in references on modularity and commonality. Modularity descriptions also often encompass a combinatorial element, i.e., modules can be mixed and matched to create new variants of a product. Some modularity descriptions incorporate an assessment of how a product's functionality is provided by the product's components. Engineering text books encourage to begin designing a product on the functional level, i.e., to establish a function structure first. This function structure can then be explored in search of possible modularization opportunities [133]. In fact, the way in which functions are allocated to physical components has been suggested as one of the dimensions to describe modularity [40,169]. The level of interdependence between modules has been suggested as another [9,54,55].

The actual measurements for modularity and commonality also come in a variety of flavors. They range from measurements directly on the component level to measurements in very indirect or abstract dimensions. For example, some researchers suggest a simple fraction count: The 'ratio between the total number of product design modules and the product size' [127: 390]. Mikkola and Gassmann [121] develop their modularization function based on the number of components and the degree of coupling between them. Focusing on the interdependence between modules, Kaski and Heikkila [87] construct a similar measure: Their dependency index divides the sum of the number of affected modules when a functional option is changed by the number of variable functions. Other studies describe product modularity also quantitatively, but entirely indirectly. For example, Anderson and Parker [4] in their study of outsourcing use the ratio of initial component cost to initial integration cost as a measure of product modularity. The often combinatorial nature of modularity becomes apparent in Kumar [98] who proposes to measure modularity as the number of options that the customer is free to choose from. Researchers that explore the product architecture issue from the variety perspective suggest to develop the architecture not for a single product but for the entire product family, consequently the measurement moves to the product family level [26]. Studies that research digital products and services, sometimes use the digitization itself as a measure for modularity [117], use an entirely qualitative-descriptive approach to describe modularity's effect on outsourcing IT processes [122], or assume interfirm modularity to be present industry-wide [159]. Growing modularity on the industry-level is often interpreted as changing the competitive landscape towards more network-like industry structures [108]. In a very indirect approach, Kodama [94] approximates modularity by the degree to which technological competence as measured in patenting activity has shifted from OEMs to their suppliers.

Studies of the phenomenon of product or component commonality have also suggested a variety of metrics. For example, Kota et al. [95] suggest a product line commonality index that measures the fraction of parts

Table 1. Reference selection process.

No.	Journal Title	References identified in initial search			References removed due to				
		Modularity	Commonality	Total	Non-Core (M)[2]	Non-Core (C)[3]	Commentary[4]	Reference added	References included in final analysis
	Engineering Journals								
1	Artificial Intelligence for Engineering Design Analysis and Manufacturing	3	2	3[1]					3
2	CIRP ANNALS - Manufacturing Technology	0	2	2					2
3	Concurrent Engineering - Research and Applications	5	6	10[1]	1	1			8
4	Design Studies	1	0	1					1
5	European Journal of Operational Research	2	9	10[1]					10
6	IEEE Transactions on Systems, Man, and Cybernetics A - Systems and Humans	1	0	1					1
7	IEEE Transactions on Systems, Man, and Cybernetics B - Cybernetics	2	0	2					2
8	IEEE Transactions on Systems, Man, and Cybernetics C - Applications and Reviews	0	1	1		1			0
9	IIE Transactions	2	8	10	2				8
10	International Journal of Advanced Manufacturing Technology	4	2	6	3				3
11	International Journal of Flexible Manufacturing Systems	1	1	2					2
12	Journal of Engineering Design	4	2	6					6
13	Journal of Intelligent Manufacturing	6	3	8[1]	1				7
14	Journal of Mechanical Design	8	6	12[1]	1				11
15	Operations Research	0	12	12		2		1	11
16	Production Planning & Control	5	9	13[1]	2	2			9
17	Research in Engineering Design	0	1	1		1			0
18	Robotics and Computer Integrated Manufacturing	3	0	3	2				1
	Engineering Books							3	3
	Total Engineering References	*47*	*64*	*103*[1]	*12*	*7*	*0*	*4*	*88*
	Management Journals								
19	Academy of Management Journal	1	0	1					1
20	Academy of Management Review	2	2	4		2	1		1
21	Administrative Science Quarterly	1	0	1				1	2
22	Harvard Business Review	3	0	3			1	1	3
23	IEEE Transactions on Engineering Management	3	2	4[1]		1			3
24	International Journal of Technology Management	8	1	9	1	1			7
25	Journal of Engineering and Technology Management	1	1	2					2

(Continued)

Table 1. Continued.

No.	Journal Title	References identified in initial search			References removed due to				
		Modularity	**Commonality**	**Tota**	**Non-Core (M)[2)]**	**Non-Core (C)[3)]**	**Commentary[4)]**	**Reference added**	**References included in final analysis**
26	Journal of Operations Management	7	4	7[1)]	1				6
27	Journal of Product Innovation Management	3	1	4			1		3
28	Management Science	5	23	28	1	1	2		24
29	Organization Science	5	1	6	1	1			4
30	Production and Operations Management	1	4	5					5
31	R&D Management	1	0	1					1
32	Research Policy	3	1	4	1	1		2	4
33	Sloan Management Review	1	1	2			1		1
34	Strategic Management Journal	6	0	6	1				5
35	Technological Forecasting and Social Change	2	0	2					2
36	Technovation	2	1	2[1)]					2
Management Books								4	4
Totla Management reference		*55*	*42*	*91[1)]*	*6*	*7*	*6*	*8*	*80*
GRAND TOTAL		**102**	**106**	**194[1)]**	**18**	**14**	**6**	**12**	**168**

[1)]Total is less than the sum of 'Modularity' and 'Commonality' because one or more references were found with both search terms.
[2)]In these references'Modularity'does not apply to product, process, or organization.
[3)]In these references 'Commonality' does not apply to product, process, or organization.
[4)]References are commentaries on other reference(s) in the initial list (e.g., book review), or reponse letters.

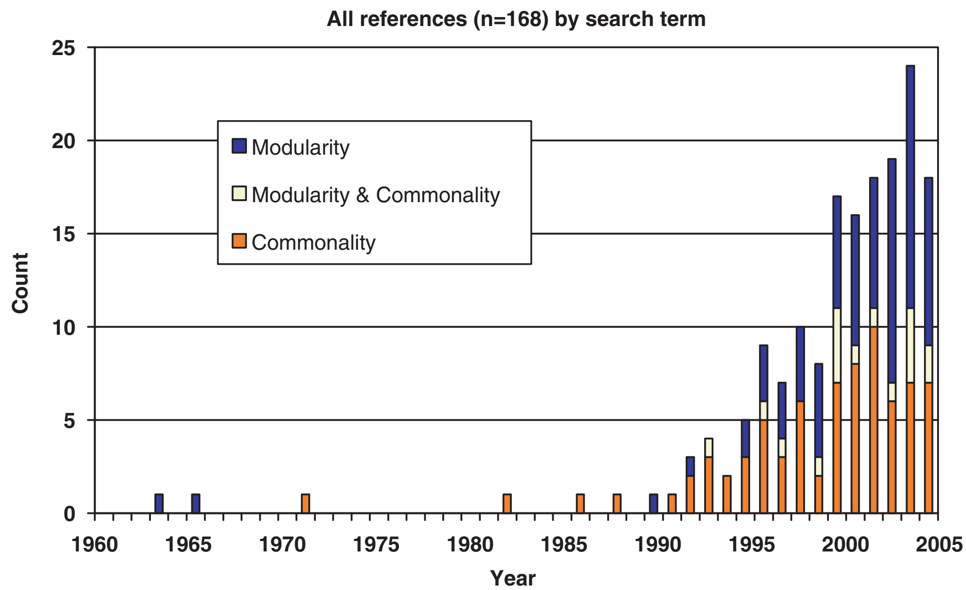

Figure 1. All references by publication year (1960–2005) and search term.

that is shared across a product family relative to the parts that could have been shared, adjusted for materials, manufacturing and assembly processes. A concept whose origin is separate but whose content is closely related to commonality is group technology (GT). GT strives to partition products and processes into product families and machine cells. The measure to increase in GT is typically some similarity metric. For example, this has been approached from a part perspective [84] and a tool perspective [56]. Loh and Taylor [113] find in their simulation study that commonality helps to decrease the number of set ups but can increase the average processing time due to increases in batch size. Just as modularity, commonality can also be determined on a rather abstract level. For example, another way in which products can exhibit commonality is when they are similar in brand reputation or feature presentation. Hui [76] finds that firms with high brand value tend to suffer higher degrees of cannibalization from commonality than firms with lower brand values.

Finally, in the operations research community the terms 'modularity' and 'commonality' started with having their own specific meaning. Modularity, as laid out in Evans' work on modular design [31,32] was described as the problem in which to determine the best configuration of small multi-use parts (in Evans' case kits of screws) to satisfy a variety of demands. Commonality, in contrast, was the idea of using identical components in a one-per-product setting, but in different products. Downward compatibility [139] allowed the use of one type of component in multiple products. Twenty years later, Thomas [164] viewed commonality as a partitioning problem and suggested clustering techniques for its solution. More recently, the commonality optimization approach suggested by Thonemann and Brandeau [165] uses a logic that strives for common parts to be identical, often also implying downward compatibility.

3.1.2 PROCESS

A small number of studies focuses exclusively on the modularity and commonality of processes. For example, Upton and McAfee [171] in their study on the role of information technology in manufacturing, suggest modularity as a key process feature to allow for continuous improvement. Similarly, modularity of processes is what Leger and Morel [106] argue allows to break up the monitoring process of a part of an hydropower plant maintenance process into four sub-processes.

Connecting both product and process, Watanabe and Ane [174] find that product modularity increases the processing flexibility of machines, and in turn, the agility of a manufacturing system. Also linking product and process structure, Jiao et al. [80] propose a data structure that integrates the bill of materials with the bill of operations; and combining product commonality with process commonality considerations, Jiao and Tseng [79] develop a process commonality index that incorporates concerns as process flexibility, lot sizing, and scheduling sequencing into their measurement instrument. In their work on aluminum tube manufacturing, Balakrishnan and Brown [6] view 'commonality across products as the shared set of processing steps from ingot casting to some intermediate hot or cold forming step.' [6 : 9] As a consequence, their trade-off balances upstream economies of scale with potentially increased individual effort downstream.

A more loosely related view on process similarity is explored by Bartezzaghi and Verganti [10]. For the environment of low uncertainty and delivery times longer than what customers accept, they develop a technique that uses the commonality of orders to reduce planning uncertainty. The elements that are common across orders can be either products or processes. Yet another way in which modularity and commonality influence process design has been described by Muffato and Roveda [125]. In their empirical analysis of three companies producing product families of electromechanical products they find that to achieve commonality across products requires defining the process for product platform development differently from those for the development of product derivatives.

3.1.3 ORGANIZATION

Using the term 'organization' here is intended to include both intra-firm and inter-firm organizational structures. The observation of similarities between the structure of a product and the structure of the organization that creates it has led scholars to study both jointly [48]. Applying both empirical and modeling research techniques, scholars have targeted their efforts to measure and explain the nature and character of organizational modularity and commonality. For example, Schilling and Steensma [147] approximate the degree of organizational modularity with the use of contractual manufacturing, alternative work arrangements, and alliances. Similarly, in their longitudinal study of the luxury fashion industry in France, Italy, and the US, Djelic and Ainamo [24] find different degrees of organizational modularity. They explain the persistence of these differences over time with differences in national environments and firm legacies.

Some researchers have argued that the link between organizational structure and product structure affects performance. Studying six different product families Salvador et al. [143] define two different types of modularity, combinatorial and component swapping, and find a correspondence between mass customization requirements from the market, product modularity type, and supply chain configuration. Similarly, modeling the trade-offs in 3D-concurrent engineering, Fine et al. [38] measure the supply network by including the dimension of dependency and argue for a match between product structure and supply chain structure.

Studying the relative effectiveness of changes in organizational design versus local adaptations, Ethiraj and Levinthal [29] find that near-decomposability, an aspect often equated with modularity, is beneficial for organizations in identifying appropriate structures. A similar view is presented by Sinha and Van de Ven [153] in their research on work systems. They suggest that 'a modularity problem could be that of deciding at what points to cleave work systems into components for allocation among subunits contained within a firm's boundaries or outsourcing with external organizational units' [153 : 391].

On a more abstract level it might not be the organization itself but rather some of the organization's capabilities that exhibit different degrees of modularity. In their work on organizational capabilities in product development, Kusunoki and co-authors [100] focus on 'whether organizational capabilities are based on individual knowledge units or related to capabilities to link and combine each unit of knowledge' [100: 700]. They find that in system-based industries the non-modular capabilities (architectural and process capabilities) have a strong impact on firm performance whereas they do not in materials-based industries.

Finally, the best solution of matching product and organizational structure might be dynamic, i.e., changing over time. Siggelkow and Levinthal [148] in their work on the impact of intermediate degrees of cross-divisional interdependence of undecomposable systems suggest the existence of such a dynamic solution: temporary decentralization and subsequent centralization. Based on their modeling results they argue that this sequencing can lead to higher performance than maintaining either pure form. Similarly focusing on the dynamic aspect of organizational modularity, Helfat and Eisenhardt [64] suggest that rearranging organizational units could be a mechanism for firms to deal with rapid environmental changes.

3.1.4 INNOVATION

Not only organizations, but also a concept such as innovation can exhibit modular characteristics. These characteristics have been linked to an innovation's surprise element, to its decrease in being radical, to increases in its option value, and to its diffusion potential. Many authors have stated the finding that organizations tend to mimic in their structure the structure of the products they produce. This alignment, that has been found efficient in stable environments, can make an organization blind to competitive challenges via a change in product architecture, described as architectural innovations by Henderson and Clark [65]. Others have suggested the idea that increasing modularity will – on average – decrease the likelihood of a breakthrough innovation [44,45]. However, modularity can increase the innovation rate because it offers option value [9,102,107]. The possibility that innovative activity can proceed in parallel in multiple module alternatives of which not all have to be selected can be represented as an option. Finally, Galvin [47] links the degree of product modularity to an innovation's diffusion potential. He argues that radical and architectural innovations in the Henderson and Clark framework require what he calls active information structures, i.e., interfaces that can change or evolve at least at some rate, whereas incremental and modular innovations can occur with either active or passive information structures.

3.2 Effects Investigated in Modularity and Commonality Studies

The broad array of research on modularity and commonality also has considered a broad range of performance dimensions that are affected by modularity and commonality. The discussion is structured along the dimensions product performance, product variety, cost, time, and others.

3.2.1 PRODUCT PERFORMANCE/QUALITY

The most obvious implication of modularity and commonality on product performance is the potential product performance degradation due to the use of common components across different products because the common components are most likely non-optimal for any product individually. Not surprisingly, primarily the design engineering community has presented work on the ensuing trade-off between product performance and typically production cost. For example, considering the structural strengths of components that can be common across products and their manufacturing costs, Cetin and Saitou [15–17] develop models that allow to find optimal modular designs. Similar ideas are pursued by Nelson et al. [128] and Fellini et al. [36] in their exploration of performance penalties of potentially common components. Sometimes the economic consequences are considered indirectly by using a commonality index in lieu of using cost numbers. For example, Simpson et al. [152] study the trade-off between commonality and individual product performance with the help of two indices: the non-commonality index and the performance deviation index. Alternatively, engineering performance criteria can drive the analysis. Salhieh and Kamrani [141] suggest the use of a similarity measure to cluster components into independent modules. Most of their objectives are engineering criteria, such as operational functional requirements that focus on product performance (as opposed to market or explicit cost targets).

3.2.2 PRODUCT VARIETY

Whereas product performance predominantly is an engineering dimension, for the commercial success of the product ultimately relevant is whether customers are willing to buy it. In today's markets where many products already satisfy the customers' performance expectations, the way in which products allow the customers to adjust the products to themselves and their own lifestyle becomes increasingly relevant. In a broad sense, there is a trade-off between modularity's and commonality's effects on generating revenues and their effects on saving costs, and the revenue generation potential depends to a non-trivial portion on product variety. Research on this trade-off has a long history: Balancing the disutility of not offering the customer the exact product she wants with the gain of economies of scale was already discussed 35 years ago [139]. More recently, Desai et al. [22] demonstrate in their model the effect on profits due to parts commonality by considering simultaneously the effects on cost savings and value decrease. Similarly, Kim and Chhajed [91] model the trade-off between reduced production costs and reduced relative valuations of products in low-price and high-price segments due to commonality and show the conditions that affect the optimal degree of commonality. Robertson and Ulrich [138] also discuss in detail the trade-off that exists between the cost savings potential due to commonality and the revenue decreasing potential due to loss of distinctiveness. However, they also propose that a well-thought out product plan can push the trade-off curve to improvements on both dimensions.

Whereas the idea of product variety suggests to offer the customer multiple options of a product, the concept of product customization takes this approach a step further and suggests to offer each customer exactly the product she wants [134]. Since product customization can result in an explosion of the number of product versions, the combinatorial aspect of mixing-and-matching parts that modularity permits appears to be very promising for this strategy. In addition to providing the customized product at the point of purchase, this aspect of modularity has also been identified as 'modularity in use' [8].

3.2.3 COSTS

The flipside of offering product variety while keeping costs under control is maintaining product variety while reducing costs. The effects through which product architecture characteristics, such as modularity and commonality can reduce costs are typically reduction of process complexity, increase of economies of scale, and risk pooling, and these effects can vary across and within different activities [41], such as design, manufacturing, inventory, and use.

3.2.3.1 Product Design

During the design stage, a major trade-off is to balance the gains through scale economies via design reuse with the costs of additional complexity through common or platform architectures. Finding the optimal balance is the target of some modeling research. For example, modeling the effects of product platforms on product development performance Krishnan and Gupta [96] demonstrate the limits of developing common platforms caused by their cost increase. This cost increase is in practice not always easy to determine, particularly not in advance. Responding to this difficulty, Holtta and Otto [73] develop a metric of design effort complexity to approximate the difficulty some architecture poses for redesign.

3.2.3.2 Manufacturing

During the manufacturing stage the cost effects attributed to modularity and commonality vary. The results of modularity's effects on cost are mixed. For example, building on their own modularity measures Zhang and Gershenson [178] study a number of small consumer products and do not find a general relationship between modularity and cost. In addition, it has been suggested that the number of modules affects the parts fabrication and assembly costs in opposite directions, hence the optimal number of modules needs to balance these two effects [167].

Studies of the cost effects of commonality in manufacturing often focuses on increasing scale economies [48]. Typically, the goal is to distribute fixed costs (e.g., dedicated tooling) over larger product volumes, and thus reduce unit costs. For example, component commonality can allow to reduce machine setup times when the assembly of common components is separable from the assembly of specific components [116]. While mostly researched in parts fabrication and assembly, scale effects due to common components can also occur in purchasing through order pooling, an effect that can be significant [68]. Note that cost savings due to scale increase might be outweighed by potential increase in variable cost [101].

3.2.3.3 Inventory

The probably largest body of research on cost effects of commonality is concerned with its effects on inventory costs. In particular, the operations research and operations management communities have established a considerable body of research in this field. The fundamental effect of reducing inventory through pooling demands for different products has been modeled in earlier works by Collier [21], Baker et al. [5], and Gerchak et al. [51]. These early studies used a number of simplifying assumptions with respect to the product, the demand, and the time horizon for their work. Subsequent research over the last 20 years has relaxed these assumptions and has determined a number of factors that represent bounds to a commonality strategy. Most of these bounds are concerned with context-related aspects, such as demand distributions and correlations, cost structures, time horizons, and process and supply networks. Other factors impacting the usefulness of commonality strategies are decision-related, such as selected product hierarchy levels and type of commonality strategies, as well as performance measurement-related factors, such as service levels and procurement times.

One direction in which the earlier works has been extended is with respect to demand distributions. For the most part, it shows that there is great savings potential in using common components. For example, Gerchak and He [50] show that the risk pooling benefits are non-decreasing with increasing demand variability under most circumstances. Alfaro and Corbett [2] demonstrate that the value of pooling is fairly robust with respect to various distributions, whereas it is more sensitive to the use of suboptimal inventory policies. The advantage of commonality can even be increased by reshaping the demand between substitute products [33], or by using stock rationing via different delivery thresholds for different demand classes [23]. However, some demand conditions can also reduce the savings through pooling substantially. Gerchak and Mossman [52] show that under certain demand conditions risk pooling, i.e., demand aggregation through the use of common parts, does not lower physical inventory but rather increases it, and Lee and Zipkin [105] demonstrate that the inventory savings in sequential refinement systems (i.e., without assembly) can be smaller than expected if the ratios of demand to processing rates are unbalanced across stages.

A second extension of the initial work by Collier et al. is the consideration of correlated demands. Commonality among components introduces a correlation between the demand patterns of these components, and it is the joint probability for end item demands that needs to be determined [63]. This is true not only for costs as performance measure but also for the order fill rate [155]. In addition to determining the base stock levels, these situations require careful consideration of the component allocation policy [1]. Van Mieghem [172] points out that commonality can provide benefits even in the presence of perfectly correlated demands via an ex-post revenue maximization option: 'Stocking the common component creates the option to produce more (compared to stocking only dedicated components) of the higher-margin product at the expense of the other product when demand exceeds capacity.' [172: 422] Interestingly, demand patterns can also be correlated if the products are substitutable, i.e., they are to some extent 'common' in the eyes of the customers. Not surprisingly, this demand correlation has implications for the optimal inventory policy [154]. Using appropriate rationing policies and allocation rules is a way a company can address the issue that is created when several products compete for common components [7,163]. It is possible that the use of common components in inventory also affects a firm's revenue. Ha [60] shows how commonality can allow inventory rationing when a sale in one lower-value demand class is foregone in favor of an anticipated sale in a higher-value demand class. Under certain circumstances, a single-state variable called work storage level can capture the entire system and the optimal rationing policy is a sequence of work storage levels [61]. At the same time, component commonality can substantially increase the difficulty of finding an optimal inventory policy in situations in which customers order multiple partially overlapping sets of components (order-based approach), because the common components essentially link the demand distributions of components with otherwise independent demands [114].

A third direction in which initial constraints have been relaxed covers the components' cost structures. In cases in which component costs are dominated by variable costs (e.g., materials) component commonality has significant limitations [123,165]. Commonality's benefits are also bound if the value difference between products are large and when the lead-times between common and product-specific components are close [156]. Similarly, different cost structures for common and unique components affect the value of commonality [34].

A fourth direction in which the work on commonality's effect on inventory has been extended is the time horizon. In his work on multi-period systems Hillier [67] finds that the benefits of commonality that are known in the one-period situation tend to be lower in a multi-period setting because only the savings on holding costs remain whereas the savings due to purchasing disappear. Likewise, Cheung [18] shows that some of the properties of Baker's model do not hold in the infinite horizon case.

Process and supply networks represent the fifth direction in which this research has been extended. Lee [103] has suggested that a strong lever to reduce inventory costs and forecasting errors lies in the redesign of products and production processes. In particular, he proposes to delay the point of differentiation, a strategy also labeled as late customization, to achieve these goals. Hill and co-authors [66] add capacity constraints to model reorder intervals in a production system with common components. Comparing product and process networks, Kulkarni et al. [97] show that in a process network the advantage through risk-pooling is mitigated when common subassembly capacity costs are either very high or very low. But also distribution channels and suppliers got integrated in the studies of the effects of commonality. For example, commonality at the end-item level may be detrimental to the manufacturer's interest if there exists a secondary market where retailers can engage in lateral transshipments of their products [104], and minimizing the sum of design, procurement, and production costs requires the simultaneous consideration of component and supplier selection [59].

Additional factors that impact the usefulness of component commonality are the hierarchy level of the product at which commonality occurs and the type of commonality strategy. The hierarchy level at which common structures are formed, i.e., component commonality versus subassembly commonality, has an impact on assembly sequences and subsequently on inventory and cost [58]. A similar problem is addressed by the idea to build generic versions of a product ('vanilla boxes') and to customize them later [160]. Fundamentally, the suggestion is a system that operates somewhere between a make-to-stock and an assemble-to-order system. Where in between these extreme points the system lies, i.e., the number, and consequently the size, of the vanilla boxes (or the hierarchy levels at which they are formed) is to a large part a product design decision. Hillier [69] has broadened the investigation of superiority between no-commonality and pure commonality strategies by introducing a third option, commonality-as-a-backup. He finds that this option is superior for both the one-period and the multi-period cases, because it gains much of the inventory reducing benefits even if the common component carries the penalty of higher component cost.

Finally, the degree to which commonality is measured as advantageous (or disadvantageous) for inventory is impacted by the choice of the performance measure. For example, using product-specific service levels Mirchandani and Mishra [123] show that inventory savings through risk pooling are larger as compared to those originating from models using aggregate service levels, and Choobineh and Mohebbi [20] find in their simulation study on commonality across production kits that commonality helps to counter uncertainty in both demand and component procurement time.

3.2.3.4 Use

The cost effects through modularity and commonality on the costs during a product's use phase build on similar ideas as the inventory literature. For example, Cheung and Hausman [19] study the role of part commonality on spare optimization under multiple failure regimes, i.e., the demands for the replacement of individual components become linked. In general, a major role for the cost of operations, particularly for industrial equipment, play maintenance costs. Modularity of the product structure can be used to minimize these costs [168].

3.2.4 TIME

Similar to the discussion of the cost effects, modularity and commonality affect the performance dimension time typically via complexity reduction and process parallelization. For example, Ma et al. [115] show that in a multistage assembly system the benefits of component commonality are dependent on the lead time dynamics of the system, i.e., how fast can components be replenished. Lead times can also affect the decision of whether to use generic components for certain low revenue products or to keep the generic components in anticipation of shortages for high revenue products during the replenishment time [166].

Commonality can also contribute to a reduction in setup times. Gunther and co-authors [57] develop a scheduling algorithm to minimize makespan in printed circuit assembly, and find that component commonality significantly improves system performance because it reduces changeover time for the part feeders between consecutive jobs.

An important factor responsible for time and resource consumption during product development is testing. The effect of work parallelization on testing time through modularity is demonstrated by Loch et al. [112]. They show that a modular structure allows testing designs with fewer tests and in a shorter time. A similar idea underlies what Blackburn et al. [12] call architectural modularity in software development: the decoupling of the structure to allow work to proceed in parallel. But not only the process dimension 'time' is affected by modularity: Complexity reduction is also one of the major goals in design of software systems whose response is particularly time critical. Modularity, that is the purposeful separation into subsystems, has been found an attractive solution for this problem for robot controllers [89] or speech recognition controller [135].

3.2.5 OTHERS

Beyond the standard industrial performance measures, such as product quality, cost, and time, modularity and commonality affect also additional performance dimensions, such as firm strategy and the environment. These effects are typically visible only over the long term. One aspect of firm strategy is to increase flexibility, and it has been suggested that modularity permits relatively higher degrees of flexibility [145]. This flexibility includes product adjustments after product launch [173], the option to add complementary products [127], and the ability to adjust faster to radical technological changes through appropriate product derivative generation [81]. This flexibility gained through modularization, however, might require new incentive structures for employees in the product creation process. Instead of maintaining a knowledge stock, the employees should be evaluated on how well they manage an incoming knowledge flow [144]. A second aspect of firm strategy impacted by modularity is relevant in industries that exhibit network effects. Since these industries tend to be winner-take-all markets, the standard setting role that must precede inter-firm modularization becomes strategically critical [131].

Most research that considers environmental considerations as relevant performance dimensions look for material similarity (to ease material recycling) and fast disassembly (to reduce disassembly costs and allow better product refurbishing). To facilitate recycling, Newcomb et al. [129] propose to determine modules by similarity measures concerning their material content. Kimura et al. [93] extend this idea by adding other life cycle considerations, such as maintenance and upgradeability in their approach to identify modules. Note that material similarity is only one out of several options for component, or module, similarity. For example, Kusiak and co-authors [74,99] suggest an algorithm to structure products in which one major driver is the 'suitability' for components to share the same module. What is suitable, of course, depends on the objective function.

A disassembly-related problem is addressed by Kim et al. [90]. Assuming the existence of common components across members of a product family and the demand for these items, they develop an algorithm to optimize the scheduling of the products' disassembly. In another approach linking product retirement to production, Silver and Moon [149] study how the presence of common components that are convertible into end items – at an end-item specific cost – affects the optimal production and inventory plan. Approaching the reuse of components in the remanufacturing environment Ferrer and Whybark [37] develop a materials management system that takes part commonality into account, and Taleb et al. [162] present an algorithm for disassembly scheduling that applies to parts commonality and materials commonality. Finally, modularity can also enable more flexible return policies because it enables easier product refurbishing, an aspect considered increasingly relevant as shopping over the Internet increases [126].

3.3 Research Methods Employed in Modularity and Commonality Studies

The research methods that have been used to study the implications of modularity and commonality cover a broad set of approaches. They range from theory-building work, to frameworks and process models, to mathematical modeling and simulation, to experiments, empirical studies (both small-*n* and large-*n*), to reviews.

3.3 THEORY-BUILDING

Probably because it is much less straight forward to define modularity [42] than it is to define commonality, it is modularity who has received the bulk of theory-building attention. One type of theory-building for modularity focuses on the description of a product or system. For example, according to Schilling's [146] theory, the degree of a system's modularity is determined by the balance of the forces in four categories: product, input technology, demand, and competitive context. Similarly, Salvador et al. [142], based on an empirical study of six companies, propose a new type of modularity, combinatorial modularity, and suggest that this type of modularity is operationally effective if the demand for product variety is high. A second type of theory-building has been conducted by Baldwin and Clark [9]. They formulate the genesis of a system as the consequence of the application of one or more of six modular operators: splitting, substituting, augmenting, excluding, inverting, and porting.

3.3.2 CONCEPTS AND FRAMEWORKS

Concepts and frameworks tend to be mostly descriptive and qualitative in nature. They provide a way of thinking about modularity and commonality and their implications rather than ways to quantify their effects. These approaches often cover higher-level and long-term considerations. For example, Hofer and Halman [71,72] suggest to focus on the modularization of the layout of complex products and systems, rather than on modularizing products themselves. Another example is a taxonomy of modularity technology in manufacturing that covers both the determination of a modular architecture and the determination of a modular system configuration [11]. Two very influential frameworks were introduced through two books during the 1990s. One is the idea of mass customization, put forward by Pine [134]. The idea of mass customization is driven by the insight that a customer not necessarily wants product variety per se but rather his own version of a product, and that the production of the individualized product at near-mass production costs can be achieved via product modularity. The other influential idea, which is closely related to the first, is the concept of product platforms, elaborated by Meyer and Lehnerd [119]. They introduce how product platform strategies can be used to conquer new markets and expand old ones without developing entirely new products every time. In both works, modularity and commonality play a major role.

3.3.3 PROCESS MODELING

Process models are often multi-step procedures to conduct all or portions of the design process when designing products with modularity, commonality, platforms, or product families in mind. For example, Jiao and Tseng [78] present a detailed process to establish product families, and Germani and Mandorli [53] propose a procedure leading to self-configuring components in product architecture design. Another five-step model for product family design is presented by Farrell and Simpson [35]. They recommend to start with a market segmentation grid, then to specify factors and ranges, to build and validate metamodels, to aggregate product family and platform specifications, and finally to develop the product family. Yet a different approach to commonalize product subsystems has been suggested by Qin et al. [136]. They use actual data on critical parameters of existing products to construct similarity matrices which in turn enable cluster formation, i.e., common platform definition. In general, the engineering literature, and in particular text books, tend to provide detailed step-by-step advice on how to proceed when designing modular products and products with common components, e.g., [86, 170].

3.3.4 MATHEMATICAL MODELING

Various techniques have been used to mathematically model modularity and commonality. In particular, the optimization community in engineering design and in operations research and management has developed numerous models for, and applied to, the study of finding optimal degrees of modularity and commonality. For example, Fujita and Yoshida [46] develop an algorithm to simultaneously optimize module attributes and modular combinations. In their model, commonality is operationalized as a trichotomous variable, i.e., modules are either independent, similar, or common. Simpson and D'souza [151] suggest the use of deviation functions to increase commonality across the members of a product family. Genetic algorithms (GAs) have also been used to study the implications of modularity and commonality. For example, using GAs to reduce iterations during product development, Whitfield et al. [175] point out that the structure of the GA is implicitly linked to the specific application. Li and Azarm [109] use GAs to evaluate and select candidates from a set of potential product family members. For product families that vary in scale along some of their design parameters, Messac et al. [118] develop a product family penalty function to help select the parameters suited for scaling, and Kamrani and Gonzalez [85] develop a GA to create modular designs, in this case represented by a combinatorial search. Another way of selecting a feasible solution is the application of a scenario aggregation approach to a stochastic inventory problem with common components [82]. Finally, focusing more on the process rather than the product, Loch et al. [111] find that marginal local improvements in complex designs can cause much greater disruptions for the entire system. To prevent this problem, they promote a locally 'satisficing' approach instead of an optimizing one. In the product arena the application of the mathematical modeling approaches range from the design of logic controllers [62,177] to kinematic modeling of reconfigurable machine tools [124].

3.3.5 SIMULATION

Three types of simulations can be identified in the selected set of references. The first type is found in papers using mathematical modeling approaches that supplement and test their models with numerical simulations. For example, considering downward substitution in their multi-period model Rao et al. [137]

demonstrate the size of the inventory savings that their model predicts with simulation. Similarly, Dong and Chen [25] illustrate the impact of component commonality on order fill rate, delivery time, and total cost via simulation. A second type of simulation that has experienced a recent increase in popularity is agent-based modeling. A number of recent studies use agent-based modeling in the framework of complex-adaptive systems [88]. For example, Ethiraj and Levinthal [30] explore the performance effects of what they call under- and over-modularization. They find that over-modularization, i.e., a partitioning that is too fine, hurts performance more than under-modularization. Finally, a third type of simulation study uses real data to simulate effects of commonality. For example, Lin and co-authors [110] study the inventory reduction effects of different complexity reduction approaches, such as feature elimination, feature substitution, and feature postponement with data of a IBM midrange computer family with over 200 members and hundreds of feature codes.

3.3.6 EXPERIMENTS

A somewhat rare research method in the study of modularity and commonality is the use of experiments. One example is the study by Kim and Chhajed [92] in which they test the impact of parts commonality on customers' product valuation with the help of an experiment. Studying the effects of commonality in vertical-line extensions from both low-end and high-end products, they find that the use of commonality can increase the valuation of the low-end product but decreases the value of the high-end product. They recommend that firms consider this valuation change when considering commonality strategies.

3.3.7 EMPIRICAL STUDIES (LARGE-N)

Studies exploring the impact of modularity on business performance tend to employ indirect, perceptional measures, i.e., they ask managers about the degree to which their products can be customized [27,28,176]. The difficulty to operationalize modularity for a broader product set appears to cause both fairly indirect measures and only a small number of large-*n* empirical studies. Commonality and its effects have also been studied empirically. In their empirical study of the product-process matrix, Safizadeh et al. [140] find that parts commonality allows sustaining high plant performance despite violating the alignment between product and process.

3.3.8 CASE STUDIES (SMALL-N)

While many references analyzed for this study present small case studies to illustrate a newly developed framework or mathematical model, some articles exclusively present extensive case studies. For example, in his descriptive account of the project that an aircraft manufacturer co-develops with his suppliers, O'sullivan [132] demonstrates how design rules for modular design slowly emerge as social processes. An example for a case study using quantitative data is Sosa et al.'s [157] study of the development process of an aircraft engine. They constructed design structure matrices for the product and for the development process, and studied the degree of congruence between the matrices for different engine subsystems. In a follow-up study Sosa et al. [158] find that the mismatches between component interactions and team interactions are particularly likely between modular subsystems. The view that increasing component commonality in real organizations can actually be quite difficult due to the lack of downstream information and often misfitting incentive structures is supported through a couple of case studies by Nobelius and Sundgren [130].

3.3.9 REVIEWS

Review articles that the initial search identified covered a variety of topics, albeit all at least related to modularity or commonality. Browning [13] reviews the literature on design structure matrixes (DSMs), a tool helpful for exploring the effects of the structure, including modularity, of products and processes on their performance. In his review on the product platform literature Simpson [150] includes a discussion on optimization techniques developed for product platform assessment and development. In contrast, Jose and Tollenaere [83] present in their review a selection of more qualitative approaches of modular and platform methods. In their review of the modularity literature, Gershenson et al. [54] find that there is little precision on what modularity actually represents. They distill characteristics such as an element of independence between modules and an element of similarity within modules and state that benefits of modularity are claimed to be found across the entire product life cycle, although they find little evidence. Similarly, they find little consensus on modularity measures and modular design methods, particularly when the level of detail increases [55].

4. Looking Ahead: Charting New Territory for Modularity and Commonality Research

The growing literature body on modularity and commonality has produced significant discoveries of the product and process development landscape. The previous section provided a detailed overview of this landscape. The overview was structured along the dimensions subject, effect, and research method, and used individual references to illustrate the insights and findings. To identify the white spots that remain on this map it is helpful to look at the preferences and

Table 2. Distribution analysis of reference set.

	References by Search Term Association			
	Modularity	**Modularity & Commonality**	**Commonality**	**Total**
Reference count	75	17	76	168
Subjects				
Product	62	17	76	
Process	21	4	13	
Organization	16	1	0	
Innovation	8	0	0	
Average number of subjects/reference	1.43	1.29	1.17	1.30
Effects				
Quality	19	6	7	
Variety	19	12	7	
Cost	33	13	68	
Time	15	1	10	
Other	39	4	18	
Average number of performance measures/reference	1.67	2.12	1.45	1.61
Research Methods				
Theory-Building	5	4	0	
Framework	26	9	5	
Process Model	8	5	5	
Mathematical Model	20	4	61	
Simulation	6	0	6	
Experiment	0	0	2	
Empirical (large-*n*)	11	0	5	
Case Study (small-*n*)	21	10	8	
Review	5	1	0	
Average number of research methods/reference	1.36	1.94	1.21	1.35

distributions of the population of references across the landscape, both separately for the sets of references associated with either modularity or commonality, and for the population as a whole (Table 2). The three regions for future research that are suggested below are extracted from this analysis. Current changes in the economic environment provide additional motivation. The regions attractive for future research are concerned with the intersection of established research areas, the intersection of research methods, and the dynamics of change processes and learning.

4.1 Look at the Intersection of Established Areas

The top third of the first data column of Table 2 shows the number of references that are associated with the search term 'modularity' and that have as their subject focus product, process, organization, or innovation, or any combination thereof. For example, 21 references of this pool of 75 address process issues. Note that a reference can address more than one subject. The top third of the second and third columns shows the corresponding numbers for references that are associated with either both search terms, or only with the search term commonality, respectively. The analysis shows similar distributions across the subjects for both modularity and commonality research (as well as for the small overlapping contingent). References in all categories are focused strongly on products, followed by processes. References that focus on organizations and innovations are small in numbers and occur really only in the modularity cluster. While this prioritization itself is not surprising in a product and process development context, the fact that each reference focuses – on average – on only 1.30 subjects, is. In other words, the majority of the references identified for this analysis concentrates on a single subject. The current developments of industrial processes, however, point in the direction of increasing complexity. Many systems increase in complexity, primarily for two reasons: Increase of interconnections, and increase of customization. Industrial processes are increasingly interconnected in supply chains and production networks, and, consequently, the way to understand them better is to study them in their interconnectedness; products together with the processes to design, produce, sell, use, and recycle them; organizations together with their suppliers and their customers. The emergence of data management systems, such as enterprise resource planning (ERP) and product life cycle management (PLM) systems signals the direction in which most industries are progressing to handle this increase in interconnectedness. While the research community has made some steps to incorporate more aspects along the supply chain and across functions – for example, extending the idea of concurrent engineering scholars have begun to develop concepts and models to accommodate product, process, and supply chain variables simultaneously and to make the interactions between them visible [38,40,75] – much work still remains to be done.

The second reason for increasing system complexity is the increase in customization. From a producer's perspective this means that many more, but individually much smaller markets need to be served. Effects described in the 'Long Tail' story – initially mainly for entertainment [3] – seem to be appearing for other products as well. With falling costs of customization new but smaller markets will appear. This makes the linkages between marketing, engineering, and production even more relevant. Who wants which product feature customized, and for what price? Which components can be common; viewed from a variety of supply chain participants?

For companies to develop these concurrent enterprising capabilities Jiao and co-authors determine that '[t]he missing gap probably lies in the capacity to put the systems, involving organization, process, and business models, all together and make them customer driven' [77]. It seems that future research has a good chance of producing relevant insights by exploring the increasingly important intersections between subjects and between functions. One major requirement for the development of models and frameworks that can cope with this increasing complexity is the simultaneous consideration of multiple performance measures, i.e., effects. In the set of references reviewed here each reference considers – on average – only 1.61 performance measures. Interestingly, the commonality research is dominated by a focus on cost, in large part due to the substantial literature body on the inventory cost effects through commonality. In contrast, modularity research is more evenly distributed across the different performance measures (Table 2 – second section). In either case, however, to improve trade-off decisions in increasingly complex and interconnected systems will require to substantially increase the number of effects that are considered simultaneously.

4.2 Look at the Intersection of Methods

The analysis of research methods employed by the set of references illustrates both an uneven and singular use of individual methods. The research methods used to study the phenomenon modularity are to a large degree different from those investigating the phenomenon commonality. Commonality is overwhelmingly studied with mathematical models, whereas modularity tends to be examined more with frameworks and small-*n* case studies (Table 2 – third section). Interestingly, in the modularity cluster the number of frameworks (26) far outnumbers the relatively small number of large-*n* empirical studies (11). This suggests that the operationalization of modularity across products and industries is still difficult, which in turn presents a promising research challenge.

Across both clusters, each reference applies – on average – only 1.35 methods. Just as the above discussion hinted at promising regions for future research at the intersection of established functional areas, it appears as if there is great potential for new insights by clever combinations of research methods. A good example of research that strives to explain the reasons for and the extent of parts commonality with both modeling and empirical work is Fisher et al.'s [39] study on automotive break rotors. These multi-method research approaches offer not only the potential for new theoretical insights but also for the development of practical tools. For example, it is conceivable that the integration of aspects of organizational dimensions into process and simulation models can help to develop robust models that practitioners can use to run their organizations. A recent review on process models in product development calls for process models that allow a better assessment of real-time changes and their implications to be useful for people making the day-to-day decisions [14]. Explorations of the multi-method white spots carry the opportunity to fill this gap.

4.3 Look for Evolution and Learning

The third region that offers promising research opportunities is represented by longitudinal studies. Both modularity and commonality have been studied mostly in static situations, i.e., conditions are identified in which one type of modularity is superior to another, or in which commonality is superior to non-commonality while all other conditions are held constant. In reality, however, no system is really static. Products change, processes evolve, organizations adapt, and innovations appear, and all of these changes are accelerating. All of the above changes influence each other; but in which way do the causalities run? Are modular products causing organizations to be modular [70], or vice versa? Early empirical studies find a mixed picture. Modularization developments can be uneven across components and uneven across supply chain levels [43]. Future work should try to understand better the dual role of engineering products and processes as decision variables on one hand, and as constraints on the other.

Paying attention to change processes also will help to develop a better understanding of the associated learning processes. Earlier work [49] suggests that modularity-in-design is associated with learning by studying, modularity-in-production with learning by doing, and modularity-in-use with learning by using. If this holds true, one would expect to see different learning rates and directions by different participants in the supply chain. Some researchers have directed their attention to the effects of product modularity on organizational learning, both within firms [4] and between firms [120]. But the effect might also run the other way. Schilling [146] suggests that, for example, advances in scientific understanding can increase modularity. It seems that learning can be both cause and effect of modularity and commonality in products and processes. This question presents another rich opportunity for research explorations.

5. Conclusions

In this study over 160 references on modularity and commonality have been reviewed with respect to the subjects they have studied, the performance effects they have investigated, and the tools they have applied in doing so. The field as a whole has been growing substantially over the last 15 years without showing a slowdown. Most of the references have selected products as their focus, followed by smaller numbers of references focusing on processes, organizations, and innovations. The references have studied a range of implications of modularity and commonality in product and process development, by far dominated by the performance measure cost, particularly in commonality research. Overall, the set of references has applied a broad range of research approaches to its research questions. However, the methods profile for modularity research differs significantly from the one for commonality research.

Future research opportunities have been identified by bridging subjects, implications, and research methods, and by conducting studies over time. Both researchers and practitioners can benefit from conducting such cross-disciplinary research applying multiple methods. The increasing interconnectedness of people, products, processes, and organizations, and the increasing degrees of product customization will continue to make the questions concerning modularity and commonality an interesting field of research that can be both rigorous and relevant.

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Appendix A: Data Set Construction

To construct the data set for the analysis in this study a four-step procedure has been followed. First, an extensive list of relevant academic journals was developed. This list of journals encompasses 36 English-language journals, half from the engineering domain, half from the management domain.[1] These journals cover a wide range of topics, such as design, manufacturing, operations, management, organization, and strategy. The net was cast purposefully wide to ensure a comprehensive coverage of the literature that is relevant for 'managing modularity and commonality in product and process development,' as the call for papers for this issue requested.

In a second step, a search was conducted in all 36 journals, using the ISI Web of Science database which includes the Science Citation Index, the Social Science Citation Index, and the Arts and Humanities Citation Index. The search covered over 35 years of publications 1971–2005.[2] The search terms used were 'modularity' and 'commonality.' The ISI Web of Science system searches for these terms in title, keywords, and abstract of the articles. The initial search resulted in 102 hits for 'modularity' and 106 for 'commonality.' Of these 208 references 14 were 'doubles,' i.e., these articles were identified by the search using the search term 'modularity' and by the search using the term 'commonality.' This overlap of references was surprisingly small (14 out of 194 articles, i.e., 7.2%).

[1]In Table 1, the journals are listed in two categories, one for engineering journals, the other for management journals. While for some journals an association to either category could have been justified, particularly for the operations journals, for most of the journals the assignment to one of the categories is rather straightforward.
[2]The searched timeframe was actually much larger. The three in the ISI Web of Science database included indices cover 106 years (Science Citation Index Expanded: 1900-present), 50 years (Social Sciences Citation Index (SSCI): 1956-present), and 31 years (Arts & Humanities Citation Index (A&HCI): 1975-present) of publications. The earliest reference found by the search, however, was from 1971.

The third step constituted the removal of all references from the list that were caught by the initial search procedure but that did not touch modularity or commonality in a product and process development context, or only tangentially. For example, in the 'modularity' column papers were removed that used modularity to describe an abstract type of innovation [3] or the logic of face-to-face joined cubes for a shape recognition program [9]. The 'commonality' search caught articles that used the word 'commonality' to describe non-engineering events, such as the commonality of objectives across federal and state governmental innovation policies [10] or the commonality across goods and services [1]. Finally, all references that reviewed other individual works, e.g., book reviews, or were communications between researchers, e.g., comments and responses to comments were excluded. In total, 38 references were removed.

In a fourth step, 12 references were added to the list. In five cases these were references that were widely cited in the community working on the topics of modularity and communality (but not caught in the initial search because they do not contain either search term in title, abstract, or keyword list).[3] The remaining seven references are books. These books are either widely known text books for product development and product design classes [4,6,8], or they are books that have established important ideas in which modularity and commonality play a central role, for example mass customization [7], product platforms [5], or modularity itself [2]. The final list contains 168 references; 92 of those are associated with modularity and 93 are associated with commonality (which means 17 references are associated with both modularity and commonality). Table 1 provides the details of the data set construction process.

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[3] An example is the 1990 ASQ article by Henderson and Clark on Architectural Innovation that had been cited 612 times as of May 2006 but was not caught by the original search.

Appendix B: Data Tables.

	Source Information		Search Results		Subjects				Analysia Results: Performance Effects					Analysia Results: Research Methodologies									
No	**Author(s)**	**Year**	**Modularity**	**Commonality**	**Product**	**Process**	**Organization**	**Innovation**	**Quality**	**Variety**	**Cost**	**Time**	**Other**	**Theory-Building**	**Framework**	**Process Model**	**Math. Modeling**	**Simulation**	**Experiment**	**Empirical (large n)**	**Case Study (small n)**	**Review**	**Notes: Product/Industry/Application**
1	Akcay and Xu	2004		1	1						1						1						Non-product specific assemble-to-order systems
2	Alfaro and Corbett	2003		1	1						1						1				1		Chemical films for the automotive industry
3	Anderson and Parker	2002	1		1						1		1				1						Automobiles as examples
4	Baker et al.	1986		1	1						1						1						Non-product-specific inventory model
5	Balakrishnan and Brown	1996		1	1	1					1						1				1		Aluminum tube manufacturing
6	Balakrishnan et al.	1996		1	1						1						1						Non-product-specific assemble-to-forecast systems
7	Baldwin and Clark	1997	1		1	1				1	1				1								Examples from computer and auto industries
8	Baldwin and Clark	2000	1		1		1	1					1	1			1				1		Computer
9	Bartezzaghi and Verganti	1995		1	1	1							1				1						Telecommunication equipment
10	Bi and Zhang	2001	1		1	1				1	1	1			1							1	Several conceptual products as descriptions
11	Blackburn et al.	1996	1		1				1		1	1			1								Software
12	Browning	2001	1		1	1	1				1	1	1		1							1	Automobile climate control
13	Cetin and Saitou	2004	1	1	1				1	1	1					1	1				1		Bicycle frame example
14	Cetin and Saitou	2004	1		1				1	1	1					1	1				1		Automotive space frame
15	Cetin and Saitou	2005	1		1				1	1	1					1	1				1		Automotive space frame
16	Cheung	2002		1	1						1						1						Non-product-specific inventory model
17	Cheung and Hausman	1995		1	1						1						1						Aircraft engine repair
18	Choobineh and Mohebbi	2004		1	1						1	1	1					1					Non-product-specific inventory (kit preparation) model
19	Collier	1982		1	1						1						1						Non-product-specific inventory model
20	Desai et al.	2001		1	1				1	1	1						1						Model balancing cost savings and revenue decrease; examples from the auto industry
21	Deshpande et al.	2003		1	1						1						1						Non-product-specific inventory model
22	Djelic and Ainamo	1999	1				1						1								1		Luxury fashion industry
23	Dong and Chen	2005		1	1						1				1			1					Non-product-specific supply chain model
24	Du et al.	2001	1	1	1					1	1			1		1					1		Power supplies
25	Duray	2004	1		1								1							1			Manufactured products
26	Duray et al.	2000	1		1								1							1			Manufactured products
27	Ethiraj and Levinthal	2004	1		1		1						1					1					Non-product-specific simulation study
28	Ethiraj and Levinthal	2004	1		1	1			1									1					Microchip
29	Evans	1963	1		1					1	1						1						Screw assortment for creating kits
30	Eynan and Fouque	2003		1	1						1						1						Non-product-specific demand reshape model
31	Eynan and Rosenblatt	1996		1	1						1						1						Non-product-specific Inventory Model
32	Farrell and Simpson	2003		1	1						1	1				1							Yokes used to mount valve actuators
33	Fellini et al.	2005		1	1				1		1						1						Automotive body side frame
34	Ferrer and Whybark	2001		1	1						1		1				1				1		Automobile component remanufacturing

35	Fine et al.	2005	1		1	1	1				1	1					1						High-level example from the auto industry
36	Fisher et al.	1999		1	1					1	1						1			1			Automotive Brakes
37	Fixson	2005	1	1	1								1		1						1		Automotive Doors
38	Fleming and Sorenson	2001	1					1	1						1								Walkman as illustration
39	Fleming and Sorenson	2001	1					1	1											1			Patents
40	Fujita and Yoshida	2004		1	1				1		1						1	1					Family of aircrafts
41	Galvin	1999	1		1			1		1			1		1						1		Bicycles
42	Garud and Kumaraswamy	1995	1		1		1				1	1		1	1								Microcomputers, automobiles as examples
43	Garud and Kumaraswamy	1996	1		1								1		1								Object-oriented programming; automobiles
44	Gerchak and He	2003		1	1						1						1						Non-product-specific inventory model
45	Gerchak and Mossman	1992		1	1						1						1						Non-product-specific inventory model
46	Gerchak et al.	1988		1	1						1						1						Non-product-specific inventory model
47	Germani and Mandorli	2004	1		1								1			1							Woodworking machines
48	Gershenson et al.	2003	1		1					1	1											1	Examples from the automobile industry as illustrations
49	Gershenson et al.	2004	1		1						1		1									1	Discussion of mostly conceptual modularity measures
50	Gray et al.	1993		1	1	1					1				1								Machine tools
51	Gunther et al.	1998		1	1	1						1					1				1		Printed circuit boards
52	Gupta and Krishnan	1998		1	1	1					1						1						Assembly-sequence model (including industrial assembly as example)
53	Gupta and Krishnan	1999		1	1						1						1						Data acquistion products
54	Ha	1997		1	1						1						1						Non-product-specific inventory model
55	Ha	2000		1	1						1						1						Non-product-specific inventory model
56	Hanisch et al.	1997	1		1	1			1								1						Logic Controllers
57	Hausman et al.	1998		1	1						1	1					1						Non-product-specific multi-item inventory system with dependent item demands
58	Helfat and Eisenhardt	2004	1				1						1		1						1		Manufacturer of electronic instrumentation, computing, and information technology
59	Henderson and Clark	1990	1		1				1				1		1						1		Photolithography Alignment Equipment
60	Hill et al.	1997		1	1						1						1		1				Non-product-specific inventory model
61	Hillier	2000		1	1						1						1						Non-product-specific inventory model
62	Hillier	2002		1	1						1						1						Non-product-specific inventory model
63	Hillier	2002		1	1						1						1						Non-product-specific inventory model in assemble-to-order system
64	Hofer and Halman	2004	1	1	1					1	1				1						1		Postprint Management Systems, Electro-locomotives, Wires and Cable
65	Hofer and Halman	2005		1	1					1	1				1						1		Postprint Management Systems, Electro-locomotives, Wires and Cable
66	Holtta and Otto	2005	1		1						1	1				1							Gas Sensor
67	Huang and Kusiak	1998	1		1								1			1	1						Desk Lamp/Electric Motor
68	Huang et al.	2005	1	1	1	1					1						1						Notebook assembly as illustration
69	Hui	2004		1	1								1				1			1			Computers
70	Jiao and Tseng	1999	1	1	1				1	1	1					1					1		Power supplies
71	Jiao and Tseng	2000		1	1	1					1		1		1		1						Power supplies
72	Jiao et al.	2000		1	1	1				1	1		1			1							Customized souvenir clock manufacturing
73	Jones	2003	1		1								1							1			Telecommunication switches
74	Jonsson et al.	1993		1	1						1						1						Non-product-specific inventory model
75	Jose and Toolenaere	2005	1		1					1	1											1	Examples from the automobile industry as illustrations
76	Kamel et al.	1994		1	1	1					1		1				1						Non-product-specific machine assignment model

(*Continued*)

Appendix B: Continued.

	Source Information		Search Results		Subjects				Analysia Results														
									Performance Effects					Research Methodologies									
No	Author(s)	Year	Modularity	Commonality	Product	Process	Organization	Innovation	Quality	Variety	Cost	Time	Other	Theory-Building	Framework	Process Model	Math. Modeling	Simulation	Experiment	Empirical (large n)	Case Study (small n)	Review	Notes: Product/Industry/Application
77	Kamrani and Gonzalez	2003	1		1				1								1				1		Gear reducer
78	Kamrani and Salhieh	2002	1		1				1	1	1				1	1							Four-gear speed reducer
79	Kaski and Heikkila	2002	1		1						1							1			1		Cellular network base stations
80	Kaya and Alhajj	2004	1			1						1	1				1						Robot controller
81	Kim and Chhajed	2000	1	1	1				1	1	1						1						Model balancing cost savings and revenue decrease; examples from the auto industry
82	Kim and Chhajed	2001		1	1				1		1								1				Bicycles
83	Kim et al.	2003		1	1						1		1				1						Ink jet printers
84	Kimura et al.	2001		1	1								1			1					1		Automotive air conditioner unit
85	Kodama	2004	1		1								1							1			Computers, Automobiles
86	Kota et al.	2000	1	1	1								1		1						1		Walkman
87	Krishnan and Gupta	2001		1	1						1						1						Data processing equipment as an example
88	Kulkarni et al.	2005		1	1	1					1						1						Non-product-specific plant network configuration model
89	Kumar	2004	1		1								1		1								Computer family
90	Kusiak	2002	1		1	1					1		1		1								Non-product-specific modularization models
91	Kusunoki et al.	1998	1				1		1		1		1		1					1			Various materials and systems industries
92	Langlois and Robertson	1992	1		1			1		1	1		1	1							1		Stereo systems, Microcomputers
93	Lee	1996		1	1	1					1	1	1				1				1		Printers
94	Lee and Whang	2002		1	1						1						1						Electronic market exchanges as illustration
95	Lee and Zipkin	1995		1	1						1						1						Non-product-specific inventory model
96	Leger and Morel	2001	1			1							1			1					1		Hydropower plants
97	Lei	2000	1		1			1		1					1								Various products as examples; none directly in the section on modularity
98	Lei	2003	1		1					1			1		1								Computers & consumer electronics as examples
99	Li and Azarm	2002		1	1						1		1				1						Cordless screw driver
100	Lin et al.	2000		1	1						1						1	1		1			Computer family
101	Loch et al.	2001	1		1						1	1					1						Door lock mechanism as an example
102	Loch et al. 2003	2003	1		1	1						1	1				1	1					Non-product-specific product development model
103	Loh and Taylor	1994		1	1	1					1	1						1					Printed circuit board assembly
104	Lu and Song	2005		1	1						1						1						Non-product-specific inventory model for assemble-to-order systems
105	Ma et al.	2002		1	1						1	1					1						Non-product-specific inventory model
106	Maimon et al.	1993		1	1						1						1						Printed circuit board assembly
107	Majumdar	1997	1		1					1										1			U.S. Telecommunication
108	Messac et al.	2002		1	1	1			1		1						1						Family of electric motors

109	Meyer and Lehnerd	1997	1	1	1					1	1				1							Electric Iron; Power tools
110	Mikkola	2003	1		1						1		1							1		Windshield wiper control module
111	Mikkola and Gassmann	2003	1	1	1								1				1			1		Traction and hydraulic elevators
112	Miozzo and Grimshaw	2005	1		1	1		1	1		1		1							1		IT Outsourcing
113	Mirchandani and Mishra	2002		1	1						1		1				1					Non-product-specific inventory model
114	Moon and Kota	2002	1			1							1				1					Machine tools
115	Muffatto and Roveda	2000	1	1	1	1				1	1				1					1		Automobiles, earth moving equipment, houshold appliancees
116	Mukhopadhyay and Setopu	2005	1		1				1		1		1				1					Non-product-specific model to explore return policies in build-to-order environments
117	Nambisan	2002	1		1								1						1			Software
118	Nelson et al.	2001		1	1				1													Nail gun
119	Newcomb et al.	1998	1		1								1				1			1		Automobile center console
120	Nobelius and Sundgren	2002		1	1						1									1		Automotive, White Goods, Printers
121	O'Grady	1999	1		1					1	1		1		1							Computer/Appliance
122	O'Sullivan	2003	1		1	1						1								1		Aerospace product
123	PahlandBeitz	1996	1	1	1				1	1	1			1	1	1						Gearboxes
124	Pine	1993	1	1	1					1	1				1							Lighting controls
125	Pulasinghe et al.	2004	1			1						1	1				1					Controller drivern by spoken language commands
126	Qin et al.	2005		1	1	1							1			1			1			Girder pumps (for oil extraction)
127	Rao et al.	2004		1	1						1						1	1				Non-product-specific inventory model
128	Robertson and Ulrich	1998		1	1					1	1				1							Automotive instrument panel
129	Rutenberg	1971		1	1					1	1						1					Example of automobile engine and drivetrain combination
130	Safizadeh et al.	1996		1	1						1								1			Empirical study across various manufacturing industries
131	Salhieh and Kamrani	1999	1		1				1						1							Four-gear speed reducer
132	Salvador et al.	2002	1	1	1								1	1						1		Smal motorocycles, custom phones, microwaves, trucks, multiplexers, techovens
133	Salvador et al.	2004	1	1	1	1	1			1	1	1		1	1					1		Smal motorocycles, custom phones, microwaves, trucks, multiplexers, techovens
134	Sanchez	2000	1		1	1				1	1	1	1		1							Inkjet printer as an example
135	Sanchez and Mahoney	1996	1		1		1						1	1	1							Aircraft, automobiles, consumer electronics as examples
136	Schilling	2000	1		1		1			1	1			1								Stereo systems, Textbooks, Computers
137	Schilling and Steemsma	2001	1			1	1						1						1			different manufacturing industries
138	Siggelkow and Levinthal	2003	1		1		1		1									1				Non-product-specific simulation study
139	Silver and Moon	2001		1	1						1		1				1					Refurbishing of telefon equipment
140	Simpson	2004	1	1	1				1	1	1										1	Various products as examples
141	Simpson and D'Souza	2004		1	1								1				1					Small aircraft (to 6-seater)
142	Simpson et al.	2001		1	1				1				1				1					Small aircraft (2 to 6-seater)
143	Sinha and VandeVen	2005	1				1			1	1				1							Examples from a variety of industries
144	Smith and Agrawal	2000		1	1						1						1					Retail
145	Song	1998		1	1						1	1					1					Non-product-specific inventory model
146	Song 2002	2002		1	1					1	1						1					Non-product-specific inventory model
147	Sosa et al.	2003	1		1		1						1							1		Aircraft engine
148	Sosa et al.	2004	1		1		1		1						1					1		Aircraft engine
149	Starr	1965	1		1					1	1				1							Abstract examples from the auto industry
150	Staudenmayer et al.	2005	1		1	1			1											1		Seven firms from the telecommunications technology industry
151	Swaminathan and Tayur	1998		1	1						1	1					1					Computer product line as illustration

(*Continued*)

Appendix B: Continued.

Source Information			Search Results		Subjects				Analysis Results: Performance Effects					Analysis Results: Research Methodologies									
No	**Author(s)**	**Year**	**Modularity**	**Commonality**	**Product**	**Process**	**Organization**	**Innovation**	**Quality**	**Variety**	**Cost**	**Time**	**Other**	**Theory-Building**	**Framework**	**Process Model**	**Math. Modeling**	**Simulation**	**Experiment**	**Empirical (large n)**	**Case Study (small n)**	**Review**	**Notes: Product/Industry/Application**
152	Taleb et al.	1997		1	1						1		1			1							Non-product-specific disassembly model
153	Tang	1992		1	1						1						1						Non-product-specific production model
154	Thomas	1991		1	1						1						1						Space station water tank
155	Thonemann and Brandeau	2000		1	1						1						1						Automotive wire harness
156	Tibben-Lembke and Basso	2005		1	1						1	1					1						Non-product-specific inventory model
157	Tsai and Wang	1999	1		1						1	1					1						Automated guided vehicles (AGV)
158	Tsai et al.	2003	1		1						1						1						Hydraulic squeezing machine
159	Ulrich	1995	1		1				1	1	1				1								Abstract trailer as example
160	Ulrich and Eppinger	2000	1	1	1	1			1	1	1				1	1							Printer cartridge
161	Upton and McAfee	2000	1			1							1		1						1		ERP systems
162	Van Mieghem	2004		1	1						1		1				1						Non-product-specific model balancing cost and revenue effects of common components
163	Vergantiand Buganza	2005	1		1	1					1		1								1		Two internet service firms
164	Watanabe and Ane	2004	1		1	1						1						1					Automobiles
165	Whitfield et al.	2003	1			1						1					1						Non-product-specific product development model
166	Worrenetal.	2002	1		1								1							1			Home appliances
167	Xu and Van Brussel	1998	1		1				1						1		1				1		Logic controller of AGVs
168	Zhang and Gershenson	2003	1		1						1					1				1			Several small consumer products (flashlight, coffeemaker, etc.)

Sebastian Fixson

Sebastian Fixson received the degree of Diplom-Ingenieur (M.S.) in mechanical engineering from University of Karlsruhe, Germany, and the PhD degree in Technology, Management, and Policy from Massachusetts Institute of Technology, Cambridge, MA.

After graduation from MIT he joined the faculty of the Industrial and Operations Engineering department at the University of Michigan, and is currently Visiting Assistant Professor at the MIT Sloan School of Management. His research interests include technology and innovation management and operations management in the product development context. In his recent research he focuses on the intersection of technical design decisions, such as modularity and product architecture, and organizational design decisions, such as process structure and granularity, and their joint effects on both strategic and operational performance.

His work has appeared in books and journals including *Journal of Operations Management, IEEE Transactions on Engineering Management*, and *Technological Forecasting and Social Change*. He is a member of the Academy of Management, IEEE, INFORMS, and POMS. He has served as vice chair communications and program chair, and is currently chair of the Technology Management Section at INFORMS.