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Modularity, product variety, production volume, and component sourcing: theorizing beyond generic prescriptions

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Abstract

Research in operations management suggests that firms can mitigate the negative impact of product variety on operational performance by deliberately pursuing modularity in the design of product family architectures. However, modularity is not a dichotomous property of a product, as different types of modularity can be embedded into a product family architecture. The present paper explores how manufacturing characteristics affect the appropriate type of modularity to be embedded into the product family architecture, and how the types of modularity relate to component sourcing. The study is based on a qualitative research design involving a multiple case study methodology to examine six product families belonging to six European companies. The themes derived through case analyses are synthesized in the form of empirical generalizations. Insights from these empirical generalizations are subsequently developed into two propositions explaining why and under what conditions these empirical generalizations might hold for a product family outside of the original sample. The theoretical results formalize, first of all, a type of modularity (i.e. combinatorial modularity) not currently described in literature. Second, the theoretical propositions suggest that when the desired level of product variety is low (high) relative to total production volume, component swapping modularity (combinatorial modularity) helps to maximize operational performance. Finally, the complexity of component families outsourced to suppliers and the geographical proximity of component family suppliers affect the extent to which the product variety–operational performance trade-off can be mitigated through modularity.

Keywords: Case study research; Product variety; Sourcing; Modularity; Supply chain management; Operational performance

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1. Introduction

In an effort to better respond to heterogeneous customer needs, many firms find it appropriate to increase product variety, i.e. the number of different products offered to customers (Pine II, 1993). In doing so, firms are convinced that they maximize the fit between product offerings and customer desires, which can allow them to defend, if not increase, their market shares. While this conscious decision might allow a firm to better align what it offers in the market to customer requirements, such a decision tends to also present the firm with a number of challenges with respect to the performance of its operations. In fact, as product variety increases, a firm would experience lower performance of its internal operations because of higher direct manufacturing costs, manufacturing overhead, delivery times, and inventory levels (Anderson, 1995; Child et al., 1991; Fisher and Ittner, 1999; Flynn and Flynn, 1999; Forza and Salvador, in press; Kotteaku et al., 1995; Miller and Vollmann,

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1985; Prasad, 1998). Likewise, as product variety increases, there would likely be an increase in the variety of at least some purchased product components (Fisher et al., 1999), especially when vertical integration is low. Consequently, suppliers may experience diseconomies due to component variety, with potential negative impact on component prices, delivery times, and component inventory levels (Krishnan and Gupta, 2001; McCutcheon et al., 1994). From the firm's perspective, therefore, a trade-off exists between product variety and operational performance, which includes, in this study, performance of its internal operations, as well as its component sourcing performance.

Both research and practice commonly suggest that firms may mitigate this trade-off by deliberately pursuing modularity in designing their final product architectures, which obtains final product configurations by mixing and matching sets of standard components (Starr, 1965). At the crux of this suggestion, is the notion that modularity permits firms to increase product variety without incurring substantial negative impact on operational performance.

This notion has encouraged, at least, two parallel streams of research, with one stream in the operations management/management science domain (Erens and Verhulst, 1997; Feitzinger and Lee, 1997) and the second in the design theory/engineering management domain (Huang and Kusiak, 1998; Pahl and Beitz, 1984). While research in operations management/management science has generally leaned towards understanding how internal operations change, or should be managed, when firms modularize their product architectures, research in design theory/engineering management has focused more centrally on the issues of how to formally define what a modular product is, how a product architecture can, or should be modularized, and how design activities change, or should be managed, in the design of modular products.

While both operations management/management science research and design theory/engineering management research have contributed substantially to current comprehension of how and why product modularity may alleviate the product variety–operational performance trade-off, one limitation is that only sporadic attempts have been made to integrate results across the two domains for richer theoretical and pragmatic insights (He et al., 1998; Ulrich, 1995). As such, we have an opportunity to bridge these two research streams and to respond to the growing awareness of the interdependence between product design and operations strategy (Fine, 1998; Hoekstra and Romme, 1992).

In this research, we aim to extend our understanding of how the product variety–operational performance trade-off can be reduced by borrowing from the design theory/engineering management discipline the fundamental argument that different "types of modularity" can be embedded into a product family architecture. More precisely, we develop, articulate, and justify a set of theoretical propositions explicating the conditions that make a given type of modularity better than another, in reducing the product variety–operational performance trade-off. To this end, we first review, in Section 2, pertinent literature related to the issues under investigation. We then describe, in Section 3, the qualitative research design involving a multiple case study methodology. In Section 4, we present brief profiles of each case, highlighting how the product variety–operational performance trade-off is manifested for the product families included in our study. We devote Sections 5 and 6 to report the results of across-case analyses. Section 5 describes and defines a type of modularity that we observed from our sampled product families, and which is not currently present in published typologies. Section 6 reports a set of empirical generalizations relating the types of modularity to product variety to component sourcing. In Section 7, we articulate and justify theoretical propositions drawing on the insights from the empirical generalizations. We conclude in Section 8 with suggestions for theory and practice.

2. Background

Researchers and practitioners alike have sought, for a long time, to identify interventions to reduce the product variety–operational performance trade-off. Among many suggestions, one commonly considered intervention revolves around modular product design, or simply, modularity. The basic idea behind modularity is to "... design, develop, and produce ... parts which can be combined in the maximum number of ways" (Starr, 1965, p. 38), thereby enhancing the compatibility between product variety requirements and operational performance for discrete products (Hoekstra and Romme, 1992; Karmarkar and Kubat, 1987). Research on how to reduce the product variety–operational performance trade-off through modularity in the design of products can be further classified into one of the two disciplinary areas: operations management/management science and design theory/engineering management.

2.1. Modularity research in operations management/management science

In general, operations management/management science research has treated modularity as a means to increase commonality across different product variants within a product family, i.e. to allow for the same component(s) to be used in multiple product variants, and when feasible, in all product variants (Evans, 1963). As such, one motivation underlying the operations management research stream has been to understand the benefits of component commonality on operational performance, as well as the various factors that might affect these benefits (Baker et al., 1986; Collier, 1981; Fisher et al., 1999; Karmarkar and Kubat, 1987; Mather, 1986; Sheu and Wacker, 1997; Vakharia et al., 1996).

In addition, research in operations management/management science has highlighted that modularity in product design may allow for the design of a loosely coupled production system in which different subassemblies can be made independently, and then rapidly assembled together in different ways, given technical constraints, to build the final product configurations (Ernst and Kamrad, 2000; Novak and Eppinger, 2001). One important consequence of this increased flexibility in the allocation of manufacturing tasks, as many scholars have observed, is that firms can more effectively pursue a postponement strategy (Feitzinger and Lee, 1997; Lee and Tang, 1997; Mather, 1986; van Hoek, 2001; van Hoek and Weken, 1998).

2.2. Modularity research in design theory/engineering management

While research in operations management tends to treat modularity as given, one primary focus of modularity research in design theory/engineering management is epitomized by the question of how to implement modularity into the design of product families with multiple variants (Erens and Verhulst, 1997; Erixon, 1996; Gonzalez-Zugasti et al., 2000, Huang and Kusiak, 1998; Jiao and Tseng, 1999; Parnas, 1971; Parnas et al., 1985; Stevens et al., 1974). The motivating perspective underlying this research pursuit is the realization that a modular product family architecture, by mapping specific functional requirements to specific product components, facilitates design activities. Accordingly, changes in a specific functional requirement would affect only a given product component and not the entire product family architecture (Huang and Kusiak, 1998; Pahl and Beitz, 1984; Suh, 1990; Ulrich, 1995), and would, therefore, ease product configuration activities both in the design and in the manufacturing realms.

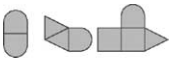
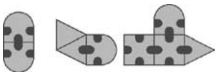
Furthermore, research in design theory/engineering management has explored the properties a modular product family may display, implicitly suggesting that there are different types of modularity (see Table 1). Pahl and Beitz (1984) hinted at multiple properties that may differentiate a module from another, exploring in particular the notion of module function, distinguishing between basic, special, and adaptive modules. Ulrich and Tung (1991) proposed a classification for types of modularity based on the geometric configurations of a product family architecture. In fact, their typology captures different possible approaches to combining modules, distinguishing between variant and common modules. Ulrich (1995), more recently, proposed a typology that relied on the property of the interface among modules as the classification criterion.

Finally, we should note that modularity research in design theory/engineering management has also been conducted for reasons unrelated to product variety. For example, research in this domain has sought to decompose complex design problems into more easily manageable sub-problems (Baldwin and Clark, 2000 von Hippel, 1990; Sundgren, 1999) or to investigate the impact on product performance (Kusiak and Huang, 1996).

2.3. Synthesis

Although, modularity research in the two domains has mostly advanced independently of one another (Swaminathan and Tayur, 1999), there have been some

Table 1
Typologies of modularity

References	Classification criterion		Types of module/modularity
Pahl and Beitz (1984)	Stability of the function allocated to the component		Basic and auxiliary modules implement functions that are common throughout the product family
			Special modules implement complementary and task-specific functions that do not need to appear in all the product variants
			Adaptive modules implement functions related to the adaptation to other systems and to marginal conditions
Ulrich and Tung (1991)	How the final product configuration is built		Component swapping modularity: product variants are obtained by swapping one or more components (▷, ◗, ■) on the common product body (▬)
			Fabricate-to-fit modularity: product variants are obtained by changing a continuously variable feature (▭, ▭, ▭) within a given component
		 	Bus modularity: product variants are obtained by matching any selection of components from a set of component types (▷, ◗, ■) with a component that has two or more interfaces (▬)
			Sectional modularity: product variants are obtained by mixing and matching in an arbitrary way a set of components (▷, ◗, ■), as long as they are connected at their interfaces
Ulrich (1995)	Nature of the interface between components		Slot modularity: interfaces between different components are different (⊏, ⊂)
			Sectional modularity: all the components are connected via identical interfaces (╪)
		 	Bus modularity: special case of sectional modularity where there is a single component, the bus (┷━┷━┷━┷━┷), performing the connection function

recent attempts to bring the two domains together. Some of these attempts have generated theoretical discussions on the interdependencies between product design and manufacturing decisions in planning product families with multiple variants (Erens and Verhulst, 1997; Forza and Salvador, 2002a; Ishii et al., 1995; Shirley, 1990; Ulrich, 1995). Others have adopted a more quantitative orientation, developing algorithms and procedures for designing modular product families while considering manufacturing constraints (Garg, 1999; Gupta and Krishnan, 1999; He et al., 1998; Krishnan and Gupta, 2001; Krishnan et al., 1999; Raman and Chhajed, 1995). With the exception of Duray et al. (2000), none of the published researches bridging product design and operations management issues attempted to develop insights on the implications of implementing different types of modularity on the product variety–operational performance trade-off. Neither has there been any attempt to discuss the conditions under which a given type of modularity may be more appropriate than another, provided that they are viable.

The present research aims to fill this gap in the literature. First, our intent is to understand, whether or not the type of modularity that should be embedded into a product family architecture relates to key manufacturing variables from the product–process matrix (Hayes and Wheelwright, 1984), namely, product variety level (i.e. the number of final product variants within a given product family) and production volume (i.e. total yearly production output of the product family), and how these relationships affect the operational performance (e.g. inventory, delivery times, manufacturing overhead costs, etc.) of the production system assembling the product family. Our first research question, as such, can be stated as follows.

> What are the relationships, if any, among the types of modularity, product variety level, production volume, and operational performance within a given product family?

Second, as previously observed, since product variety tends to affect component suppliers as well, especially when vertical integration is low, and, therefore, demands increased flexibility from the supply chain, we intend to explore a second related question as follows.

> Given the decision to allocate to suppliers the making of components that come in multiple variants, how is the type of modularity embedded in the product family architecture related to the final assembler's component sourcing performance [e.g. component inventories and sourcing lead-times] and, more generally, operational performance?

3. Research design

To develop theoretical and pragmatic insights into the researched problem, we employed a qualitative research design involving six case studies. The multiple case study approach, as noted by Eisenhardt (1989) and Voss et al. (2002), is well suited for the empirical development of testable theories and like other qualitative research methods, "(is) particularly oriented towards exploration, discovery, and inductive logic . . . " (Patton, 1990, p. 44).

3.1. Unit of analysis and level of analysis

The unit of analysis, in this study, is the product family, defined as (a) a set of final products that are offered by a single company; (b) are partially substitutable in their demands, possessing underlying similarities in their functionality; and (c) share the same common design and assembly process (Gupta and Krishnan, 1998; Meyer et al., 1997). Given the research agenda, the product family is an appropriate unit of analysis, since modularity in product design is essentially a property of product sets offered by a company (Shirley, 1990) that typically address heterogeneous, but interrelated, customer needs (Sanchez, 1999), and that can be produced by the same process, thus allowing for economies of scope (Garud and Kumaraswamy, 1995).

Specifying the product family precisely is an important task that needs to be complemented with the second task of specifying the hierarchical level within the product family at which measurements are to be taken (see *Academy of Management Review*, April 1999). In this context, we have to clearly denote the hierarchical level of the bill of materials defining the product family architecture at which we wish to make statements about, and related to, the type of modularity. Consider, for example, the typical personal computer (PC) comprising a set whose constituents are the motherboard inside a case, mouse, keyboard, printer, and monitor. In the language of the bill of materials, the PC is at level 0, whereas the motherboard, mouse, keyboard, printer, and monitor are all at level 1. If we were to specify the PC as the product family and we are interested in the type of modularity embedded into the PC architecture at level 0, then the type of modularity that the PC embeds is "slot modularity." However, we may be interested in the modularity property of the PC at a lower level of the bill of materials, say at the level of the motherboard, and if such were the case, then the prevailing type of modularity, we would observe, becomes "bus modularity."

3.2. Reference population and sampling

Besides specifying the unit of analysis and the level of analysis, it is also important to identify clearly what the reference population is. Doing so, helps to control for variation within cases and implicitly sets the boundaries of the theoretical insights that will eventually be developed (Eisenhardt, 1989; Yin, 1988).

First, the reference population, given the unit of analysis, is necessarily constrained to product families with the potential to embed modularity in the design of the final product architecture. As such, we consider only discrete products that can be built by assembling two or more components. Second, we include in the reference population only firms selling durable goods, either for the industrial market, or for the consumer market. Durable, typically more expensive, goods are more likely to be chosen through quasi-rational, rather than prevalently emotional, decision processes. As such, it becomes more critical for the firm to optimize the product variety–operational performance trade-off, rather than to bias the customer buying decision through marketing actions. Third, in order to control for variation in the manufacturing environment, as well as in its relationships to entities upstream and downstream within the supply chain, we consider only final assemblers (or product integrators, according to the practitioner jargon) in the reference population. Finally, we include, as part of the reference population, only product families with a relatively large production volume (>10,000 units), so as to exclude manufacturing environments with extremely low production volume. In fact, when production volume is very low there is generally very little margin to improve sourcing performance and, therefore, exploring modularity issues related to sourcing performance, in this context, is of little practical relevance.

Having delimited the reference population, we then identify the specific cases using two sampling strategies: criterion sampling and stratified purposeful sampling (Patton, 1990). Whereas the criterion sampling approach increases the chance of selecting information-rich cases whose study will illuminate the issues under study (Patton, 1990), the stratified purposeful sampling approach aims to maximize observed variance among selected cases.

In executing the criterion sampling approach, we consider two criteria—firm size and market presence. The first criterion leads to the selection, from the reference population, of firms with at least 1000 employees so as to improve the opportunities to interact with professionally trained managers, reducing language barriers and simplifying interaction during qualitative interviewing. The second criterion selects only those firms with an international market presence, using this criterion as a proxy for the firm's ability to develop, produce, and market a successful product family. Market success for durable goods would reduce the chance that product families and operations strategies of the selected firms were fatally flawed, while increasing the likelihood of getting important insights on the topics of interest.

In addition, we stratify the sampling from the reference population in two ways: by industry and by considering simultaneously product variety level and production volume. We considered three different industries: transportation vehicles, telecommunication equipment and food processing machines. Having more than one industry in the sample reduces the risk of developing theoretical insights that are bounded to a specific industry or a specific type of product. Within each industry stratum, we select two cases—one case with low product variety level and high production volume and a second case with high product variety level and low production volume. This stratification approach is consistent with our research questions and is motivated by the product–process matrix by Hayes and Wheelwright (1984) and by McCutcheon et al. (1994).

The sampling grid, along with the six selected cases, is identified in Table 2. From Table 2, we can see that product families with high product variety level and low production volume tend to be more complex than their counterparts with low product variety level and high production volume, since they tend to be comprised of a larger number of elementary parts (e.g. nuts, o-rings, bushings, etc.). Intuitively, this makes sense since a product whose architecture has many elementary parts offers a larger potential for generating variants than one with fewer elementary parts. However, a complex product does not necessarily mean that the product must offer a large number of variants (e.g. Ford Model T). As such, product variety and complexity, as defined here, are indeed intertwined and directly related for cases with high product variety level and low production volume. On the other hand, for

Table 2
Sampling grid

Low product variety level, high production volume		High product variety level, low production volume	
Industry			
Transportation vehicles			
Trendy-moped		Heavy-truck	
Product	Mopeds	Product	Trucks
Family turnover	165	Family turnover	N/A
No. of variants	64	No. of variants	2500
Production volume	55000	Production volume	30000
No. of variants/product volume (×1000)	1.16	No. of variants/product volume (×1000)	83.3
Telecom equipment			
Custom-phone		Multiplexer	
Product	Cell-phones	Product	Multiplexers
Family turnover	350	Family turnover	N/A
No. of variants	250	No. of variants	>1000
Production volume	2000000	Production volume	30000
No. of variants/product volume (×1000)	0.12	No. of variants/product volume (×1000)	>30
Food processing equipment			
Microwave		Techoven	
Product	MW ovens	Product	Convection ovens
Family turnover	52	Family turnover	38
No. of variants	280	No. of variants	300
Production volume	320000	Production volume	10000
No. of variants/product volume (×1000)	0.8	No. of variants/product volume (×1000)	30.0

cases with low product variety level and high production volume, the product architecture can have either a few or many elementary parts. More importantly, in reality, it would be impossible to identify any product family with over 10,000 variants that is comprised of only a relatively few elementary components.

3.3. Data collection

Table 3 provides an overview of the procedures we follow for the collection and subsequent analyses of data. In collecting field data, we rely primarily on qualitative, open-ended interviews with key organizational informants, including the department heads of product development, of manufacturing, and of purchasing. Because a firm's operations strategy and its approaches to managing the product variety–operational performance trade-off are largely the outcomes of decisions by top and middle managers, interviewing these upper-level managers is, therefore, a legitimate way to directly tap their mental models. Once key themes begin to emerge from the first round of interviews, we augment the data sources with ancillary data sources (Denzin, 1978), while contemporarily triangulating the information obtained from manager interviews.

Furthermore, during the first round of data collection, we make a conscious decision to not perform in-depth case-by-case analyses of the interview data so as to "avoid imposing meaning from one participant's interviews on the next" (Seidman, 1998, p. 96). Instead, in the second round data collection, we dynamically adjust follow-up interview protocols in order to gain maximum insights into the themes emerging from first round interviews.

3.4. Case analyses

Once the interviews are concluded, we perform intra-case analyses adopting the coding techniques recommended by Strauss (1987). We first cluster interview data into large conceptual categories (open coding) and subsequently identify sub-categories (axial coding) according to an indented coding scheme

Table 3
Main research phases, data sources, data collection and analytical tools

Research phase	Firm contact	First round data collection	Data analysis	Second round data collection + data analysis	Final analysis + synthesis of findings
Data sources	High level managers, head of human resources	Middle and high level managers, plant visits	Tape written interviews, field notes	Middle and high level managers, tape written interviews, field notes archival data, videotapes, company profiles, query to the information system, commercial documentation, industry press	Middle and high level managers, coded interviews, and all the other data sources
Data collection instrumentation	Phone contact, study presentation sheet issued to the managers	Interview protocol: few broad open-ended questions invariant across the cases; specific questions follow based on the themes emerging during the interview; field notes collected during, and immediately after, plant visits		Interview protocols are case and respondent-specific; they are created dynamically as second round data collection process unfolds; and they end asking for comment upon the interpretations emerged in previous data analysis	Specific questions or information asked by phone to some respondents, in order to verify alternative explanations and correctness of interpretation
Data analysis tools			*Case summary sheets* synthesize the basic messages and puzzles; *coding procedures* are followed for capturing the main constructs, patterns and highlight interpretations	*Coding procedures*: same; *comparative matrix*: variable oriented comparisons are made to highlight patterns	*Comparative matrix*: variable oriented comparisons are made to highlight patterns

(Rubin and Rubin, 1995, pp. 248–249). The purpose of these analyses is to gain a clear understanding of the different contexts embedded within the cases and to identify the main themes and/or variables relevant to the research agenda. We subsequently analyze across the six cases, looking for patterns among different themes and/or variables, as suggested by Runkel (1990).

3.5. Empirical generalizations and theoretical propositions

The themes derived through case analyses are then synthesized in the form of empirical generalizations, i.e. isolated statements summarizing observed uniformities of relationships between two or more variables along the sample (Merton et al., 1959). Empirical generalizations, by definition, are not theoretical propositions or laws (Merton et al., 1959; Zetterberg, 1954) since they are not backed by a fully deployed theoretical basis (Wallace, 1971). Therefore, in order to develop theoretical propositions from empirical generalizations, we would need to: (1) state the boundary conditions for theoretical propositions; (2) define relevant constructs that play a role in the theoretical development; and (3) provide explanations for the proposed relationships among constructs (Dubin, 1969).

4. Case profiles

In this section, we provide a brief outline of the six firms, highlighting specifically the market and environmental forces behind the need to reduce the product variety–operational performance trade-off in the considered product families. All six firms are multinational companies doing business in, at least, the European market.

4.1. Case 1: Trendy-moped

This particular firm is a major European firm operating in the moped market. The product family under study—which we label Trendy-moped—is targeted at the sports moped market segment. In 1996, Trendy-moped had three competitors, offering five to six rival product families. By the end of year 2000, the number of competitors had increased to 13, with approximately 40 rival product families, all competing for the same market segment. The growing number of competitors, especially the entrance of low-cost far-east manufacturers, has led to escalating price competition, which the firm expects to become even fiercer in the next few years. Because price is an important factor in the typical customer's purchasing decision, and the product is expected to be readily available at the dealership, these factors force the industry, as a whole, to respond to the market in a make-to-stock fashion. In turn, the industry is required to hold finished product stocks in the distribution channel, making it extremely difficult to keep costs low.

4.2. Case 2: Heavy-truck

This particular firm is a global player in the truck (light, medium, heavy, and quarry/construction) industry. The product family under study—which we label Heavy-truck—is a "heavy road truck" product family. Deregulation of the European transportation industry had resulted in the focalization of logistic service providers on specific transportation missions and, consequently, the requirement for differentiated vehicles. At the same time, deregulation had led to the consolidation of logistic service providers, increasing their bargaining power, and putting higher pressure on prices. From the customers' perspective, reliable, rather than short, delivery times are critical.

4.3. Case 3: Custom-phone

This particular firm is a fast-growing actor in the cell-phone industry, operating in Europe and in the far-east. The product family under study—which we label Custom-phone—is the "cellular-phones" product family complying with the GSM standard. In order to gain a foothold in a market dominated by a few technology leaders, the firm's strategy is to support the marketing campaigns of mobile communication providers by customizing cell phones to the needs and to the specific technical features of each provider's telecommunication infrastructure. This customization strategy, however, cannot come at the cost of substantial price increases, since competitors are mass producers with low unit production costs.

Furthermore, short delivery times, given the very dynamic cell-phone market, are mandatory for the firm.

4.4. Case 4: Multiplexer

The firm is a global leader in telecommunications equipment. The product family under study—which we label Multiplexer—is a data transmission unit deployed in building the telecommunications infrastructure of the so-called "information highways". Liberalization of the European telecommunications market had initiated radical changes not only to the competitive scenario for the telecommunications services industry, but also to the supplying firms of telecommunications equipment. Customers now require promptly available, relatively inexpensive, tailored solutions that allow them to rapidly and efficiently adapt to the effervescent and competitive telecommunications services market.

4.5. Case 5: Microwave

This particular firm is a diversified multinational company serving the home appliances industry. The product family under study—which we label Microwave—is a microwave oven product family commercialized in the European market. The firm began to offer greater product variety during the last decade for various competitive reasons. The firm wanted firstly to escape from the pressure of low-cost, entry-level products imported from far-east manufacturers, and secondly to respond to the requirements of more and more powerful retailers, who wish to differentiate their retail product offerings from each other. At the same time, powerful distributors had been exerting increasing pressures on price and service levels that, operating the industry according to a make-to-stock fashion, tended to translate into final goods inventory. The firm is, therefore, squeezed between the requirement for variety and the requirements for competitive price.

4.6. Case 6: Techoven

This particular firm is part of a multinational group in the food service equipment industry. The product family under study—which we label Techoven—is a convection oven product family. The highly diversified needs of food service equipment customers (e.g. hotels, restaurants, canteens, etc.), both in terms of the kind of cooking capability required and oven capacity, as well as the multiple commercial brands owned by the firm, forced the firm to develop a very articulated product range. At the same time, pressure on delivery times is extremely high for two reasons. Delivery times can affect whether or not a customer places an order with the firm or with a competitor. Also, when an existing oven has to be replaced due to wear or age, the replacement unit, in general, needs to be available in a very short time period.

5. A new type of modularity

From the within-case and across-case analyses, we identified four significant empirical findings, the first of which is presented and discussed here separately from the remaining three. We do so because this first empirical finding was not posed in our original research agenda. Another reason is that this empirical finding provides the foundation upon which we derive the remaining three empirical findings most directly relevant to the two research questions.

More particularly, the first empirical finding provides insights into a new type of modularity that, although present in practice, is not currently captured in previously articulated typologies. Before we present and discuss this new type of modularity, it is imperative that we provide precise definitions for a number of key terms that are incorporated into our explanation. These definitions, we trust, should help to avoid confusion from terminological ambiguities (e.g. how is a "part" different from a "component"?) and to prevent misunderstandings regarding the unit of analysis and the level of analysis.

5.1. Definitions

In the ensuing description and discussion, we distinguish between "components" and "product family variants", considering components of a product family to be all parts brought together in the final assembly stage, including those parts required for functionality reasons and any optional add-on parts. Different sets of components can, therefore, be combined in the final assembly stage into different product family variants.

Consider, for example, a bicycle, assembled from such components as the gear set, the brake system, the seat, wheels, the fork, and the handlebar. In this example, a component can be a one-piece element, such as the fork, or an entire subassembly made of many parts, such as the gear set. If multiple gear set variants are offered, the different gear set variants make up what we call a "component family", with each gear set variant being referred to as a "component family variant". This notion of the component family is similar to that of "replaceable component set" advanced by Gupta and Krishnan (1999) and that of "module type" proposed by Chakravarty and Balakrishnan (2001). When the component family consists of only one option (i.e. there is only one component family variant), then the component family degenerates into a "common component", meaning that the label "component family" is no longer applicable.

From these definitions, we can now discriminate between the unit of analysis and the level of analysis in this study. Whereas the product family constitutes the unit of analysis whose behavior we wish to describe, explain, and predict for purposes of theory development, the level of analysis, or the level at which we observe the type of modularity embedded within the product family, is the components making up the product family architecture.

5.2. Component swapping modularity and combinatorial modularity

With these terms and definitions, we can compare and contrast two of the six product families—Custom-phone and Heavy-truck—to illustrate and define "combinatorial modularity."

In Custom-phone, product family variants differ primarily in terms of the faceplate and a few other details (e.g. the aerial shape), while the PCB, back panel, battery, display, and keyboard remain identical across product family variants. In terms of Pahl and Beitz's (1984) typology, all components essentially implement basic functions. Applying Ulrich's (1995) typology further reveals that the interfaces between the basic product body and different component families (e.g. the external faceplate and the aerial) are different, with the product family embedding essentially slot modularity. Finally, at the schematic level, component variants from a component family are swapped over a basic product body made of a number of common components, or component swapping modularity per Ulrich and Tung (1991).

Conversely, in the Heavy-truck product family, the various components (gearbox, rear axle, chassis, cabin, engine, front brakes, etc.) are all component families that are to be combined, subject to a few technological constraints, to obtain product family variants. Two product variants within Heavy-truck may, in fact, differ in terms of all components. Like Custom-phone, the Heavy-truck product family comprises of components implementing what Pahl and Beitz (1984) refer to as basic functions. Considering Ulrich (1995), since different component families have different interfaces and cannot be arbitrarily connected to one another (e.g. the cabin cannot be connected with the rear axle; the cabin and the engine do not connect to the chassis in the same manner), the most appropriate type of modularity describing the product family is slot modularity, not sectional modularity, and not bus modularity. But, in terms of Ulrich and Tung's (1991) typology, none of the four types of modularity apply. Hence, a type of modularity that would describe the product family architecture of Heavy-truck appears to be missing from Ulrich and Tung's (1991) typology.

Comparing the product architectures between Custom-phone and Heavy-truck reveals that the key difference between the two is the ratio of common components to component families. Whereas all components in Custom-phone, with a few exceptions (e.g. the external faceplate), are common components, in the case of Heavy-truck, virtually all components are component families, meant that no basic product body can be observed. This significant difference has implications for both product design and operations management. For product design, the presence of a common body allows the adoption of integral (i.e. non-modular) designs for that particular portion of the product, with potentially positive implications on product performances (Ulrich and Seering, 1989). For operations management, the number of common components compared to component families has important implications in terms of component commonality and, hence, for operational performance (see Section 2.1). Reflecting on this key difference, the ratio of common components to component families, a type of modularity that is the complement of component

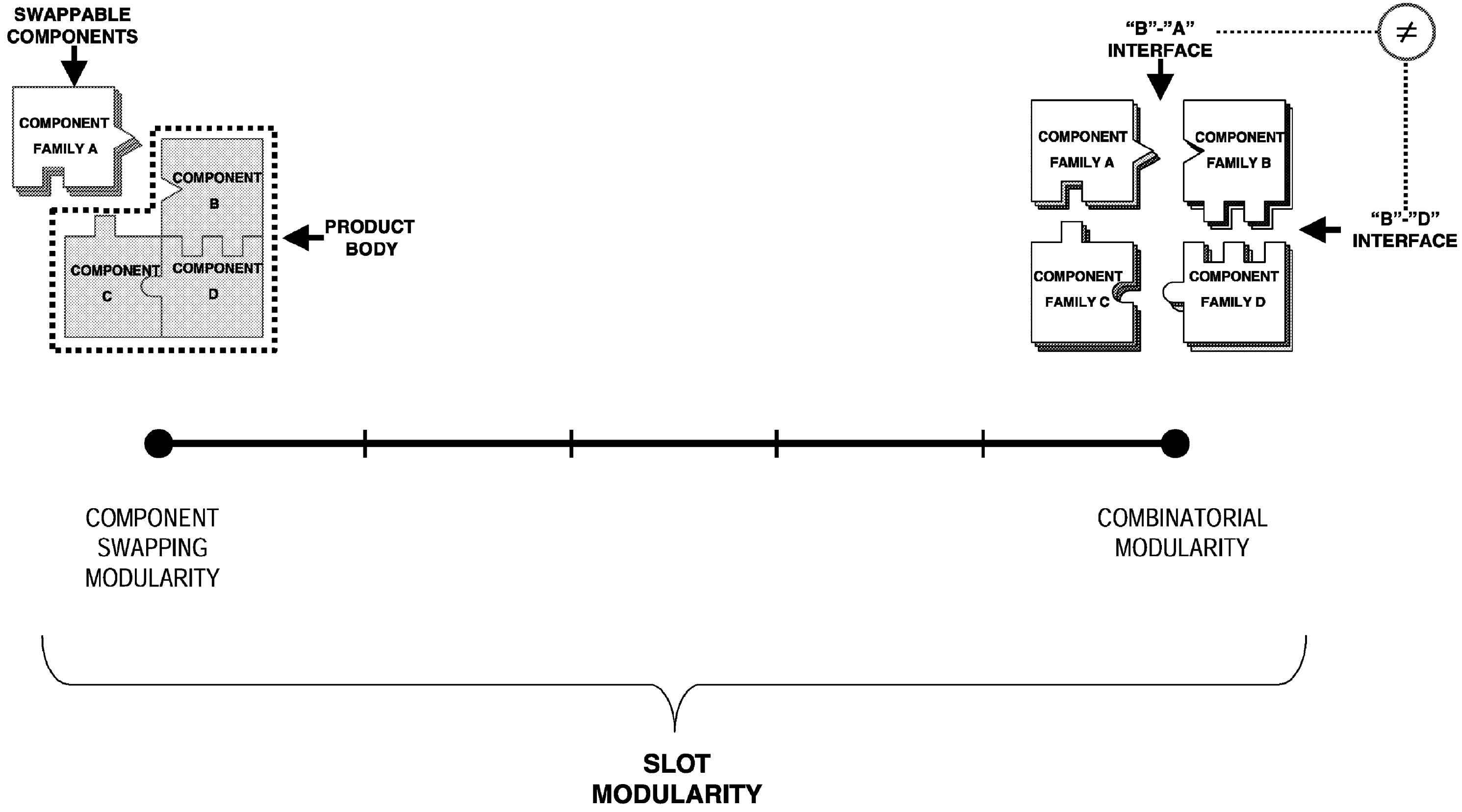


Fig. 1. A graphical representation of the component swapping modularity–combinatorial modularity spectrum.

swapping modularity can be inferred. Labeling this complement as "combinatorial modularity", we can more formally characterize combinatorial modularity as follows.

1. All components making up a product family variant belong to component families, meaning that each component itself is a variant.
2. Each component family interfaces with a subset of other component families, with the interface being standardized by pairings of component families. The interface refers to a set of rules that constraint how two components are to connect and to interact (Parnas, 1971; Baldwin and Clark, 2000).
3. The interface between two component families is dependent upon the specific coupling of component families, but is independent of the specific component variants selected from the two component families that need to be combined.

From this characterization, we can make three observations. First, it is evident that (1) and (2) are inherited from the definition of slot modularity, of which combinatorial modularity is a special case. Second, by stating the converse of (1): "only one of the components making up a product variant is a component family", we can state a formal definition of component swapping modularity that is consistent with that suggested by Ulrich and Tung (1991). Component swapping modularity and combinatorial modularity, therefore, have to be considered as two extremes, divided by a spectrum of situations with a gradually increasing incidence of component families to common components—all of which fall in the general case of slot modularity (see Fig. 1). Finally, we must realize that combinatorial modularity represents an ideal, particularly given (3). Pragmatically, technological constraints may make it very difficult to achieve interface standardization across all possible pairings of interfacing component family variants.

6. Empirical generalizations

Besides uncovering a new type of modularity, within-case and across-case analyses also generated three empirical insights into the relationships among the type of modularity, product variety, and component sourcing decisions.

6.1. Types of modularity, product variety level, and production volume

For Trendy-moped, Custom-phone, and Microwave, the three product families with low product variety level and high production volume, product variety appears to be obtained mostly through component swapping modularity. For each case, it is possible to identify: (a) a set of common components that are invariant across different final product configurations—the basic product body; and (b) a set of components that can be swapped in order to generate product variants (see Table 4).

When the requirements for product variety are not too stringent, firms that deploy a batch process in the final assembly stage, such as Custom-phone, Trendy-moped, and Microwave, appear to derive two benefits from embedding component swapping modularity into their product family architectures. First, this type of modularity allows the three firms to concentrate on economies of scale in manufacturing the basic product body. Consider, for example, this comment by Custom-phone about the PCB, a key basic product body component.

> This level two code, which is the PCB with all the components mounted on it, is combined with many aesthetic variants, so that it ends up being shared by hundreds of [product] variants. The assembled PCB is all the same throughout all variants. Given our volumes [this] allowed us to heavily invest in automated equipment ... we have SMD lines capable of mounting up to 35,000 components per hour [and] testing lines capable of fully testing 3000/4000 PCBs per day.

Likewise, at Microwave, the standardization of the frame justified the installation of an automated welding line that provided a reasonable return on investment and, more importantly, did not affect oven aesthetics and user interface.

Second, it appears that component swapping modularity enables the three firms to postpone the generation of product family variants until the final assembly stage without negatively affecting operational performance. For Custom-phone, which operates on a make-to-order basis, postponement actually translates into shorter delivery times, while at Trendy-moped and Microwave, which operate on a make-to-stock

Table 4
Observed types of modularity

Product family	Trendy-moped	Custom-phone	Microwave	Heavy-truck	Multiplexer	Techoven
Manufacturing environment	Low variety, high volume	Low variety, high volume	Low variety, high volume	High variety, low volume	High variety, low volume	High variety, low volume
Observed modularity type	Component swapping modularity	Component swapping modularity	Component swapping modularity	Combinatorial modularity	Combinatorial modularity	Combinatorial modularity
Components and component families	Multiple external body variants (different colors and decals) are combined with the same engine, chassis, braking system, etc.	Multiple front body variants (different materials, colors and decals) are combined with the same back, battery, PCB	Multiple door and control panel variants (different styles, colors, user interfaces and decals) are combined with the same frame, side and backpanels, cavity, magnetron, transformer, revolving plate	All the main components (engine, gearbox, rear axle, chassis, cab, except the front axle) can be different for different product variants, but the way they are connected is invariant	All the main components (aggregates, tributaries, controller, backpanel, except sub-shelf) can be different for different product variants, but the way they are connected is invariant	All the main components (door, heating unit, power control, boiler, control panel, forced air unit, cavity, external body) can be different for different product variants, but the way they are connected is invariant
Interfaces	Standardized	Standardized	Standardized	Increasing standardization (as the required product attributes change, the connections between different component families tend to change)	High standardization (although different backpanels can be selected, the way a given group connects to the backpanel is fixed)	Partial standardization (the interface of certain component families changes when different component variants are matched)
Observed operational benefits of modularity	Scale economies; lower final inventory risk; lower average delivery time	Scale economies; lower delivery time	Scale economies; lower final inventory risk; lower average delivery time	Lower final assembly throughput time; lower component inventory levels	Lower final assembly throughput time; lower component inventory levels	Lower final assembly throughput time; lower component inventory levels

basis, postponement translates into decreased inventory risks and/or shorter average delivery times. As one Trendy-moped manager said:

> It is not by chance that the factory performs only assembly, it is our very approach saying: let's shift all product customization at the last ring of the chain, ... giving ourselves an asset that allows us to assemble as near as possible to the market ... minimizing risk of understock or unsold final inventory.

In summary, final assemblers deploying batch processing and facing moderate levels of product variety can benefit most readily from embedding component swapping modularity into their product family architecture. Component swapping modularity, to be precise, appears to provide these firms with the specific means to extend the capability of what is basically a mass production system and make it compatible with the requirement for moderate levels of product variety, without serious penalties to productivity.

Conversely, for the remaining three product families with high product variety level and low production volume (i.e. Heavy-truck, Multiplexer, and Techoven), product variety appears to be achieved by embedding combinatorial modularity into the product family architectures. In each case, the product family is structured fundamentally as combinations of component families, with different paired component families having different interfaces, and with the interfaces between paired component families tending to remain stable.

The case of Multiplexer deserves additional explication since one might think, from a strictly technical point of view, that the embedded type of modularity is bus modularity, since the connection between the various groups of components and other external devices is effected through a bus. However, careful evaluation of how product family variants are generated reveals that different choices available from the key component families (aggregates and tributaries) may actually require different variants of the back panel component. Moreover, since the back panel provides connection between the machine and other telecommunications equipment, different requirements in terms of such connections may also necessitate different versions of the back panel. Therefore, because the individual back panel variant cannot accept any combination of component families, and the back panel itself may be chosen in multiple variants based on customers' needs, combinatorial modularity, not bus modularity, is a more accurate description of the type of modularity embedded in the Multiplexer product family.

For all three firms, the decision to embed combinatorial modularity into the product family architecture is primarily driven by the need to offer customers a much larger set of choices than the number of product family variants made available when only a few components are swappable. To satisfy this need, all three firms sacrificed the opportunity to standardize and maintain a common product body in the product family architecture. Instead, they maximize the number of choices by defining component families that can vary according to customer requirements. At the same time, so as to minimize the increase in the number and levels of inventoried items, especially when the combining of different components during assembly also requires an interfacing component to change as well, all three firms chose to standardize as much as possible the different interfaces between pairs of component families that have to be matched in final assembly. Standardizing the interfaces among components does not, however, mean that all the interfaces between all pairs of component families are standardized to a single interface, for a standardized interface that would work for all possible component family pairings would be a property of sectional modularity.

A manager at Techoven, for example, pointed out that standardizing the interface between pairs of component families results in lower inventory levels vis a vis a non-modular product with the same level of product variety.

> Differences between oven doors for different brands are [basically] restricted to the oven handle ... At one time, different handle variants had different sockets [connecting them to the locking mechanism], so that when we had to assemble a certain door variant, we needed the specific locking mechanism interface that could slot that specific handle ... This meant that we had to carry more line inventories of different locking mechanisms—door handle interfaces ... Then we looked at our basic door locking mechanism, and we imposed that the handle socket be standardized for all handle variants. Now all the brands have the same locking mech-

> anism and defining the front door brand variant is dependent [for a given height] only on the handle . . . The basic idea is to have standardized, pluggable interfaces among the different components.

Similarly, at Heavy-truck, in the past, as different gear variants were selected, the interfaces for control signals between gear, engine, and cabin had to change. This led to assembly problems, since the manner in which the different components had to be connected by operators changed with the specific component variants changed. Instead, by introducing a unique circuit connecting electronic control units that are scattered throughout the various vehicle components alleviates assembly problems and quickens the final assembly operations.

Hence, when the requirements for product variety are high, combinatorial modularity appears to allow the three firms in our study to reduce the necessity of carrying a larger number and a higher level of inventories via interface standardization between pairs of component families. In doing so, these firms are able to move the processing step responsible for the product family variants upstream from the final assembly stage to the preceding stage, where component family variants are manufactured—essentially, doing the opposite of what postponement suggests. Furthermore, in all three firms, combinatorial modularity enables them to economically justify and implement, for the final assembly stage, a mix-model production system instead of a batch system that, in turn, reduces final assembly time and provided faster response to heterogeneous customer requirements. For example, a Multiplexer manager stated:

> We have a very, very high variety of final product configurations [more than 10,000 product variants], which we obtain by combining certain types of PCBs [approximately 1000 component family variants], each one performing a certain function . . . we do this because we want to cut the lead-time the customer sees . . .

In conclusion, when we compare and contrast Trendy-moped, Custom-phone, and Microwave to Heavy-truck, Multiplexer, and Techoven, we can observe the following empirical generalization about the relationship between the types of modularity and the variety:volume ratio.

Empirical generalization 1: *When product variety level is low and production volume is high, the appropriate type of modularity is component swapping modularity, whereas when product variety level is high and production volume is low, then the appropriate type of modularity is combinatorial modularity*.

6.2. Types of modularity and component sourcing

The within-case and across-case analyses also led to the identification of two empirical generalizations relating the types of modularity to component sourcing or the external allocation of manufacturing tasks to either firm-owned or independent supplying entities. Since all six firms are basically final product assemblers, many, if not all, component manufacturing activities are performed by external suppliers that are either sister units belonging to the same firm, or plants owned by other firms. What appears to be novel, however, are the complex interactions between the types of modularity, i.e. component swapping modularity or combinatorial modularity, and the way firms manage to reduce the negative impact of component variety on manufacturing and sourcing performance.

For Custom-phone, Trendy-moped, and Microwave, we can make two common observations that are summarized in Table 5. First, all three firms allocated the manufacturing for swappable components to suppliers who tended to be located in closer proximity to the final assembly facility than those suppliers manufacturing the basic product body components. Second, all three firms were able to exert more pressure and stronger influence over the swappable component family suppliers than over the basic product body component suppliers. For example, consider the following quote from Custom-phone:

> In order to customize the cell-phone body in terms of color and decals, and for product packaging, we rely on suppliers that work with us in real time, with delivery times of 15 and, sometimes, 7 days. We know them [i.e. cell-phone body suppliers] well and we control them well . . . our agreement with them is that they have to produce from time to time based on what we need, even working through the night . . . and, you know, this is a good area for plastic molding and painting [i.e. there are many potential suppliers nearby]. Their proximity is a logistic

Table 5
Component swapping modularity, component sourcing, and operational performance

	Trendy-moped	Custom-phone	Microwave
Main swappable components families	External body	Front body	Door and control panel
Supplier proximity	Near (nearby region)	Near (nearby region)	Near (same region)
Ability of the final assembler to exert control over the supplier	High (suppliers owned by the final assembler)	High (suppliers easily substitutable and very small compared with the final assembler)	High (suppliers small compared to the final assembler; suppliers absorb a significant portion of firm production)
Impact on operational performance	Very short sourcing lead-times for swappable components variants	Very short sourcing lead-times for custom swappable components	Very short sourcing lead-times for swappable component variants

> advantage, as we can save time and money in transportation . . .

By locating swappable component suppliers nearby and over whom they can influence strongly, Custom-phone, Trendy-moped, and Microwave were able to reduce the suppliers' response and delivery times, while postponing the generation of product variants until the final assembly stage—a benefit echoed by Trendy-moped:

> Saying that we [the final assembler] have great flexibility [in generating product variants], but then that our suppliers are not flexible, is nonsense, because this would mean that my input inventory would skyrocket. Therefore, our job is to ensure that . . . all suppliers responsible for components generating customization . . . are [located] as near as possible to the final assembly facility in terms of time. [If suppliers are not near, and] we were to keep these components in stock . . . [this] would generate a foolish proliferation of codes, such as painted plastics. Because we need extremely short sourcing lead-time, . . . we require suppliers to react with a 1-week delivery time.

Similarly, in the case of Custom-phone, the ability of the supplier of the cell-phone external body (i.e. the swappable component) to respond quickly enabled the firm to contemporarily issue purchase orders and make orders to the cell-phone external body component suppliers and to the internal automated PCB assembly operations, respectively. This ability to do so, in turn, made it possible for both the cell-phone external body and the PCB to be available quickly for final assembly. At Microwave, since the frame is highly standardized and is manufactured by a highly automated process, it is critical for suppliers of aesthetics-related parts to keep pace with this frame manufacturing process and deliver with short lead-times.

Based on this discussion, we can, therefore, derive the following empirical generalization about component swapping modularity and component sourcing.

Empirical generalization 2: *Firms that choose component swapping modularity limit the negative implications of product variety on operational performance by relying on component family suppliers located near their final assembly facilities and which tend to be smaller or directly controlled by the final assembler*.

On the contrary, when we consider Heavy-truck, Techoven, and Multiplexer, the three product families embedding combinatorial modularity, a number of observations about component sourcing decisions, different from those for Custom-phone, Microwave, and Trendy-moped emerges (see Table 6). First, with combinatorial modularity, in principle, the larger the number of different component families and the larger the number of different variants within each component family, the larger the number of different final product configurations that can be obtained. Yet, all three firms strive to keep, as low as possible, the number of different component families to be allocated to external supplying entities. Techoven, in fact, is in the process of shrinking the number of different component families and says:

> Today, just to give you an idea, our ovens are built from about 400 component [families], without

Table 6
Combinatorial modularity, component sourcing, and operational performance

	Heavy-truck	Multiplexer	Techoven
No. of component families	Low (a relatively low number of component families is gathered for final assembly)	Low (a relatively low number of component families is gathered for final assembly)	Decreasing (the firm is trying to reduce from 400 to 50 the number of components that have to be brought together in final assembly)
Component family modularization	Yes (cabin, engine, transmission, axles all embed some modular design concepts)	Yes (component families are designed according with the hourglass concept)	Increasing (some component families, as the steam generation module, embed component swapping modularity)
Relationship with component families suppliers	Intense (multiple year purchase agreements involving also product development issues)	Intense (suppliers are part of the same group, but they also work as independent contractors and are heavily involved in product development)	Developing (the firm is shifting from a arm's length approach to a relation-building approach)
Impact on operational performance	Relatively short component delivery times, simpler internal flows in final assembly plant	Relatively short component delivery times, provided that elementary electronic components are available	Relatively short component delivery times, simpler internal flows in final assembly plant

> counting nuts, bolts, and screws ... The future on which we are working ... that will [still] be a future of strong product modularity [and] is a situation in which these 400 component families will be shrunk to about 50 component families ... [Techoven].

At Multiplexer, the relatively large number of final product configurations (>1000) are essentially assembled from just 10 component families. Likewise, for Heavy-truck, only a few component families—the cab, transmission, pre-assembled chassis, etc.—are assembled together to create approximately 2500 final product variants.

Of course, reducing the component families count in a given product family inevitably increases the average number of sub-components that make up each component family. In other words, for a given product family variant, putting together a smaller number of component families for final assembly means that these component families, themselves, are more complex. Again, Techoven illuminates why it should seek to reduce the number of component families and how this pursuit affects operational performance.

> If I make [the component families] more complex, then the final assembly lead-time is drastically cut ... But if the component [family] is made inside the plant then the overall lead-time is higher ... The idea works if my module comes from outside the plant. [Otherwise] we are wasting resources in inventory, resources in terms of money and people, in optimizing inventory management, in optimizing material flows inside the factories. Obviously when we go from 400 to 50 component families, then we have great simplification [in final assembly]. It is a matter of flexibility, as we will obtain with a small number of modular components all the product variants we need ... The front door is a perfect module, as it is complex, heavy and expensive. It is a module because if a supplier arrives and delivers it to me, I just have to install it and the game is done! [Techoven].

Likewise, by reducing the count of component families, Multiplexer was able to simplify final assembly operations. At Heavy-truck, the same reasoning leads to the following comment.

> If we took upon us all the complexity deriving from the variability of components in a heavy truck vehicle, then we will die from this complexity. Hence, we made a drastic decision ... since we are not able to manage this complexity well, we have to delegate it [Heavy-truck].

Therefore, while there would be simplification for the final assembler, it appears that the component family suppliers would be subjected to greater operational complexity, higher costs, and lower delivery performance. In fact, one could argue that by allocating the manufacturing task for component families to suppliers, the three final assemblers in our study have simply shifted the product variety–operational performance trade-off up the supply chain. As multiple managers at these firms have pointed out, the potential transfer of the trade-off from the final assemblers to the component family suppliers can be overcome through the pursuit of modularity in the component families that are allocated to suppliers.

> The groups we source from feeder plants are made by combining a certain set of common intermediate objects into a wider set of end items [components], ... according to the classical hourglass concept. Then we expand these end items [components] into final product configuration [Multiplexer].
>
> Another important module we consider for outsourcing is the steam generator, the heating element connected to the oven cavity ... it is a case filled with water with resistors placed inside it ... If I sell it in the USA it comes with a 208 V resistor, in Europe with a 400 V resistor, and so on, depending on the country ... simpler it is impossible! ... All the other features are standardized [Techoven].
>
> The entire heavy vehicles engines' product range has been designed so that they are modularized and manufactured in a single plant. Even engines with different displacements share the same concept, and hence they can be made with the same machines ... They also share many components ... can be customized by changing certain components as the compressor: no compressor, low compression rate, high compression rate, variable geometry blades, etc. [Heavy-truck].

Finally, we can observe that the allocation of the manufacturing tasks for component families along with the requisite necessity of seeking modularity in these component families moves the nature of the relationship with the supplier away from one that is characterized by unilateral decisions, as we observed in the cases of Trendy-moped, Custom-phone, and Microwave, towards a more collaborative, bilateral relationships. This quote from Heavy-truck reiterates this observation:

> We wanted to equip our product line with an optional automated gear ... The electronics controlling the gear must consider the behavior of many systems in the truck ... the braking system, the pneumatic suspension system, the engine control system, etc. ..., all of which can come in multiple variants. In developing the automated gearbox, our supplier told us "we cannot do it by ourselves, we are not able to consider all these variables" ... so we formed a joint venture [Heavy-truck].

The formal joint venture arrangement between Heavy-truck and the automated gearbox supplier facilitated the definition of a standard electronic gear management system that works as a standard interface between the automated gear and the other varying subsystems within the truck. In this particular incident, the interdependencies between truck features and specific gear features were minimized to just the gear torque, which is unavoidably related to the engine power that is desired. All other gear variants (e.g. the external case material, the integrated hydraulic retarder, the number of gears, etc.) depended exclusively on specific, customer-defined gear features.

In summary, for combinatorial modularity, the following empirical generalization appears to be supported by the case analyses.

Empirical generalization 3: *Firms that choose combinatorial modularity limit the negative implications of product variety on operational performance by reducing the overall number of component families defining the final product architecture, by working with suppliers to modularize the respectively allocated component families, and by setting up bilateral relationships with suppliers of component families.*

7. Theoretical development

In this section, we build upon the insights from the empirical findings with the purpose of deriving why and under what conditions the three empirical generalizations might hold for a product family outside of the original sample. In doing so, we state the boundaries of our theory development, identify and define, where needed, relevant constructs that inform our theoretical development, and provide a rationale for the proposed theoretical relationships among these constructs.

7.1. *Boundary conditions*

For the purpose of theory development, we delimit the scope of the propositions to discrete manufacturing firms of product families: (i) whose production volumes are large enough to justify their manufacture on a dedicated assembly line; (ii) whose product family architectures can generally embed slot modularity; and (iii) whose constituent components are externally sourced so as to allow firms to focus their internal operations on final assembly. These boundary conditions are consistent not only with the specifications of the reference population and sample, but also with the unit of analysis and the level of analysis that guided the within-case and across-case analyses. Furthermore, these boundary conditions exclude firms with discrete product families that have very low production volumes and the need to consider interactions between multiple product families made on the same final assembly process.

7.2. *Types of modularity, product variety level, and production volume*

Recall, first of all, from our discussion in Section 1 that product variety generally has a negative impact on operational performance. Second, recall that empirical generalization 1 in Section 6 suggests a relationship between types of modularity, product variety level, production volume, and operational performance. Third, recall, from Section 5, that slot modularity can be more precisely described as a spectrum anchored by the two extreme cases of component swapping modularity and combinatorial modularity (Fig. 1), with the spectrum being defined by the ratio of common components to component families. Synthesizing these three insights suggest that the appropriate position of a product family within the slot modularity spectrum (more descriptively, the component swapping modularity–combinatorial modularity spectrum) that would minimize the negative impact of product variety on operational performance is impacted by the two manufacturing variables of product variety level and production volume.

7.2.1. *Product variety level*

To understand how and why product variety level impacts the appropriate positioning of a product family within the slot modularity spectrum, we need to understand two interrelated points. First, consider that a product (e.g. an automobile) can generally be described as a vector of attributes, including exterior color, engine power, interior color, safety devices, etc. (Lancaster, 1971; Dobson and Kalish, 1988; Raman and Chhajed, 1995). Deciding to offer a particular car model, say Honda Accord, in multiple variants would involve two decisions: (a) what are the attributes that customers are allowed to express choices (e.g. the customer can choose the exterior color, but not the engine size)? and (b) what are levels of these attributes (e.g. exterior color: four choices of blue, red, silver, or white)?

In making these decision, economic consumer theory informs us of a phenomenon known as “satiation” (Lancaster, 1979, pp. 147–149), i.e. as the number of levels offered for a given attribute increases, the marginal increase in the consumer utility decreases. For example, consider the extreme scenario wherein a car manufacturer increases the number of color options over which the customer can choose from zero (i.e. only color is available) to five to 1000 colors. The customer, consequently, experiences greater utility up to a point beyond which there would not be any significant impact on consumer utility. Extending this phenomenon to the current context suggests that offering 1000 product family variants based on a single attribute (scenario A: for example, 1000 cars differentiated by exterior color) may not generate for the consumer the same level of utility as offering 1000 product family variants based on combining choices among multiple attributes (scenario B: for example, 1000 different cars differentiated by choosing from 10 exterior colors, four engines, five interior colors, and five stereo brands). In fact, scenario B, in this case, results in higher consumer utility than scenario A. More generally, we can, therefore, state that for any given level of consumer utility, the product variety level is positively and directly related to the number of product attributes allowed to vary (point 1). Hence, if customers were demanding greater product variety, it would be better, from a consumer utility perspective, to allow more attributes to vary than to increase the number of levels within a few attributes.

Second, by definition of modular product architecture, there is a one-to-one mapping of product functions, which are the engineering equivalents of product attributes, onto components. As such, with respect to slot modularity, consistent with boundary condition (ii), changes to the number of levels of a product attribute would impact only a single, individual component (Ulrich, 1995). More specifically, this implies that the number of levels of a product attribute is directly tied to the number of component family variants, while the number of product attributes allowed to vary is directly tied to the number of component families (point 2). Realize, therefore, that by relaxing boundary condition (ii) and considering product families whose architecture can generally embed not only slot modularity, but also sectional modularity, then product attributes may not necessarily be strictly related to components, but may, instead, be related to the way they are connected. For example, consider three sofas that are modular, connected via two corner pieces to form a U-shape or an S-shape depending on customer preference. In this case, the "sofa layout" product attribute corresponds not to components that vary, but to the way the components, or sofa pieces, are connected.

When we consider points 1 and 2 together, we can, therefore, infer that for any given level of consumer utility, the product variety level is positively and directly related to the number of component families (which as defined comprises multiple component variants). Hence, when demands for product variety are not excessive, many components can be fixed to define a common body while a few become component families, with the appropriate type of modularity leaning more towards component swapping modularity than combinatorial modularity. However, as customers demand greater and greater product variety, most, if not all, components should become component families and, as such, the appropriate type of modularity approaches combinatorial modularity.

By directly translating the demand for product variety into the ratio of component families to common components (which, de facto, specifies the position of the product family along the component swapping modularity–combinatorial modularity spectrum), slot modularity allows the exploitation of the satiation phenomenon to maximize internal operational performance, essentially by minimizing the negative impact of providing product variety on operational performance. For both component swapping modularity and combinatorial modularity, this minimization is achieved essentially by limiting variety at the component level to only what is strictly required to match a given level of consumer utility, so as to derive maximal benefits from component commonality. In the case of component swapping modularity, economies of scale derive maximal benefits from the common body, while focusing attention on how to mitigate the negative operational impact of a relatively few swappable components. In the case of combinatorial modularity, the minimization of the negative impact of product variety on operational performance derives from the fact that we can achieve the same level of product variety (e.g. 1000 car configurations) by having to manage for fewer variants within component families. Furthermore, because product attributes map directly onto specific components whose variations do not propagate to other components, the complexity and costs of recovering from incorrectly specifying market demand for a product attribute are reduced.

7.2.2. Production volume

Production volume, like product variety level, also impacts the positioning of a product family along the slot modularity spectrum and, hence, the appropriate type of modularity to embed within the product family architecture. The explanation as to how and why is relatively straightforward. When the product family production volume is high, there is a greater incentive to pursue component commonality, because of the potentially high magnitude of scale economies. In fact, this incentive further supports the specification of a common product body, consistent with component swapping modularity. At the same time, since product family variants can be generated simply by swapping a few components on a mass-produced product body, component swapping modularity becomes an effective means to allow repetitive, high volume production systems to basically deliver some product variety.

On the contrary, when the production volume of a product family tends to be low relative to the number of product family variants available within the same product family, the relative advantage of sharing a common product body throughout a product family tends to decrease. The benefits from economies of scale production of a standardized product body, consistent with component swapping modularity, consequently diminish. As such, the differential disadvantage in terms of economies of scale from pursuing combinatorial modularity instead of component swapping modularity becomes reduced and, perhaps, trivialized.

7.2.3. Conceptual synthesis

Integrating the above arguments concerning the appropriate position of a product family within the slot modularity spectrum, in light of product variety level, production volume, and consequences for operational performance, we can advance the following proposition.

Proposition 1. *As the product variety level increases* (*decreases*) *and/or production volume decreases* (*increases*), *the type of modularity that maximizes operational performance in building product family variants moves away from component swapping modularity* (*combinatorial modularity*) *and towards combinatorial modularity* (*component swapping modularity*).

7.3. Types of modularity, component family complexity, and geographical proximity (to suppliers)

Recall, firstly, from the earlier discussion in Section 1, that product variety tends to increase component family variety (Fisher et al., 1999), affecting the performance of not only the final assembler, but also component family suppliers as well (Krishnan and Gupta, 2001). Recall also that empirical generalizations 2 and 3 in Section 6, in essence, suggest how a final assembler, given the positioning of its product family within the slot modularity spectrum, can mitigate the negative impact of component family variety on component sourcing performance and, consequently, its operational performance, via component sourcing decisions relating to two key variables—component family complexity and geographical proximity to suppliers.

Before we develop the theoretical rationale for why these two variables can mitigate the product variety–performance trade-off, given the position of the product family within the slot modularity spectrum, two additional points need to be clarified. First, we have to realize that the final assembler's objective in pursuing product variety is to deliver product family variants as quickly as possible and as efficiently as possible. In light of boundary condition (iii), one way to achieve this objective is to maintain high inventory levels of the component family variants. However, doing so would significantly increase manufacturing costs. So, in order to avoid increasing manufacturing costs in pursuing product variety, the final assembler must strive to maintain minimal inventory levels of component family variants without negatively impacting the ability to deliver product family variants quickly (point A).

Second, the positioning of a product family within the slot modularity spectrum defines, a priori, the portion of the supply chain that would be directly affected by the demands for product variety (point B). In the extreme case of component swapping modularity, only one swappable component supplier would be directly affected, whereas, in the extreme case of combinatorial modularity, all component family suppliers would be directly affected.

7.3.1. Component family complexity

The first variable, component family complexity, intends to capture not only the number of component family variants within a component family, but also the number of parts making up each component family variant, on average, and the innovativeness of the component family technology. The importance of component family complexity in mitigating the negative impact of component family variety on component sourcing performance and, consequently, operational performance can be considered at the two extremes of the slot modularity spectrum.

7.3.1.1. The case of component swapping modularity. At the end anchored by component swapping modularity, the product family architecture is divided, by definition, into common body components and swappable components. For component body components, the objective of keeping inventory levels low, while ensuring quick delivery from common body component suppliers (as stated in point A) can be readily attained via long-term purchasing agreements that specify component pricing, delivery schedule, etc. For swappable components, such an approach is riskier, since it is difficult, if not impossible, to specify in advance not only what specific component variants are required, but also how many and when. Hence, in the case of swappable components, the ability of these suppliers to react quickly and deliver with short notice becomes of critical importance (implied by point B), since being able to do so necessarily impacts the ability of the final assembler to deliver product family variants quickly without carrying high inventory levels of various swappable components.

To enable and facilitate quick response from swappable component suppliers, low component family complexity is a key factor for three reasons. First, it is intuitively obvious that the speed at which a swappable component variant can be made is a direct function of the number of parts defining the component. Second, the less innovative the technology embedded into the swappable component and the fewer the number of parts, the greater the likelihood of finding small, substitutable suppliers with relatively low bargaining power vis a vis the final assembler and over whom the final assembler can demand shorter delivery times without paying a premium. Third, and more generally, the fewer the number of parts in a swappable component, the less complex the interface is likely to be between the swappable component and the common product body, which, as a result, reduces the risk of having a complex coupling requiring excessive processing time during final assembly.

7.3.1.2. The case of combinatorial modularity. At the opposite end of the slot modularity spectrum (i.e. combinatorial modularity), all component families, by definition, are allowed to vary while the interface between specific pairs of component families is standardized. In this case, all suppliers are directly affected by the pursuit of product variety (point B) and must be taken into consideration to help the final assembler attain its objective of delivery product variety quickly and efficiently.

Component family complexity remains a critical factor and keeping component family complexity low remains theoretically sound for the same reasons as provided in the case of component swapping modularity. However, we can provide three arguments as to why high rather than low component family complexity is preferred when the position of a product family within the slot modularity spectrum approaches that of combinatorial modularity.

First, the benefits of interface simplification and quick delivery, when component family complexity is low, may be more than offset by the operational challenges that a final assembler faces in the case of combinatorial modularity. In particular, when component family complexity is low, more component families needs to be combined during final assembly than when component family complexity is high. Compare, for example, a situation in which we define a product by 100 component families that have to be combined during final assembly to another situation in which we now define the same product as only 10 component families that have to be combined during final assembly. By increasing component family complexity, the final assembler gains from reducing the complexity of materials flow within the final assembly process, the number and complexity of connections to be performed during final assembly, the overhead costs of manufacturing planning and control, etc. However, given boundary condition (iii), these gains come at the expense of the component family suppliers, since product variety is effectively translated into higher component variety.

Second, the benefit of shorter component delivery times from low component family complexity may also be offset by the degradation of the delivery reliability of the overall supply chain. *Ceteris paribus*, component variety lowers component delivery reliability, or the ability of the component supplier to deliver on time, largely because of the complexity induced within supplier operations by component variety (Fisher et al., 1999). Otherwise, the component family supplier is forced to increase its component family variants inventory in order to ensure delivery reliability. In the case of combinatorial modularity, since all component family suppliers have to deliver multiple component family variants, and since overall supply chain delivery reliability, assuming independence across suppliers, is the product of all individual suppliers' delivery reliabilities, the more component family suppliers (i.e. low component family complexity) there are, the worse off the overall supply chain delivery reliability. Stated in terms of component family complexity, there is direct relationship between component family complexity and overall supply chain delivery reliability.

However, high component family complexity necessarily implies, for a given product variety level, a higher average number of component variants per component family. This, in turn, has the potential to affect component delivery reliability from specific suppliers. Consequently, in order to mitigate this potential disadvantage, the complexity associated with the manufacture of component family variants needs to be reduced. Modularity, this time at the component level rather than at the product family level, offers a way to do so. Furthermore, when the component family is not an off-the-shelf item, but is specifically designed to fit within the final product architecture, the necessity of embedding modularity into the component family would naturally encourage greater collaboration between the final assembler and the component family supplier, particularly during product development. As a result, the nature of the relationship between the final assembler and component family suppliers is also affected by component family complexity.

Third, recall that in the case of component swapping modularity for which component family complexity is low, the less innovative the technology embedded into component families outsourced to suppliers the more favorable the operational performance results would be for the final assembler. But, when innovative technology that might affect component design becomes available, the final assembler, in order to avoid shifting bargaining power towards the specific component family supplier, can choose to standardize this technology in such a way that would anticipate varying customer requirements and make the component part of the common product body. This allows the final assembler to also maintain low component family complexity consistent with component swapping modularity. However, as we move towards the case of combinatorial modularity, component family complexity, in terms of the innovativeness of component technology, is, by definition and on average, higher since an increasing portion of product components are component families. In fact, the fewer the number of component families, the more difficult it becomes to not have technologically complex component families.

7.3.2. Geographical proximity (to suppliers)

The second variable, geographical proximity, refers to the physical distance (and, hence, logistical distance) between component suppliers and the final assembler. Generally speaking, geographical proximity (to suppliers) is always desirable in terms of component sourcing since it allows for the opportunity to reduce sourcing lead-times. In fact, since component variety has negative effects on supplier delivery performance, geographical proximity may provide the means to counterbalance this operational disadvantage for final assemblers. More specifically, for a final assembler that responds to product variety requirements in a purchase-to-order fashion, geographical proximity reduces delivery times of components from suppliers to the final assembler. Moreover, for a final assembler that purchases components based upon forecasts of product variety requirements, the shorter sourcing lead-times for component families reduces uncertainty in materials planning and, subsequently, lower component inventory risks.

Like component family complexity, the importance of geographical proximity in mitigating the negative impact of component family variety on component sourcing performance and, consequently, operational performance can also be considered at the two extremes of the slot modularity spectrum. In the case of component swapping modularity, the geographical proximity of the suppliers of a few swappable components translates directly into one of the two advantages already mentioned.

In the case of combinatorial modularity, the benefits of geographical proximity should generally hold as well. However, geographical proximity is not of equal critical concern across all component family suppliers, but is of primary concern for suppliers of component families with relatively longer throughput times. These suppliers are essentially external bottlenecks that constrain the overall delivery performance of the final assembler and force the final assembler to lengthen the materials planning time horizon. As a result, placing them as close as possible to the final assembler can overcome some of these operational disadvantages.

7.3.3. Conceptual synthesis

Integrating the above arguments about component family complexity and geographical proximity, in light of the positioning of the product family with the slot modularity spectrum and the consequences for operational performance, we can advance the following proposition.

Proposition 2. *As the type of modularity embedded in the product family architecture moves away from component swapping modularity towards combinatorial modularity* (*or conversely*, *from combinatorial modu-*

larity towards component swapping modularity), *the extent to which the negative effect of component family variety on operational performances can be mitigated depends upon*:

A. *The extent to which the component family complexity of component families can be increased* (*reduced*).
B. *The extent to which the component family supplier with the longest throughput time can be located in geographical proximity relative to other suppliers of component families.*
   (*The extent to which all suppliers of component families can be located in geographical proximity relative to the suppliers of common components to the final assembler.*)

8. Conclusion

The issue of the interdependence among product design, process design, and supply chain design has been recognized and brought to the attention of scholars and managers as early as Hoekstra and Romme (1992). Since then, this issue has become prominently discussed in Fine (1998). Despite the undeniable appeal and importance of this issue to both science and practice, we know very little about how decisions in product design, process design, and supply chain design should be coordinated to maximize operational and supply chain performance.

To further our understanding of the interdependence among product, process, and supply chain design, the present research explores the implications of modularity in terms of such manufacturing characteristics as the level of product variety and the production volume of the final assembly process. Furthermore, the present research ties the decision to embed a specific type of modularity into the product family architecture to component sourcing decisions that relate to supplier selection and supplier location, with consequent implications for buyer–supplier relationships.

The empirical findings and theoretical development presented here, while enhancing our understanding of the intricacies of coordinating product, process, and supply chain design, suggest several promising research opportunities that can be pursued. First, future research should seek to test the theoretical propositions posed in this paper via case-based and/or survey-based research designs. A second possibility is for future research to consider the issue of multiple product families, which essentially relaxes one of the boundary conditions and allows enrichment of current theoretical propositions and/or generation of new theoretical propositions. Yet, a third research opportunity is to integrate the results here with more formal operations research perspectives (e.g. the product line design problem (Yano and Dobson, 1999)). A fourth and final research opportunity is to consider the implications of the theoretical propositions in the context of other operations management prescriptions (e.g. JIT, Lean Manufacturing, TQM, etc.), as well from other functional and theoretical perspectives (e.g. organizational theory, strategic management, etc.).

Pragmatically, we are reminded that research in professional schools needs to provide practical theory that would not only advance science, but would also inform the practice of the profession (van de Ven, 1989). The theoretical results reported here should provide guidance to managers facing the need to coordinate product, process, and supply chain decisions. In fact, such advice could be portrayed as a roadmap for managers to traverse as they navigate through decisions about what type of modularity would be most appropriate, what components to outsource and to which suppliers, and how should the relationship with suppliers be structured.

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