Modularity in product development: a literature review towards a research agenda

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Abstract: Modularity, which offers a very general set of principles for managing complexity, has become increasingly important because of the growing complexity of modern technology. The literature describes modularity as the process of building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole. There are, in fact, three distinct perspectives in modularity: modularity in design, modularity in production, and modularity in organization. These types of modularity have gained much attention in several industrial sectors. Although the concept and application of modularity has been a subject of research over the past decade or so, various authors have pointed out the need for further progress in its research. This paper makes a review of the literature on modularity with the purpose of establishing a research agenda. To this end, a number of works are examined considering their research focus and approaches, seeking to draw up and propose such an agenda. The paper concludes that research agenda should consider issues such as the need to develop a conceptual model to represent modularity in all its perspectives, as well as studies concerning the organizational implications involved in decisions for modular product development.
Keywords: modularity, modular products, product development, modular design

1. Introduction

Many companies are being faced with the problem of providing as much variety of the product as possible for the market, while at the same time keeping as little variety as possible among products in order to achieve economies of scale (BI & ZHANG, 2001). In order to tackle this problem, industrial sectors such as automotive, computer, electronics, and others have adopted the concept of modularity. It is a process of building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole. The term indicates a high degree of independence among individual elements and seamless interfacing among them. Modularity concept then enables the scheme by which interfaces shared among components in a given product architecture are standardised and specific to allow for greater reusability and commonality sharing of components among product families (MIKKOLA, 2001).

Actually, there are three distinct perspectives in modularity (SAKO & MURRAY, 2000; CAMUFFO, 2001; DORAN, 2003): modularity in design, modularity in manufacturing, and modularity in organization. Modularity in design refers to the definition of the design boundaries of a product and of its components so that design features and tasks are independent across modules, while modularity in manufacturing refers to design manufacturing and assembly in order to reduce complexity by mean of sub-assembly, pre-fitment, testing of modules and transferring some of these activities to suppliers. Modularity in organization relates to the organizational process, governance structures and contracting procedures that are adopted or utilised to accommodate modular production at both the infra and inter-firm context.

In this sense, numerous studies have been carried out on modularity-relevant issues. All types of modularity have become a focus of attention and the idea of modularity has gained acceptance in many industrial sectors, such as automotive (e.g. CAMUFFO, 2001; DORAN, 2003; 2004; MORRIS et al., 2004), and computing and software (e.g. BALDWIN & CLARK, 1997; MARTIN & ISHII, 2000; HOETKER, 2002; ISHII & YANG, 2003).

In this context, this paper aims at contributing to the body of knowledge on modularity by presenting the first stage of a literature mapping (for this concept refer to CROOM, 2005). More specific objectives include a classification of research focus of a number of selected studies and their research approaches in relation to the published research studies. Finally, a research agenda is proposed based on the previous analysis.

The remainder of this paper is structured as follows. Section 2 contains the research approach and relevant

methodological issues. Section 3 provides the theoretical basis on modularity by expressing its main concepts and types of modularity (used for literature classification). Section 4 presents the research issues on modularity including findings from the literature mapping and analysis and, finally, section 5 draws some concluding remarks and main implications of this work as well as the next steps of this research project.

2. Methodological approach

This paper can be classified as a theoretical research, based on a literature review including a classification and its analysis. It is imperative to any research project that the field being researched is defined and understood, which involves identifying the current theoretical and empirical state of knowledge in the subject. In addition, the objective of a literature study is not merely the identification of gaps in the literature, but in fact to help in the identification of good, appropriate research questions for the research and clarification of dominant methodologies associated with the chosen research area (CROOM, 2005). In order to do so, a literature mapping can be used. According to the previous author, it is an approach which utilises mapping to locate the research topic in the context of the antecedent literature and its influence on the development of theory in the chosen topic. As mentioned earlier, mapping the antecedent literature is useful for clarifying how to frame research questions.

Therefore, this paper employs literature mapping by firstly selecting a number of papers. After that, each paper is examined in order to identify the research focus (i.e. the main issue discussed in the paper), area of application (i.e. the industrial sector), and the research approach (i.e. the research methods used in the paper). The research approaches are those used in operations management proposed by FILIPPINI (1997), namely: case study, field study, laboratory experimentation, modelling, simulation, survey, theoretical/conceptual, and "others" (meaning that the research approach is unclear or use of other approach, e.g. action research). It is worth mentioning that this work does not describe the contents of each examined paper. Nevertheless, the concept of the studied subject (i.e. modularity) is outlined as well as its types. Those types are the basis for literature classification.

A literature review can be categorised according the following criteria (NORONHA & FERREIRA, 2000): purpose (analytical or supportive – to thesis, dissertations, etc.), scope (thematic or time-based), function (historical or for updating), and approach (critical or bibliographical). Table 1 shows this work categorised according to the previous criteria in addition to the rationale for this classification.

The bibliographical sources that are used in this paper are mainly publications in leading journals although an important reference book in the subject is used (BALDWIN & CLARK, 2000). In addition, working papers gathered from the Internet are selected and, most importantly, articles in relevant international refereed journals.

3. Theoretical basis of modularity

The architecture of a product is the scheme based on which the functional elements of the product are arranged into physical blocks and the blocks interact (HUANG, 2000). Product architecture can be categorised as integrated or modular. An integrated architecture usually has the following properties (HUANG, 2000): the functional elements of the product are implemented using more than one block (a collection of interchangeable components that implement similar functions); a single block may implement many functional elements; the interactions among the blocks are ill-defined and may be incidental to the primary function of the product. Modularity (or modularization) is an approach for organizing complex products and process efficiently (BALDWIN & CLARK, 1997), by decomposing

Table 1. Classification of the literature review in this work.

Classification	Type	Definition	Rationale
Purpose	Analytical	Propose a group of the various issues in the subject and provide a literature survey in a specific chosen topic	Identify research that already exists in modularity and group them according to some criteria
Scope	Thematic	Present a specific and in-depth description about a chosen topic	Identify if the theory of modularity is well developed
Function	For updating	Describe the most relevant literature recently published in order to identify information for the development of knowledge	Identify if there are gaps in current research, if is applied or fundamental research, and the research time frame
Approach	Critical	Identify selected publications and provide value judgement about the sources. It usually provides a reflection on the chosen topic	Clarify the questions addressed by existing research while also identifying the methodologies used to explore their answer

Source: developed by the author based on NORONHA & FERREIRA (2000).

complex tasks into simpler portions so they can be managed independently (MIKKOLA, 2001). There are a number of terms that are used to describe modularity. Those terms and their references can be seen in Table 2.

In addition, the characteristics of modular and integrated architectures are compared in Table 3.

As mentioned earlier in the introduction, the literature usually grouped the concept of modularity in three principal domains: modularity in design, modularity in production, and modularity in organization (SAKO & MURRAY, 2000; CAMUFFO, 2001; DORAN, 2003). In addition, other authors also consider modularity in use (SAKO & MURRAY, 2000). Those are described next.

4. Modularity in design

Modularity in design has been researched to reduce design process complexity (ULRICH & EPPINGER, 1995; FUJITA, 2002). Modularity in design can be, therefore, defined as choosing the design boundaries of a product and of its components, i.e. on how to divide a system into modules, so that the design features and tasks are interdependent within and independent across modules (HUANG & KUSIAK, 1998; CAMUFFO, 2001).

ULRICH (1995) analysed the structures of design, in terms of product structure, physical functions, etc. and distinguished them into modular architecture and architecture integral. According to FUJITA (2002), the former indicates a one-to-one mapping from functional elements in a function structure to physical components of a product and decoupled interfaces among components. The later indicates a complex (non one-to-one) mapping functional elements to physical components and/or coupled interfaces between components.

Modularity in design can be, therefore, defined as choosing the design boundaries of a product and of its components, i.e. on how to divide a system into modules, so that the design features and tasks are interdependent within and independent across modules (HUANG & KUSIAK, 1998; CAMUFFO, 2001).

One important aspect of modularity in design is the product architecture. An important task is to find common modules across products for platforming a product family or to find a common module for joint development with a partner (HÖLTTÄ et al., 2003). However, although modularity is often seen purely as a process of decomposition of product architecture into subassemblies (WHITNEY, 1992) it is not the same (MARSHALL et al., 1998). There are fundamental differences between modular design and groups of components in a subassembly (MARSHALL et al., 1998):

- Modules are co-operative subsystems that form a product;
- Modules have their main functional interactions within rather than between modules;

Table 2. Taxonomy on modularity (constructed based on MIKKOLA, 2001).

Terms	References
Modular components	SANCHEZ & MAHONEY (1996); SHAEFER (1999)
Modular innovation	HENDERSON & CLARK (1990); CHRISTENSEN & ROSENBLOOM (1995); HSUAN (1999)
Modular product architecture	ULRICH & EPPINGER (1995); SANCHEZ & MAHONEY (1996); LUNDQVIST et al. (1996)
Modular system	LANGLOIS & ROBERTSON (1992); BALDWIN & CLARK (1997)

Table 3. Comparison of modular and integrated architectures (adapted from HUANG, 2000 and MIKKOLA & GASSMANN, 2003).

Issue	Integrated architecture	Modular architecture
Nomenclature	A collection of components that implement some functions of a product is called a block	A collection of components that implement some functions of a product is called a module
Functional element	The functional elements of a product are implemented using more than one block	Same as an integrated architecture
	A single block implements many functional elements	A module implements one or a few functional elements in their entirety
Interaction	The interactions between blocks are ill-defined and may be incidental to the primary functions of the product	The interactions between blocks are well defined and are generally fundamental to the primary functions of the product
Product performance	It can be enhanced through an integrated architecture	It may not be enhanced by a modular architecture
Changes	Changing a block in an integrated product may influence many functional elements and require changes to several related blocks	Changing a few isolated functional elements of a product may not affect the design of other modules
Example	Formula One cars, Apollo computers, satellites	Elevators, passenger cars, IBM PCs

- Modules have one or more well defined functions that can be tested in isolation from the system and are composite of the components of the module. Modularity is typically used for its inherent capability to rationalise variety through the partitioning of product functions (PAHL & BEITZ, 1996); and
- Modules are independent and self contained and may be combined and configured with similar units to achieve a differential outcome.

Aiming at providing a taxonomy on modularity, BI & ZHANG (2001) state that there are two basic categories of activities involved in modularity in design:

- Modularity of a product: it should result in architecture of a product such that the product can be made by simply assembling pre-existing components. To realise it, product functions, product life cycle issues, and costs should be considered; and
- Determination of modular configuration: it is described by O'GRADY & LIANG (1998) as 'given a set of candidates modules, produce a design that is composed of a subset of the candidate modules and which satisfies both a set of functional requirements and a set of constraints'.

BI & ZHANG (2001) provide more details on those categories by deploying them in the issues showed in Table 4. The authors also state that both product modularity and determination of modular configuration involve design evaluation, which can be performed from different points of view: function, flexibility, cost-effect, environment, technique, and complexity.

5. Modularity in production

Modularity in production means choosing plant design boundaries to facilitate both manufacturing and assembly to meet product variety, production flow, cost and quality requirements (CAMUFFO, 2001). In this direction, there are now commercial equipment for enabling and facilitating the introduction of modular plants. A 'component-based automation' solution is supplied to a modular plant at VW in Wolfsburg, Germany (SIEMENS, 2004). It is a solution for the factory paint shop; a decentralised automation approach in which intelligent is distributed to technological modules that combine the mechanics, electrical functions and control programme logically. The technological modules include robots, filling machines and other parts of a production plant (SIEMENS, 2004).

Table 4. Taxonomy of issues in modularity design (based on BI & ZHANG, 2001).

Categories of activity	Task deployment
Modularity of a product	Identification of requirements; determination of modular architecture, module design
Determination of modular configuration	Architecture and requirements description; determination of a sub-problem; constraints and objectives coordination; determination of interfaces and internal variables

In addition, modularity in production also refers to apply sub-assembly, pre-fitment testing of modules and transferring some of these activities to suppliers (DORAN, 2003). The influence of modularization on the factory floor lies in the ability to pre-combine a large number of components into modules and for these modules to be assembled off-line and then brought onto the main assembly line and incorporated through a small and simple series of tasks (SAKO & MURRAY, 2000). In this sense, FREDRIKSSON (2002) analyses the conditions provided for module assembly units performance through a case study conducted at Volvo. It considers pre-assembly and outsourcing. The paper also shows that organizational forms (ownership and location) provide different conditions for module assembly unit performance. The modularity in organization is further discussed below. Other papers discuss issues related to the concept of modular production (COLLINS et al., 1997; MARX et al., 1997; PIRES, 1998; 2002). The production is organized as known today as modular consortium. The concept is based on the transfer to all assembly operations to nine first-tier suppliers. Each module is defined by a whole logical part of assembly. The plant lay out is shown in Figure 1. It is worth observing that the automaker produces chassis for both trucks and buses, while cabins are produced only for trucks.

According to CAMUFFO (2001), many automakers such as GM, Fiat, Ford, Daimler-Chrysler, Mercedes Benz, and VW have experienced with modular assembly plants in the past years. Volkswagen was the first plant to apply modularity concepts extensively, specifically at its plants in Resende in Brazil, Boleslav in Czech Republic and Mosel in Germany (MARX et al., 1997). Ford and GM have all built new plants that specifically accommodate modular assembly (DORAN, 2003).

6. Modularity in organization

Modularity in organization relates to the organizational process, governance structures and contracting procedures that are adopted or used to accommodate modular production at both the intra and inter-firm context (DORAN, 2003). For instance, CAMUFFO (2001) presents a case study of the roll-out of a Fiat world car in a field work carried out in six countries. In this study, the author examined aspects of modularity, outsourcing, and globalisation to find out if there were a relationship among them. The case study pointed out that, at the firm level, those concepts are linked. Outsourcing and modularity, though increasingly

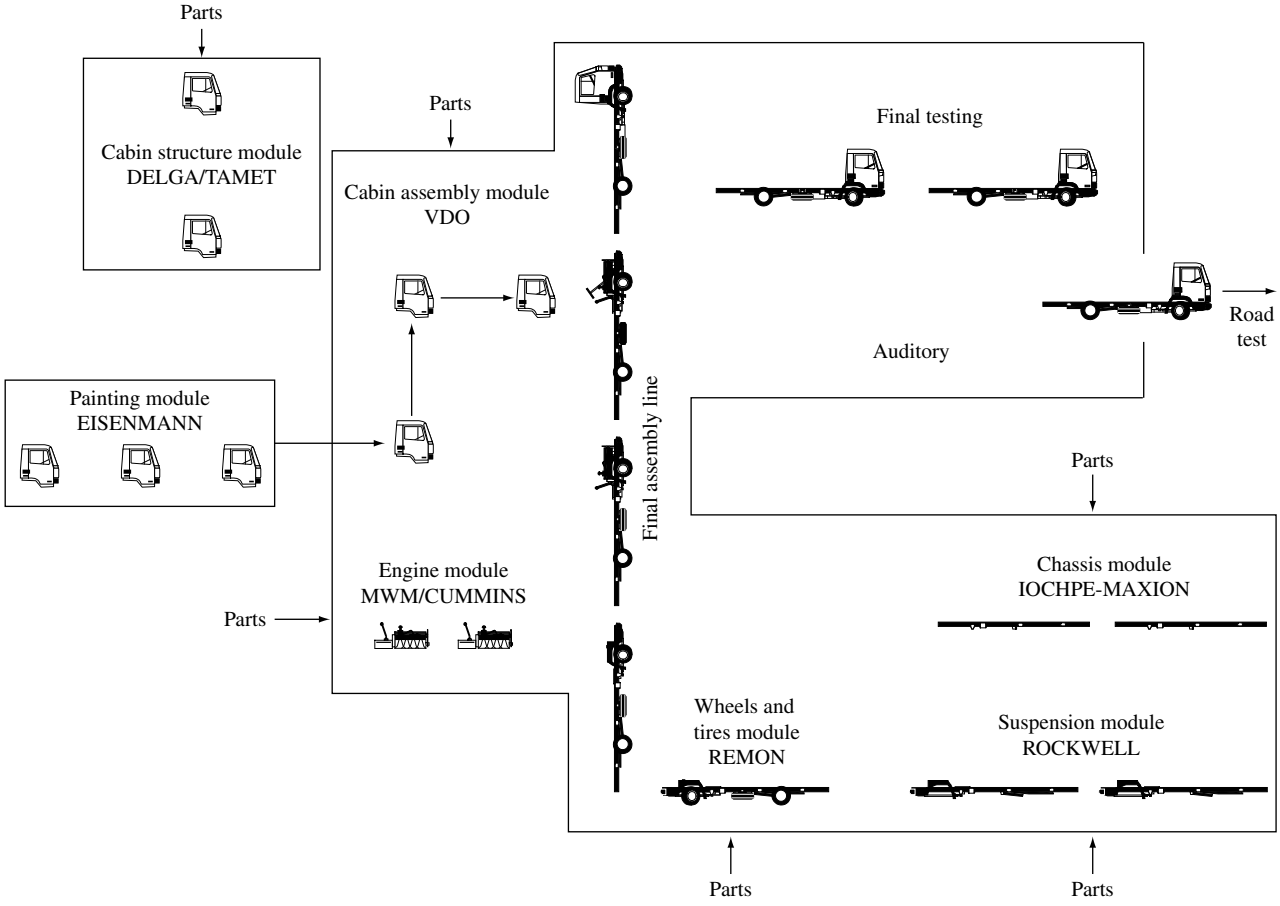

Figure 1. Modular consortium – production lay out (PIRES, 1998).

inseparable and overlapped in practice, remain conceptually distinct (CAMUFFO, 2001).

Although it is not a consensus in the literature, SAKO & MURRAY (2000) also categorise 'modularity in use' as a fourth type. It is a consumer driven decomposition of a product with a view to satisfying ease-of-use and individuality (SAKO & MURRAY, 2000). According to the authors, there are several issues, which influence the consumer perspective on modularity: easy of use, ease of maintenance and relative cost of different modules. Another aspect, which is also important, is compatibility. Examples come from the computer and automotive industry. IBM developed the modular computer in the 1960's because consumers demanded compatibility within a family of computers and across different generations of computers (SAKO & MURRAY, 2000). Modularity in use is captured in the auto-industry by the idea of consumers buying a product by mixing and matching elements to suit their individual needs and tastes, including 'modules' and "options" (e.g. sun roofs).

All types of modularity, presented earlier, have become a focus of attention in different industrial sectors. Having presented a basic theoretical background on types of modularity, attention is turned to some remarks on modularity implications.

7. Modularity implications

One of the current concerns in the literature is a question whether there is a relationship among the types of modularity presented above. Indeed, modularity in product design may impact all stages of the product life cycle. Modularity in design of products leads to modularity in the design of the organizations that produce such products (SANCHEZ & MAHONEY, 1996). It affects the design process itself by proposing solutions in terms of simultaneously designing multiple products (FUJITA, 2002). Furthermore, it concerns other issues such as supply chain factors (DORAN, 2003), outsourcing strategy (CAMUFFO, 2001), manufacturing and assembly (BI & ZHANG, 2001; FREDRIKSSON, 2002), and serviceability and recyclability (ISHII, 1998). As can be seen, modularity can be considered as a multi-faceted concept and its adoption is influential on the entire company (BALDWIN & CLARK, 2000). In summary, the adoption of modularity can be influential on the whole organization.

8. Literature Analysis on Modularity

The analysis of the bibliography involves a literature mapping, which is an approach which utilises mapping to locate the research topic in the context of the antecedent literature and its influence on the development of theory in the chosen topic (CROOM, 2005). Firstly, the papers are gathered. Secondly, each one is examined and, finally, they are categorised according to: the research focus (the main issue discussed in the paper; resulting in 4 different modularity groups: design, production, organizational, and 'various', i.e. papers that involve two or more of the previous groups or could not be placed in any of them, for instance in the case of 'modularity in use'), area of application (the industrial sector; papers represented a range of different industrial sectors including automotive - assemblers and autoparts; computer, electronics - audio and video, circuit design, etc.; and aircraft), and the research approach, i.e. the research methods used in the paper, classified according to FILIPPINI (1997): case study, field study, laboratory experimentation, modelling, simulation, survey, and theoretical/conceptual, and 'others' (research approach is unclear or use of other approach, e.g. action research). Table 5 presents relevant selected journal

Table 5. Paper classification on modularity.

Research Focus	Research Approach	Area of Application	References
Design	Theoretical-conceptual	No specific area	WHITNEY (1992)
			ASSAN et al. (2004)
		Computer	BALDWIN & CLARK (1997)
		Various (aircraft, automotive, etc.)	SANCHES; MAHONEY (1996)
	Case study	Electronics (measuring device)	MARSHALL et al. (1998)
	Theoretical-conceptual	Computer (printer)	MARTIN & ISHII (2000)
		Various (tools, boiler, etc.)	STONE et al. (2000)
		Various (aircraft, furniture, etc.)	HUANG (2000)
		No specific area	KUSIAK (2002)
		Computer (notebook)	HOETKER (2002)
		Aircraft and electronics (TV)	FUJITA (2002)
		No specific area	HÖLTTÄ (2002)
		No specific area	HÖLTTÄ et al. (2003)
	Survey and case studies	Various (aircraft, computer, etc.)	ISHII & YANG (2003)
		No specific area	EGGEN (2003)
Production	Theoretical-conceptual	Automotive	MARX et al. (1997)
			MORRIS et al. (2004)
	Case study		PIRES (1998)
		No specific area	BI & ZHANG (2001)
			PIRES (2002)
			FREDRIKSSON (2002)
Organizational	Case study	Automotive	COLLINS et al. (1997)
			MCALINDEN (1999)
		Automotive and computer	SAKO & MURRAY (1999)
		Transport equipment (elevators)	MIKKOLA (2001)
			MIKKOLA & GASSMANN (2003)
		Automotive	CAMUFFO (2001)
			SAKO (2003)
			DORAN (2003; 2004)
		Aircraft	SOSA et al. (2003)
		Electronic	LAU & YAM (2005)
		Electronic and software	STAUDENMAYER et al. (2005)
Various	Theoretical-conceptual	Automotive	MERCER (1995)
			ISHII (1998)
		No specific area	LANGLOIS (1999)
			SAKO & MURRAY (2000)
			BALDWIN et al. (2003)

papers on modularity categorised according to research focus, research approaches, area of application, and their respective reference source. The main outcome of this literature review is the 38 identified papers presented in Table 5 (the last column, 'references', shows the selected papers in each group).

As can be seen in Table 5, modularity has become a focus of attention over the past ten years or so. Several issues on modularity have been explored in the literature. It is worth mentioning that the present analysis is no exhaustive since this is part of an on-going research project. Having presented the classification in Table 5, the subsequent stage of this work was to identify research issues associated with modularity. These issues are discussed next.

9. Research issues on modularity

Table 6 presents a research agenda by suggesting topics based on the literature analysis according to the types of modularity (design, production, and organizational). In addition, potential research approaches are also suggested (AR – action research, CS – case study, SR – survey research, MS – modelling and simulation, TC – theoretical-conceptual). These research approaches are not unique, i.e. more than one may be employed. Furthermore, it is necessary mentioning that the choice of the research approach is also dependent upon the type of research question to be developed in each research design.

10. Concluding Remarks

This paper has analysed part of the literature on modularity. An understanding of the broad literature and thus the context in which the research is being conducted is a relevant step for any research project. In addition, by mapping the literature, it was possible to identify how the topic was influenced by existing theory. In doing so, a research agenda on modularity, according to its main research focus, is suggested as well as its respective research approaches. The most prominent focus for further research work is the need of developing a conceptual model able to represent modularity in its three principal domains. This could be accomplished through a theoretical-conceptual approach. In addition, another issue to be investigated is to explain how modular design concept affects other types of modularity (production and organizational) and its managerial implications.

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Table 6. Proposed research agenda.

Research focus	Topic to be investigated	Research approach
Design	representation and formulation of modular product development	TC
	cost and performance trade-offs in modular product design	CS, MS
	module size and boundaries definition	MS, TC
	knowledge management in modular product design	TC
	collaborative design of modular product design	SR, CS
	impact of modular design on manufacturing process and systems	TC
	contribution of modular design in organizational processes	SR, CS
	modular development decisions in conceptual design phase	TC
	the relation between of modularity and degree of innovation	SR, CS
	(re)organization structure for new product development	TC
Production	lead time measured from when components are ordered	CS, MS
	impact of variety/commonality of components for production	CS, MS
	efficiency in manufacturing due to modular product design	CS, MS
	production configuration due to modular decision	CS, MS
	complex and ergonomically difficult tasks in modular production	CS
	changes in quality assurance and control due to a modular production	CS, TC
	challenges in production management due to modularity	TC
Organizational	service operation complexity due to modular product design	CS
	warranty costs due to modular product design	CS, MS
	new investments in plants, and merger and acquisitions	TC
	buyer-supplier relationships within a modular concept	CS
	outsourcing decisions when adopting modular product design	AR
	strategic flexibility through modularity in organization design	TC
	choice of suppliers based on their modular technical capabilities	CS, TC

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