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A review of modular strategies and architecture within manufacturing operations

D Doran* and A Hill
Kingston University, Kingston upon Thames, Surrey, UK

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Abstract: This paper reviews existing modularity and modularization literature within manufacturing operations. Its purpose is to examine the tools, techniques, and concepts relating to modular production, to draw together key issues currently dominating the literature, to assess managerial implications associated with the emerging modular paradigm, and to present an agenda for future research directions. The review is based on journal papers included in the ABI/Inform electronic database and other noteworthy research published as part of significant research programmes. The research methodology concerns reviewing existing literature to identify key modular concepts, to determine modular developments, and to present a review of significant contributions to the field. The findings indicate that the modular paradigm is being adopted in a number of manufacturing organizations. As a result a range of conceptual tools, techniques, and frameworks has emerged and the field of modular enquiry is in the process of codifying the modular lexicon and developing appropriate modular strategies commensurate with the needs of manufacturers. Modular strategies and modular architecture were identified as two key issues currently dominating the modular landscape. Based on this review, the present authors suggest that future research areas need to focus on the development and subsequent standardization of interface protocols, cross-brand module use, supply chain power, transparency, and trust. This is the first review of the modular landscape and as such provides insights into, first, the development of modularization and, second, issues relating to designing modular products and modular supply chains.

Keywords: modularity, strategic options, product architecture, operations, supply chain management

1 INTRODUCTION

Industry experts estimate that the European market for interior modules generated approximately €23.7 billion in 2003 and is expected to more than double by 2012; the overall market for interior modules in Europe is projected to grow at more than 10 per cent annually [1]. Similar levels of growth have been reported in North America where revenue from exterior modules (front-end, door, roof, and rear-end modules) in 2004 totalled $860 million and is predicted to reach $7850 million in 2011. Such growth has led to an increase in academic and practitioner research focused upon developing frameworks and concepts to enable a clearer understanding of modularity in different sectors, the positioning of modularity within the broad field of supply chain management, the role of modularity within the context of strategic operations management, and issues relating to module design, function, and interface protocols. This paper will focus, primarily, upon two key areas that currently dominate the modular literature, namely modular strategies and product architecture, and will describe how such aspects of modularity are likely to influence the value creation process and the organization of modular supply chains. In addition, the paper will examine the influence that the modular paradigm is likely to have upon current and future research activity.

*Corresponding author: Kingston University, Kingston Hill, Kingston upon Thames, Surrey, KT2 7LB, UK. email: d.doran@kingston.ac.uk

Perhaps the pivotal and most cited reference in the field of modularity is the work of Starr [2], who called for ‘combinatorial’ production practices that could accommodate and harness the power and potential flexibility made possible by module interchangeability. Assessing modularity from a historical perspective [3] and reviewing more recent applications of modularity [4], researchers concur that combinatorial interchangeability remains a key aspect of the modular paradigm and is a necessary prerequisite for the successful development of a modular strategy. While interchangeability is at the heart of modular thinking there are a number of subresearch areas that reveal a myriad of modular perspectives [5–12]. In addition to this broadly strategic focus there is a significant and growing body of research focusing upon issues relating to the role of product architecture within a modular context [13–15].

2 REVIEW METHODOLOGY

The research reviews existing modularity literature within manufacturing operations. This review is based on journal papers within the ABI/Inform electronic database and other noteworthy research published as part of a significant research programme (such as the International Motor Vehicle Program). A keyword search for papers containing either the word ‘modularity’ or ‘modularization’ identified 283 articles. Of these, 80 per cent were subsequently disregarded because they were not relevant to manufacturing operations. The remaining 57 articles were then analysed to codify the tools, techniques, and concepts presented. The key issues currently dominating the literature were found to be modularity definitions, module drivers, modular strategies, and product architecture. Based on this analysis, the managerial implications of the emerging modular paradigm are discussed and an agenda for future research is presented.

3 MODULARITY DEFINITIONS

Modularization has been described [8] as ‘... a vaguely defined and ambiguously used term’. Such ambiguity has led to the development of a number of modular definitions (Table 1) and a plethora of terms used to describe aspects of modularity (Table 2).

Tables 1 and 2 reveal a number of key modular issues and themes: decomposition, module independence, interface protocols, managing complexity, standardization, and product architecture. The following section of this paper will address issues relating to modular strategies (determining which approach to designing and building modules is most appropriate to original equipment manufacturers (OEMs) and their suppliers) followed by a review of product architecture (particularly interface protocols, decomposition, and module independence). Finally, the paper will conclude with a discussion outlining current and future research perspectives and issues that are likely to dominate the modular landscape.

4 FACTORS INFLUENCING MODULE DEVELOPMENT

The benefits of the modular approach have been explored within a number of manufacturing (particularly the automotive manufacturing sector) and

<table>
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<th>Reference</th>
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<tr>
<td>McAlinden et al.</td>
<td>Modularity refers to components or elements of a product or process that can be made independently in different organizations and then assembled by a system integrator with predictable effect</td>
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<tr>
<td>Baldwin and Clark</td>
<td>‘... building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole’</td>
</tr>
<tr>
<td>Camuffo [8]</td>
<td>‘... a vaguely defined and ambiguously used term in the auto industry ... a broad concept, applicable and applied to a number of systems (product design, manufacturing, work organisation, etc)’</td>
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<tr>
<td>Sako and Murray [17]</td>
<td>Modularity is a bundle of characteristics that define, first, interfaces between elements of the whole, second, a function-to-function component (or task-to-organization unit) mapping that defines what those elements are, and, third, hierarchies of decomposition of the whole functions, components, and tasks</td>
</tr>
<tr>
<td>Langlois [5]</td>
<td>Modularity is a very general set of principles for managing complexity. By breaking up a complex system into discrete pieces, which can then communicate with one another only through standardized interfaces within a standardized architecture, what would otherwise be an unmanageable spaghetti tangle of systematic interconnections can be eliminated</td>
</tr>
<tr>
<td>Sanchez and Collins</td>
<td>‘... a way of improving the strategic flexibility of an organization by improving the adaptability and “evolvability” of its product and process architectures’</td>
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Table 1 Modularity: definitions
service environments [6–8, 10, 11, 16, 21–27], revealing the extent and scope of modularity across sectors. Factors influencing module development within the automotive sector include declining sales per vehicle; shorter product life cycles and the need to provide new models on a global basis have contributed to the need for vehicle manufacturers to seek ways of reducing costs while maintaining product variety [27]. The adoption of modular production and assembly can be seen as a natural progression of the lean–agile paradigm in seeking to find further ways of achieving cost efficiency within a sector characterized by over-capacity and intense competition while at the same time accommodating the need for greater flexibility. Many of the world’s leading vehicle manufacturers have embarked upon modular production and have developed plants designed specifically to accommodate modularity concepts. For example, Volkswagen (VW) designed its new ‘green field’ Resende plant in Brazil based on the ‘modular consortium’ concept. VW invested US$ 250 million in land, buildings, and infrastructure for nine first-tier suppliers who then, in turn, invested a similar amount in capital equipment. VW human resource policies are used across all facilities, but suppliers are responsible for organizing and managing all assembly operations and can only use them to supply VW products [28]. Another example is found at Mercedes–Benz/Smart where groups of suppliers called ‘system partners’ surround the car assembly plant in Hambach in France. Each system partner is responsible for building large modules such as cockpit modules, rear-axle modules, and door modules and for delivering them directly to the Smart final assembly line. Even operations traditionally kept in house, such as body welding and painting, have been outsourced [29]. Volvo’s application of modularity in production demonstrates how efficiency of a modular assembly system can be achieved [30]. The benefits of modularity have been explored by a number of researchers who contend that modularity is central to achieving reduced time to market by reducing time-consuming component redesigns by first working out and standardizing the component interface specifications in new product architecture which accommodate greater flexibility (to meet changing customer demands), speed, and expanded design capability (the use of modules should significantly shorten the time to piece together new products) and reduced costs [10, 14, 31]. Perhaps the overriding issue associated with modularity and which is implicitly or explicitly noted in the above review is the need to reduce ‘complex systems’ which are made up of many parts that interact in a composite manner [20]. Reducing the complexity is a primary objective of modularity and encapsulates the efforts being made to accommodate modular thinking and modular production.

5 MODULAR STRATEGIES

Over 40 years ago, Starr [2] wrote an enthusiastic article entitled ‘Modular production – a new concept’ which, in his words, promised ‘to put production executives once again in top management, and to give consumers wider ranges of choice among products’. According to Starr, greater choice would be possible using a ‘Modular production’ approach which would accommodate increased variety and provide the potential for greater rates of innovation. In essence, Starr’s work was to act as a catalyst for a change in manufacturing approaches and was to herald new forms of productive alliances and

Table 2 Definitions of modular terms

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<tr>
<th>Term</th>
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<tr>
<td>Modularization</td>
<td>The opportunity for mixing and matching of components in a modular product design in which the standard interfaces between components are specified to allow a range of variation in components to be substituted in a product architecture [9]</td>
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<td>Modular system</td>
<td>A system composed of units (or modules) that are designed independently but still function as an integrated whole [16]</td>
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<td>Modular innovation</td>
<td>An innovation that changes only the relationships between core design concepts of a technology without changing the product’s architecture [19]</td>
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<tr>
<td>Modularity in design (MID)</td>
<td>Choosing the design boundaries of a product and of its components so that design features and tasks are interdependent within and independent across modules [17]</td>
</tr>
<tr>
<td>Modular product architecture</td>
<td>An architecture in which each physical ‘chunk’ implements a specific set of functional elements and has well-defined interactions between the ‘chunks’ [13]</td>
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<tr>
<td>Modular architecture</td>
<td>As having a one-to-one mapping from functional elements to the physical components of the product [20]</td>
</tr>
<tr>
<td>Modular innovation</td>
<td>An innovation that changes only the relationships between core design concepts of a technology [19]</td>
</tr>
<tr>
<td>Product architecture</td>
<td>The scheme by which the function of the product is allocated to physical components, i.e. the arrangement of functional elements, the mapping from functional elements to physical components, and the specification of the interfaces among interaction physical components [20]</td>
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commercial relationships, particularly within the growing computing sector of the 1960s. It is this sector that Baldwin and Clark [16] addressed by charting the progress of IBM’s first and most significant foray into modular production in 1965. IBM developed a modular approach to producing the first modular computer (the System/360) moving from what could be described as an ‘integral’ strategy (characterized by the manufacture of unique operating systems, processors, peripherals, and application software) to a modular system of design and production characterized by ‘product families’ using the same instruction sets and peripherals. Baldwin and Clark (p. 85 of reference [16]) contended that this latter approach was premised upon ‘modularity in design, that is, the System/360’s designers divided the designs of the processors and peripherals into visible (relating to overall visible design rules that determined how the different modules of the machine would work together) and hidden (those elements that had no effect on other modules) information’. Like Starr [2], Baldwin and Clark added to the growing modular vocabulary to elucidate understanding of the three ‘visible’ design rules governing the modular approach.

1. **An architecture** specifies what modules will be part of the system and what their functions will be.
2. **Interfaces** describe in detail how the modules will interact, including how they will fit together, connect, and communicate.
3. **Standards** test a module’s conformity to the design rules (can module X function in the system?) and measure one module’s performance relative to another (how good is module X versus module Y)?

Sako and Murray [17] drawing upon the work of Baldwin and Clark and research undertaken as part of the International Motor Vehicle Program describe three arenas of modularization which accommodate current thinking and current activity within and across the modular landscape.

1. **Modularity on design (MID)** involves choosing the design boundaries of a product and its components so that design features and tasks are interdependent within and independent across modules. MID therefore accommodates a reduction in complexity resulting from interdependence of design parameters, shorter development lead times through parallel development of modules, and rapid adoption of new technology by upgrading individual modules separately.

2. **Modularity in production (MIP)** accommodates flexible manufacturing by taking complex and ergonomically difficult tasks off the main assembly to realize high product variety without increasing production costs.
3. **Modularity in use (MIU)** allows high product variety by offering consumers the choice to ‘mix-and-match’ options (or modules) to meet their taste.

In a similar vein, Arnheiter and Harren [3] presented a typology of modularity.

1. **Manufacturing modularity** is described as an approach that produces fully finished products by using only a handful of pre-manufactured subassemblies (the modules). Companies often use manufacturing modularity to accommodate mass customization (e.g. Dell).
2. **Product use modularity** implies the use of modules to accommodate product customization by the user. Examples include local area network cards, bicycle components, and computer drives.
3. **Limited life modularity** implies the use of disposable modules that are easily replaceable, are easily accessible and have well-defined interfaces.
4. **Data access modularity** consists of the use of data access modules which include pen drives, compact disks (CDs) and digital versatile disks (DVDs) whose main purpose is to provide data storage separately from the system in which they are used.

One issue that is evident from the above review is that moving from traditional to modular manufacturing is complex. Recognizing this complexity, Helper et al. [32] suggested a number of possible strategies.

1. Modular design is utilized for some subsystems but not where costs outweigh benefits.
2. Modules are automaker specific with OEMs avoiding or blocking industry in their design functionality, technical standards, and common interfaces.
3. Only some modules are outsourced with critical modules produced by the OEM outsourcing non-modular components.

Perhaps a key issue in this outsourcing environment is to consider the implications that transferring value to module suppliers has upon the ‘modular supply chain.’ In this regard, Doran [11] examined a developing modular supply chain and noted a number of distinct characteristics associated with the modular strategy. Initially, accommodating modular supply involves complexity, a need to focus upon...
core module activities, and the need to reorganize activities that are not regarded as critical to the supply of modules. Significantly, adopting a modular strategy has implications not only for the OEM and/or its module suppliers but also for other suppliers further up the supply chain (Fig. 1).

Traditionally, value creation increases as the product moves towards the OEM; within a modular supply chain the OEM transfers a degree of value creation activity towards the first-tier module supplier who is likely to transfer non-core activities to second-tier suppliers, and so on. This value transfer activity is likely to have the most impact upon the suppliers close to the module assembler within a modular supply chain where a significant degree of value creation activity is likely to reside.

While there are a number of strategic options available to OEMs and to module suppliers, it is apparent that adoption and implementation of the modular paradigm in different countries and across different sectors has yielded a variety of results.

Within an American context, Sturgeon [33] noted that Ford and General Motors have retained vehicle design and final assembly, spun off their internal components divisions and outsourced an increasing volume of component and module design and production to ‘first-tier’ suppliers. Examining supply chain modularization within a Japanese context, Ikeda and Nakagawa [31] found that the Japanese initially fell behind the European automobile industry and only embarked upon a full-scale approach to modularization in the year 2000.

It was also noted that there appear to be two approaches being adopted by Japanese OEMs:

(a) European-style modularization led by Nissan and Mazda and referred to as ‘light-type modules’ involving assembly by the module supplier rather than involvement in the manufacturing process of unit parts;

(b) the ‘corporate community’ approach led by Toyota and Honda and referred to as ‘heavy-type modules’, which necessitates module supplier involvement in the manufacturing process of unit parts.

An interesting and innovative approach to examining the role of suppliers has been explored by Momme et al. [32] who examined the link between production modularization and strategic sourcing at Bang & Olufsen, Danish producers of high-quality innovative household entertainment products (radios, music systems, etc.). Momme et al. found that the company use the biological metaphor of ‘organs’ to describe their approach to modularity. The metaphor is regarded as essential in terms of describing the interfaces between critical components, i.e. the links between vital organs such as brain, heart, and lungs and how they must operate in order for the body to function effectively. Essentially, Bang & Olufsen specify the documentation required for ready-to-assemble modules that can be sourced mainly to system suppliers within their extended supplier network; the company does not consider the task of fitting standard modules as being a critical aspect of its operations. Critical to the success of such a strategy is to ensure that decisions relating to developing an appropriate product architecture are reached at the research and development stage so that the ‘vital organs’ (modules) function as one at the system level.

6 PRODUCT ARCHITECTURE

Product architecture has been described by Ulrich [20] as ‘the scheme by which the function of the product is allocated to physical components, that is, the arrangement of functional elements, the mapping from functional elements to physical components, and the specification of the interfaces among inter-

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**Fig. 1** Value transfer activity within a modular supply chain (source: [11])
action physical components’. Ulrich states that the scheme can be divided into three distinct elements:

(a) the arrangement of functional elements (the function of a product is what it does as opposed to what the physical characteristics of the product are);
(b) mapping from functional elements to physical components (a component is defined as a separable physical part or subassembly; physical components implement the functional elements of the product);
(c) the specification of the interfaces between interacting physical components (an interface specification defines the protocol for the primary interactions across the components interfaces, and the mating geometry in cases where there is a geometric connection).

Perrson and Ahlstrom [4] applied Ulrich’s scheme using the example of a car. The function of a car is to transport and this function can be divided into subfunctions (accommodating safe (body integrity) and comfortable transportation (which may refer to seating modules, heating, ventilation, and air-conditioning systems, etc.)); these subfunctions can then be allocated to discrete operating modules. The second element of Ulrich’s scheme concerns how these subfunctions are realized through the process of mapping. In many ways this element is likely to reveal the complexities associated with modular design. Take, for example, a seating module. This module accommodates a number of functions (safety (airbags and seat belts), passenger comfort (heating and, increasingly, electrical systems)) and as such spans a number of product areas and a number of supplier skill sets and competencies. Addressing the third element of Ulrich’s scheme, namely interface protocols, Baldwin and Clark [16] stated that interfaces describe, in detail, how modules will fit together, connect, and communicate. To achieve interface compatibility it is necessary to create standard design rules that accommodate the idea of interdependence within and independence across modules. Ulrich and Eppinger [13] classified two types of product architecture which they describe as follows: first, modular architecture, where chunks implement one or a few functional elements in their entirety and the interactions between chunks are well defined and are generally fundamental to primary functions of the product; second, integral architecture where functional elements of the product are implemented using more than one chunk, a single chunk implements many fundamental elements, and the interactions between chunks are ill defined and may be incidental to the primary function of the product. Sanchez [14] noted that ‘modular product architecture is created when the interfaces between functional components are designed to allow the mixing and matching of different components to rapidly configure product variations’. A desktop computer is cited as a familiar example of a modular product architecture in which a range of microprocessors, memory cards, disc drives, monitors, keyboards, and USB slots can be combined to offer a vast number of product variations without incurring those costs that traditionally accompany product variation and flexibility. This view is supported by Ulrich [20] whose typology of product architectures distinguish between a modular architecture (which includes a one-to-one mapping from functional elements (what each element is supposed to achieve) in the function structure to the physical components of the product and specifies decoupled interfaces between components) and an integral architecture (which includes a complex (not one-to-one) mapping from functional elements to physical components and/or coupled interfaces between components). A modular architecture accommodates greater variety, build-to-order capability, and lower inventory costs. Continuing the modular classification, Erens and Verhulst [35] identified four types of product architecture (Fig. 2).

Type 1 depicts a situation where a single function is delivered using a single module while type 2 product architecture refers to functions that are represented by multiple modules; types 3 and 4 represent situations where multiple functions are designated to one or more modules. Jiao and Tseng [36] took the idea of product architecture a step further through the examination of product family architecture, which defines the underlying architecture of a firm’s product platform within which a choice of product variants can be derived from basic product designs to satisfy a spectrum of customer needs related to various market niches.

Developing their own classification, Sanchez and Collins [18] broke down product architecture into two distinct properties:

(a) the decomposition of the overall functionalities of a product into specific functional components that make up the technical structure of the product;
(b) the interface specifications that define how the various functional components will interact with each other when they function together in the product.
Furthermore, Sanchez and Collins noted that product architecture becomes modular when the following hold true.

1. Interfaces between functional components are specified to allow variations in components to be substituted into the product architecture.
2. Interface specifications are then standardized, i.e. not allowed to change during the commercial lifetime of the product. Such standardization, according to Sanchez and Collins, accommodates substitutability of component variations which allow the firm to mix and match component variations in a modular architecture to configure product variations that offer different combinations of component-based functions, features, and performance levels.

Modularity centres upon reducing the complexity associated with the manufacture of intricate products. Therefore, it is necessary to identify and evaluate how the architecture of a product is likely to be influenced by a move towards modular production from traditional manufacturing practices. For example, does it encourage or is it designed to facilitate the production of discrete elements that can then later be assigned to a larger part before being combined to form a discrete element of the larger whole?

7 DISCUSSION

This literature review has demonstrated that two key issues currently dominate research into modularity and modularization: strategies relating to developing modules and understanding how such strategies are influenced and shaped by decisions concerning product architecture. While there are many factors that both practitioners and academics will need to examine in order to explore fully the operational dynamics associated with the modular paradigm, perhaps the fundamental issue that will determine the success or otherwise of modularity (particularly within sectors that are currently developing modules, e.g. the automotive sector) will be the development and subsequent standardization of interface protocols to support the cross-brand use of modules. Although there is evidence of inter-brand modularity, there is some way to go before the automotive sector replicates the degree of MIU that is so prevalent within the computer sector. What are likely to be the overriding issues within such an environment? The debates that have dominated the supply chain and operations literature during the last two decades, namely supply chain power [32], supply chain transparency [38], and issues relating to trust [19, 39], are likely to be researched from the module supplier perspective since many of the value creation activity and supply chain management issues are likely to reside with the module supplier rather than with the OEM [11]. Turning particularly to the issue of power, it could be argued that, as the degree and pace of modularity increase, so too will the power of module suppliers (Fig. 3). However, such power transfer will depend upon the modular strategies adopted by OEMs.

Figure 4 demonstrates power dispersion using four alternative scenarios.
1. **Fringe modularity.** In this instance, the OEM controls production by either owning this operation itself or having contractual relationships in place with its suppliers. The OEM maintains tight control over all activities and has made very little, if any, attempt to pursue modularity.

2. **Controlled modularity.** Here the OEM has started to develop and implement a modular production strategy but still wishes to maintain control. This demonstrates reluctance by the OEM to transfer power to its suppliers and move into a more collaborative relationship. As such, limited benefits are achieved.

3. **Passive modularity.** The OEM has chosen to outsource most, if not all, of its production operations to suppliers. However, there is no modularity within the supply chain in terms of either the design of the products being supplied or how the supply chain operates. This demonstrates that outsourcing has typically occurred as a discrete activity rather than as part of a well-defined strategy.

4. **Aggressive modularity.** The OEM works in collaboration with its suppliers to design and develop products and to manage the whole supply chain most effectively. A significant proportion of production operations has been outsourced, but there is a well-defined modularity strategy in place. Suppliers tend to have full responsibility for the management of all assembly operations and to work together with both the OEM and other suppliers to design products and to develop long-term modularity strategies.

The scenarios identified above are likely to influence the nature and scope of buyer-supplier relationships and reposition the debates that, to a large degree, have been the preserve of the OEM and their key suppliers. Like any new approach to creating value the modular approach is not without its limitation and risk. Starr [2] noted the following.

1. Many production managers have not familiarized themselves with the technological problems of combinatorial design involved in modular production.

2. Modular production will bring with it significant costs in the form of obsolescence. Obsolescence occurs not only with respect to the present product line but also with respect to present configurations of plant and facilities.

While Starr’s work was conducted over 40 years ago, his observations are still likely to be valid today as OEMs and suppliers engage in strategies to accommodate the modular approach. Arnheiter and Harren [3], examining the risks of modularity from both the assembler and supplier perspectives, demonstrated that the assembler risks include the reduction of entry barriers, loss of design control, design limitations, and the potential lack of supplier competencies; risks to the supplier include the eventual commoditization of modules and increased labour and capital costs.

Within an organizational context, Henderson and Clark [19] contend that organizations are built around stable product architectures that define key functional relationships, information-processing capabilities, communication channels, and information filters. Once a dominant design has emerged, it is encoded and thus becomes embedded in the
organizational set-up, which is why architectural innovation represents such a subtle and dangerous challenge for incumbents (module suppliers); those OEMs that wish to embark upon modular strategies need to recognize that knowledge transfer will be critical to the success of such a strategy. In a similar vein, Fleming and Sorenson [40] and Ethiraj and Levinthal [41] suggested that, while a modular design strategy makes product development more predictable, it can undermine the innovation process and impede the opportunities for breakthrough advances. This view was supported by Araujo [42] who noted that product architectures leave imprints on organizational and supply chain architectures and, as a consequence, constrain and impede future architectural shifts. This focus upon organizational issues has been explored by Morris and Donnelly [43] who stated that modularization strategies depend for their success on shifting organizational responsibilities, functions, and risks to suppliers, which can only work in the long term if suppliers are willing to accept lower rates of return than assemblers and/or they are better equipped to undertake the responsibilities and functions required to manage the inherited risk portfolio.

8 CONCLUSION AND IMPLICATIONS FOR FUTURE RESEARCH

This paper has demonstrated that the modular paradigm is growing and has been utilized in a number of manufacturing and non-manufacturing environments. Two key issues currently dominate the modular literature: strategic options and product architecture. With regard to the former, the literature offers insights and options both for OEMs and for suppliers wishing to offer modular solutions; the latter issue in many ways demonstrates the difficulty that module suppliers may face when trying to manage the operational difficulties associated with designing, producing, and managing the module supply chain. The modular logic necessitates a new type of supplier, namely a supplier that can accommodate associated intricate products and can also manage those upstream suppliers that contribute to the various elements that constitute a module. In addition, as OEMs continue to transfer value to module assemblers, it is likely that such suppliers will in turn seek to transfer non-core elements of their activities to second- and third-tier suppliers, resulting in what can be termed value transfer activity [11].

At present, the automotive sector as a whole does not have an industry view on what constitutes a module and does not appear to be moving towards the modular ‘plug-and-play’ approach adopted in the computer sector where modules are completely interchangeable via standardized industry-wide interface protocols. This latter issue provides opportunities for future research, particularly in terms of examining the moves being made by manufacturers to establish industry standards. In addition, there is scope to apply Ulrich’s [20] modular schema at the system and subsystem level in order to explore the more intangible dimensions associated with modular production. Sako’s ‘paths to modularity’ [7] can be applied to OEMs in the major and developing automotive markets while the ‘types of product architecture’ described by Erens and Verhulst [35] can be applied at both the tangible (module) and the intangible (design) levels. The modular approach to production represents a significant shift in supply chain research; this shift presents many opportunities to codify and develop thinking within the emerging modular environment and to test and extend existing models and concepts.

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