GSB WORKING PAPER
NO. 23

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ISSN 1323-7853

ISBN 1 74067 112 0

October, 2001

CRICOS Provider Code 00301J

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Working Paper Series 01.03 (Curtin University of Technology Graduate School of Business)

ISSN 1323-7853
ISBN 1 74067 112 0
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Abstract

Product modularity has been associated with organizational advantages such as enhanced learning at the component level, rapid determination of consumer preferences and low barriers to entry across an industry, along with disadvantages such as lower levels of radical innovation, higher development costs and an inability to derive a competitive advantage on the basis of product superiority. This paper considers these advantages and disadvantages in terms of two contextual factors: the level of control that is exerted over the information structures and the degree of change across the information structures. The aim is to provide a starting point for discussing some of the contextual factors that affect the ability for product modularity to be used as a strategic tool.

Product Modularity and the Contextual Factors that Determine Its Use as a Strategic Tool

The Emergence of Modularity as a Strategic Tool

The standardization of components within products to derive economic efficiencies goes back to Adam Smith in the way that standardizing components within a product was an underlying necessity for the efficient division of labour. In the 19th Century standardization of components was underpinning considerable mass production. For example, prior to the introduction of Winchester rifles, all firearms were crafted individually. The bolt on a rifle was built for a specific rifle and could not be interchanged with any other rifle, even those of the same brand. Standardizing parts and allowing for parts to be interchanged across rifles (on the battlefield) was a key part of the success of the Union Forces in the US Civil War. By the early 20th Century industries such as the automobile industry were establishing industry-wide standards in basic components allowing for some level of interchangeability (Epstein, 1928). As competitive pressures increased various industries were driven, or chose to move towards, modular product architectures for a variety of reasons (Schilling and Vasco, 2000). In the computer industry, the modular IBM PC was a result of IBM trying to quickly catch up to Apple and thus using a series of components from other companies. In the aircraft construction industry Boeing introduced a modular structure as a way to reduce costs in the development of the 777, and in the automobile industry utilizing the same engine or platform was one way to spread the huge development costs across a greater number of vehicles. Sony has moved to modular product architectures to gain a better understanding of consumers' needs and the mobile telecommunications industry has introduced elements of modularity to the cell phone industry to ensure compatibility for users and to encourage the development of complementary products and services.

The effect of introducing modular product architectures has been inconsistent. For IBM, the PC was in many ways their first step to losing their position of dominance in the computer industry, yet the modular System/360 was hailed as one of their great successes. For many automobile manufacturers (Chrysler, General Motors and

Volkswagen), modularity has been successful in reducing overall cost structures. These and other inconsistent outcomes in relation to introducing modular product architectures compelled us to consider some of the contextual factors that we believed might explain the extent to which modularity can be used as a strategic tool. This represents the first step of the investigation process; a review of how some key contextual factors affect the outcomes of product modularity.

What is Modularity?

Modules are parts within a larger system that are structurally independent, but work together to create functional system. Where the system is a complex product, the modules are components. "A component in a product design performs a specific function or functions within a system of interrelated components whose collective functioning creates the overall functionality of the product" (Sanchez and Mahoney, 2000: 160). Thus a complex product such as a watch is made up of a series of components. Beyond the way that these components interface with each other, these components are structurally independent, but together work to provide an operational product. What differentiates modular product architectures from non-modular product architectures is the way the various components interface. Modular products have defined interfaces whereby each component connects and interacts with every surrounding component in a predefined manner. Hence the deconstruction of systems such as complex products into an architectural map of components provides us with the building blocks for modularity – components and defined interfaces.

An outcome of adopting a modular product architecture is that single components can be developed and manufactured independently of what occurs in respect to other components. Modular products therefore derive advantages in that they, "allow each functional element of the product to be changed independently by changing only the corresponding components [whereas] . . . fully integral components require changes to every component to effect change in any single functional element" (Ulrich, 1995: 426). Elements of modular systems can therefore be constantly changed or upgraded without the need for an entire system overhaul (Galvin, 1999).

Modularity as a Strategic Tool

This ability to alter individual components independently of each other has been linked to a number of organizational advantages such as the potential for enhanced learning at the component level (Sanchez and Mahoney, 1996), rapid determination of consumer preferences through releasing multiple versions of the same category of product (Sanchez and Sudharshan, 1993) and low barriers to entry for the industry through the non-integrated nature of the product (Langlois and Robertson, 1992). However, it has also been suggested that there exist some disadvantages associated with instituting product modularity, the most notable being the limitations that exist in terms of more radical forms of innovation (Galvin, 1999), higher development costs (Baldwin and Clark, 1997) and from an organizational perspective, the inability to derive a competitive advantage on the basis of product superiority (e.g. see Morris and Ferguson (1993) regarding the DEC developed RISC based operating system). Product modularity can therefore be positioned as a strategic tool that can be used by many organizations (or even industries) to advantage, but may concurrently have a number of downsides and limitations that to date have not been fully explored.

A classic example of how modularity can form something of a two edged sword is the rise of the Sun workstation relative to the early leader in the industry, Apollo. As the first mover in the industry Apollo started with a significant installed base, but Sun rapidly overtook Apollo through fully utilizing the potential of its open/modular approach (Garud and Kumaraswamy, 1993). Sun was able to attract many complementary firms into developing compatible products for the Sun workstations (most notably software products). This provided increased functionality for users as well as faster innovation rates leading to Sun becoming the leader in the workstation market. However, this open architecture/modular approach allowed a range of competitors to enter the workstation market, using the same basic architecture (Baldwin and Clark, 1997). Hence Sun became embroiled in another competitive battle, this time against building off its own product architecture. Thus the modular approach allowed for rapid development at the component level (as opposed to altering the entire system), in conjunction with developing creative scope for other firms to develop complementary products and services. However, the price for such an approach was that other firms could replicate Sun products, thus transferring the basis of competition from product performance attributes based around alternative architectures, to the speed at which innovations across a common architecture could be developed relative competitors.

The authors propose that the present quandary in terms of understanding the issues associated with modularity are typical of an area that has only relatively recently attracted considerable attention. They result primarily from the application of a basic definition to a series of circumstances without full consideration of the context. Modularity simply defines the standardisation of component interfaces within a product across time or across a family of products. But such standardization can occur in many different ways and be applied to a range of different situations. This paper seeks to outline some of those contextual factors that determine whether advantages or disadvantages can be expected on the basis of adopting a modular product architecture.

Key Advantages and Disadvantages of Modularity

Product modularity occurs when component interfaces are standardized allowing for components within a product to change without affecting other components within the product provided that the interface remains constant. Sanchez and Mahoney (1996) suggest that this allows for increased component level learning (and subsequent component level innovation) as firms are able to focus on developing capabilities in relation to single components. For example, in the computer industry, the large integrated manufacturers such as IBM and DEC have given way to specialist hardware and software producers, whereby most firms today compete in just one small segment of the industry. In this way for example, CD ROM manufacturers have been able to improve the speed of CD ROM drives enormously without being concerned about any other elements of the basic PC.

In a similar vein, by changing only one component at a time, manufactures are able to release multiple versions of a product in a short space of time, thus quickly determining consumer preferences. A good example of this was the Sony Walkman which saw over 160 variations of the product released using a modular product architecture (Sanderson and Uzumeri, 1997).

In addition, when interfaces are kept constant, components can be constantly improved, as shown in the computer example above. In many cases, such as the computer industry, this improvement process is driven by the constant rise and demise of specialist firms. Components are developed that can simply ‘plug and play’ and thus barriers to entry to the industry are kept low as an innovative product in demand and some supply capabilities are all that are required to break into the industry. It is this non-integrated nature of the product that Langlois and Robertson (1992) suggest lower the barriers to entry for the industry.

Whilst being able to focus on single components stimulates component level learning and innovation, the potential for more radical forms of innovation where component interfaces must also change is limited. In a study of the bicycle industry, Galvin (1999) showed that modularity and the fact that firms within the industry tended to specialise in limited areas meant that coordination was limited to the extent that architectural and radical innovations were extremely restricted. Thus the potential for more discontinuous forms of innovation can be limited within modular architectures as coordinating the simultaneous change of multiple components and their interfaces becomes very difficult.

In the same way, having a modular architecture whereby separate departments within IBM, as well as other firms, each worked on specific parts of the product significantly boosted the rate of component level innovation in the System/360. However, this same product is famous for the initial cost overruns incurred (Baldwin and Clark, 1997) as developing various modules of the product independently was very difficult. Thus when IBM developed its more famous modular PC, it used many existing off the shelf components and simply standardized the necessary interfaces (Baldwin and Clark, 2000).

Finally, modularity can limit the potential for a product based competitive advantage. For example, RISC [OS] (reduced instructional set computer operating system) was initially developed by DEC, but today Sun Microsystems and Microsoft dominate the field (Morris and Ferguson, 1993). Sun itself is working hard to avoid the same fate in the workstation market, having dispatched Apollo through clever usage of a modular architecture. A modular product architecture can thus limit the extent of product differentiation that can occur in respect of either the entire products or various components due to the invariable similarities in product/component functionality.

Thus, the advantages to be discussed are:

- higher levels of component level learning/innovation,
- quick determination of consumer preferences, and
- the lowering of barriers to entry within an industry.

The disadvantages to be covered are:

- the low levels of architectural and radical innovations,
- the high cost of developing a modular architecture, and
- the inability to develop a product based competitive advantage.

Key Variables Determining the Effect of Modularity

Product modularity is built around two forms of knowledge; component level knowledge of how components operate and interact, and architectural knowledge as to how components fit together to form a functional system. Component level knowledge is required to understand how different parts within a system operate. For example, in a CD player the digital data is read by a laser and is processed via a chip (microprocessor) that is at the heart of the system. Changing the capabilities of this chip has led to the advances seen in CD players in terms of their reading capabilities. However to change the chip, it is necessary to know both what the chip does (component level knowledge) and how it links with the other components as per the spatial interface (physical location of the component relative to others), the communication interface (how signals are exchanged) and the attachment interface (how the components actually interconnect). Characterizing product architectures in terms of these two forms of knowledge is not new. For example, Henderson and Clark (1990) differentiate between component level knowledge (how a component operates) and architectural knowledge (how components fit together to form a functional system).

Integrating these two forms of knowledge as to how a component operates and links to others to create a functional system has previously been termed in the product modularity literature as the product design information structure (Galvin, 1999).

Sanchez and Mahoney (1996) have also used the notion of an information structure to describe ‘the glue’ that allows a functional product to emerge from a series of interlinked components. In discussing modular products, they posit that a well defined information structure can act as an embedded form of coordination mechanism for loosely coupled organizational structures. In essence, firms that manufacture different components can operate autonomously because the critical task of coordinating the product development process no longer needs to occur as the information structure provides the coordination function ensuring that all components will operate effectively within the finished product.

Information structures are particularly important in modular products as they provide a knowledge map of how and why each component must link with others in the system to create product functionality. This knowledge of component operations and interfaces allows for a firm to focus upon a single component independently, the backbone of both the advantages and disadvantages associated with modularity.

Thus we propose that the first of the critical contextual factors to consider in modularity studies is who actually controls the information structure. The information structure can be controlled by a single organization or may be broadly diffused to form an industry standard. For example, firm controlled information structures are seen in General Motors with the Quad-4 engines that are used across a number of platforms (Ulrich, 1995), in the Black and Decker family of power tools that are built around a series of common components (Lehnerd, 1987; Utterback, 1994) or the Boeing 777 (Woolsey, 1994). Alternatively, the modularity can derive from an industry level standard. Examples of modular products where no firm has overriding control include bicycles (Galvin, 1999; Galvin and Morkel, 2000), both hardware and software in the computer industry (Baldwin and Clark, 2000) and bedding such that mattresses fit frames of the same size (e.g. queen or king size) as do sheets and other bed linen (Ulrich, 1995).

We posit that the second key contextual variable is the rate of change in these information structures. The information structure is essentially a specific form of knowledge and thus differing levels of dynamism can be expected in relation to changes in this knowledge. We suggest that the information structure can vary from being passive where virtually no change occurs through to active where change occurs on a regular basis. Passive information structures see the component interfaces remain constant over time. For example, in the bicycle industry a dominant design has existed for over 100 years. Some changes have occurred, such as in the 1980s the rear axle changed from being 130mm to 135mm (to accommodate more gears). However, most component interfaces have been constant for at least 50 years (Galvin, 1999). At the other extreme is an active information structure such as that found within the PC industry. For example, the hardware for the removable disc has changed from the 5¼ inch floppy disc to the 3.5 inch 'floppy' disc to the zip drive alternative and the new standard likely to emerge is either DVD RAM or DVD+RW formats (Weil, 1997). Distinguishing between these two contextual dimensions will now allow us to discuss the scenarios under which modularity advantages or disadvantages may arise.

The Role of the Contextual Variables

Increased component level learning

Increased component level learning (and innovation) would seem to occur under all conditions affecting modularity. Irrespective of whether the information structure is firm controlled or exists in the form of standards, entire firms or departments of firms are able to focus on just one component at a time without having to alter any other part of the product. Sanchez and Mahoney (2000: 166) suggest that the application of modular product architectures "enables more efficient learning and innovation at the component level to occur within widely dispersed, loosely coupled development organizations". Development of specialized capabilities built around a single component (or limited range of components) allows firms to focus on component innovation built around such capabilities. The classic example of this has been in the computer industry. The large integrated firms of IBM and DEC have lost their leadership positions to new specialists such as Microsoft, Intel, Cisco Systems and Sun Microsystems. Whilst the drivers for this fragmenting of the industry are complex, even IBM was unable to develop at the component level as quickly as the new specialist firms that were borne out of the introduction of the modular IBM PC in 1981.

In the same way, even passive information structures allow for high levels of component level learning. For example, even though the bicycle industry has had very few architectural changes in the last 50 years, incremental innovations have been common. Galvin (1999), using the Henderson and Clark (1990) innovation classification system showed a total of 128 incremental and modular innovations versus six radical and architectural innovations in a six year study of the bicycle industry.

Determination of consumer preferences

The rapid determination of consumer preferences is generally more common when the firm controls the information structure. Sony, for example, has used modularity for this purpose with both their Walkman product and their Hi-8 video cameras (Sanchez and Sudharshan, 1993). The basic platform remains constant and different components are trailed (such as different volume control systems) to determine the most popular designs and functions for the system. The same principle is being applied in relation to modular services such as where different financial products are packaged together under a single banner. Launching a number of these packages in short succession allows for consumer preferences to be determined in terms of the make up of these packages and the level of complexity that they may contain (in terms of number of products).

It is possible to use modularity to determine consumer preferences where information structures exist as standards. For example, an assembler such as Dell Computers can offer a range of options to the market (Magretta, 1998). However, the focus here seems to be on increasing the product range rather than determination of consumer preferences as a way of establishing the focus for future production. As the product is not built until the order is received, consumer preferences are only really determining the range of what should be offered and is not about what should be produced in large quantities (as is the case with the Sony products). Whether an information structure is passive or active does not affect the ability of a firm to derive this advantage from modularity.

Low barriers to entry

When firms control the information structure, they are able to exercise the same level of control that would exist with any firm that is outsourcing elements of production and thus barriers to entry are not lowered. Thus Chrysler retains control of their cars (Tully, 1993), Boeing maintains control over the 777 when choosing which suppliers to work with (Woolsey, 1994), and Volkswagen was able to choose the suppliers for their bus plant in South America (Lima, 1997; Marx, Zilbovicius and Salerno, 1997). Because suppliers to information structure controlling firms generally only manufacture a small number of components, they are not in a position to access the entire information structure. Thus the larger firm acts as the information structure gatekeeper, reducing the opportunity for the entire information structure to be transferred to other participant organisations. Thus in the case of the 777, the complete information structure resides entirely with Boeing.

In comparison, where information structures take the form of international standards, barriers to entry are lowered, such as in the computer hardware and software industries (Baldwin and Clark, 2000). Morris and Ferguson (1993: 88) indicate how in the computer industry "... for each layer of the network there are published standards and interface protocols that allow hardware and software products from many vendors to blend seamlessly into the network". These standards and protocols make it easy for there to be a continual move of firms both into and out of the industry.

In cases of international standards, passive information structures allow for barriers to entry to be at their lowest (as firms do not need to collaborate in any way and the industry is at its least integrated). For example, in the case of the bicycle industry Galvin and Morkel (2000) showed how the industry had fragmented into a number of sub-industries such that 90 percent of part manufacturers were producing only one type of bicycle part (Chu, 1997). When information structures are active, there needs to be some collaboration between major players in the industry to enact component interface changes, and exclusion from this key group can cause firms to be far more reactive and this alone may form some form of entry barrier. In the computer industry over twenty of the world's largest computer manufacturers collaborated to decide on the format for the next generation of disc drives (ie DVD RAM versus DVD+RW formats).

Reduced radical innovation

In relation to the disadvantages generated by modular product architectures, firm controlled information structures are unlikely to suffer from low levels of architectural and radical innovation. Nokia, for example, uses a modular approach in releasing its cellular phones. However, by controlling the information structure, radical innovations are able to be introduced. Nokia (along with Ericsson) were instrumental in moving from the initial analogue NMT air interface protocol to NMT-450 (a more advanced analogue standard utilizing some digital switching technology) and then to the TDMA based, digital GSM standard (Funk, 1998). Altering the air interface protocol meant changing the component interfaces and thus the product had to be significantly redesigned. It is for this reason we see significant differences in the technology available for CDMA (the dominant US standard) and TDMA standards. Nokia operate in both environments, but already have a chip-set that will allow for 18 days stand-by time in their TDMA phones, yet such technology will be more than a year away for Nokia CDMA phones. Thus Nokia has been able to introduce radical and architectural innovation as they move across different air interface protocols and thus need to redesign their phones. Hence radical and architectural innovation is not a problem when the firm controls the information structure.

In comparison, levels of architectural and radical innovation are believed to be very low when the information structure is broadly diffused to create international standards. The existence of international standards replaces active coordination between firms within the industry. As has been seen in the computer and bicycle industries, this in turn is likely to cause the industry to be less conducive for vertically integrated firms and see more firms specialising in a single segment of the industry, communicating only with those firms to whom they send their finished components (Baldwin and Clark, 2000; Galvin and Morkel, 2001). As architectural and radical innovations require changes to occur in the way the components are linked together for a modular product this is only possible when the component interface specifications change. Thus it is necessary for the manufacturers/developers of adjoining components to work together to institute the innovation. But with communication and collaboration between manufacturers of adjoining components not occurring, it is very difficult to introduce architectural and radical innovations unless a manufacturer makes a number of adjoining components.

As was shown previously, in the bicycle industry, there were only six architectural or radical innovations out of 134 identified by Galvin (1999) in a six year period. In the case of the computer industry, when there are moves to change components completely, many of the major players in the industry get together to decide upon a new standard. This was seen when twenty of the major hardware manufacturers worked together to agree upon a new standard for the removable disc drive.

When information structures are active, interfirm coordination tends to be systematic and thus radical innovations are possible. Overarching industry level bodies often exist to ensure that standards are jointly applied. For example, the Bluetooth consortium coordinates activities relating to the new wireless communication systems for computers and peripherals, and the International Telecommunications Union (ITU) is attempting to ensure that there is a common global standard for 3G cell phones - the next generation of broadband based cell phone air interface communication protocols (Glimstedt, 2001). In comparison, when the information structure is passive, these bodies tend not to develop as there are very few changes in the product architecture that need to be coordinated. Again the classic case is the bicycle where there is virtually no architectural or radical innovation, and no real supra-governance mechanisms for coordinating architectural or radical changes to the product architecture.

High product development costs

In terms of the high product development costs, this tends to be problematic when information structures are firm controlled. The firm needs to develop the entire architecture and does not just mix and match using existing components. The very high costs involved in developing new car platforms are a case in point. Every new platform involves a series of new interfaces and considerable development work, though it would be possible to simply develop a car using what is available from a range of component manufacturers. However, the potential for enormous cost overruns comes when a truly discontinuous innovation is attempted. The System/360 was a new generation of computers that was designed to be modular from the start and all levels of the computers in this family were to be compatible. It was a resounding success for IBM, though it has also been suggested that this was a make or break decision for IBM as the cost of the project eventually became so huge that it put the entire company at risk (Baldwin and Clark, 1997).

In comparison, when industry level standards exist, product development costs are relatively low as existing components can be combined to form the product. In comparison to the very high costs of the IBM System/360 the IBM PC was developed very quickly and cost efficiently. To counter the lead held by Apple in relation to the personal computer, IBM expanded its modular approach developed in relation to the System/360 to the extent of outsourcing many of the components of the machine and establishing standards by which all the components would eventually fit back together. Interestingly, this move is generally seen as the first step in creating international standards for the computer hardware industry (as IBM lost control of the information structure) and simultaneously, the first serious step towards IBM's demise as the dominant player in the industry. In terms of the second contextual dimension, the rate of change in the information structure, active information structures simply mean that redevelopment has to occur on a more regular basis, whereas passive information structures keep these costs to a minimum and ensure that they are infrequent.

Inability to develop a product based competitive advantage

In the same way that barriers to entry are kept high when firms control the information structures because of their integrated nature, firms are able to keep a tight rein on their technology and maintain any product derived competitive advantage under these same conditions. This is probably best seen in the motor vehicle industry and in aircraft production. Even firms that are brought into the production systems as manufacturers have access to only a small part of the information structure and they are thus less important than the information structure controlling firm. For example, in the Boeing 777 part of the fuselage and passenger doors come from Japan, tail and rudder assembly from Australia, nose cone and wing flaps from Italy, and some of the electrical systems are from England. But with the exception of the engines (Rolls

Royce, General Electric or Pratt and Whitney) no other part is used by name in differentiating and marketing the product (Woolsey, 1994).

Where industry standards exist, there are limited opportunities for products to be differentiated on the basis of the entire product. Instead, differentiation must occur at the component level. Hence most computer manufacturers/assemblers have to compete on price and service. To most consumers, Dell can probably provide the same product as IBM, Compaq or Gateway. Differentiation is reduced to the component level, such as Intel versus AMD chips and Soundblaster versus Turtle Beach sound cards.

Degree of Change / **Control**	International Standards	Firm Situated
Passive	**ADVANTAGES** Increased incremental learning Lowering barriers to entry (lower when active) **DISADVANTAGES** Low levels of radical innovation (though still possible) Inability to maintain product based competitive advantage.	**ADVANTAGES** Increased incremental learning Easy determination of consumer than preferences (though not as important as product does not change rapidly) **DISADVANTAGES** High product development costs Consumer preference determination May allow for easy imitation
Active	**ADVANTAGES** Increased incremental learning Lowering barriers to entry (higher than passive info structure) **DISADVANTAGES** Low levels of radical innovation (extremely difficult) Inability to maintain product based competitive advantage (unless a dominant player, eg Intel)	**ADVANTAGES** Increased incremental learning Easy determination of consumer what preferences **DISADVANTAGES** High product development costs

FIGURE 1: The advantages and disadvantages of modularity in relation to different dimensions of information structures (rate of change and nature of control).

The rate of change in the information structure has no bearing on the extent to which a product based competitive advantage may be maintained as it is all entirely dependent upon the industry. That is, passive information structures are no more or less likely to be able to support a product based competitive advantage than an active information structure. Our interpretation of how the advantages and disadvantages of product modularity apply to the various contextual factors is shown below in Figure 1.

Concluding Remarks

Modularity is a relatively recent topic of research. A comprehensive theory as to the drivers of modularity is still very much in its infancy and the number of quantitative studies that exist is limited (Schilling, 2000). In the studies that have considered modularity, a number of advantages and disadvantages have been considered at various points. However when and how these occur has not been systematically studied. This paper hopes to provide a starting point for discussing some of the contextual factors that will affect the ability for modularity to be used as a strategic tool by firms in a variety of situations.

We have based our analysis of the important contextual factors that may affect the extent to which modularity may form a strategic tool around the concept of the information structure. As information structures are essentially knowledge maps of how and why each component must link with others to create a functional product, they capture the key dimensions of what differentiates modular products – defined component interfaces and thus interchangeability of components without altering other elements in the system. In asking who, what, where and how questions in relation to this fundamental underlying construct, we suggest that the, ‘who controls the information structures?’ and the, ‘how often do they change?’ are the questions that make the most sense in that they show how different manifestations of information structures produce a range of outcomes for the different forms of product modularity. In discussing whether the information structures that drive modularity are active or passive, and whether they are firm controlled or industry wide standards, we acknowledge that these are not the only possible contextual variables that need to be considered. They are however, in our opinion relevant, in that on the basis of our research of the field and our own work in the area of modularity, they are capable of explaining some of the circumstances under which product modularity will lead to the previously discussed advantages or disadvantages. Thus, we believe that such a debate regarding these and other contextual factors is critical for further development of the field.

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