Modularity in the mediation of market and technology change

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Abstract: This paper examines the roles of *product and process architectures* in mediating market and technological change in a product market. The product and process architectures in use in a product market are defined as the technological *platforms* for the market. Platforms are then distinguished by whether they are based on *integrated or modular architectures*, and by whether they are *closed systems or open systems* in their availability to firms in a product market. Two polar cases – *closed-system integrated platforms* and *open-system modular platforms* – are analysed through the five stages of the Product Life Cycle (PLC) model to clarify the significantly different ways in which they enable or constrain the mediation of market and technological change, resulting in distinctive patterns of market evolution. This analysis suggests that the traditional PLC model is not a general model as previously thought, but rather is a special case of market evolution mediated by closed-system integrated platforms. A new model of market evolution – an Open-System Modular Platform Life Cycle (OMPLC) – is proposed to represent the case of a market based on open-system modular platforms.

Keywords: architectural lock-in; closed systems; modular architectures; modular externalities; modular platforms; open systems; Product Life Cycle; PLC; strategic modularity; technical modularity.

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1 Introduction

This paper seeks to clarify the important ways in which the different kinds of *product and process architectures* in use in a product market result in very different processes for *mediating* the market and technology changes that drive a product market's evolution. We first define product architectures, process architectures and the architectural platforms that they jointly form. The product and process architectures on which a product market is based are then said to form the technological *platform* for the evolution of the market. The impacts of different kinds of architectures used in platforms on the mediation of market and technology change are analysed by characterising architectures on two fundamental dimensions. First, architectures are characterised as either *integrated* or *modular* in their design. Second, architectures are characterised as either *closed systems* or *open systems.* Using these characterisations, four fundamental types of architectures can be identified: closed-system integrated architectures, open-system integrated architectures, closed-system modular architectures and open-system modular architectures.

Two polar types of architectures used in product markets – *closed-system integrated architectures* and *open-system modular architectures* – are analysed to clarify the distinctive sets of benefits, costs and risks firms face when they use platforms based on one or the other architecture to mediate market and technology changes. Open-system modular platforms are argued to offer potentially significant benefits in the form of *modular externalities* that lower the costs and risks of creating new products. The five stages of the Product Life Cycle (PLC) model – Embryonic/Introduction, Rapid Growth, Shake-out/Consolidation, Maturity, and Renewal or Decline – are then used as a framework for analysing the characteristic ways in which platforms based on each kind of architecture either enable or constrain how markets and technologies interact and change over the lifetime of a product market. These stage-by-stage analyses help to clarify how the two types of architectures considered result in very different patterns of interactions between – and in different trajectories of change within – product markets and supporting technologies throughout the evolution of a product market.

The analysis of the two polar types of architectures and their very different impacts on the mediation of market and technology change through the PLC leads to a reconsideration of the traditional PLC model's descriptions of the evolution of a product market. The descriptions of product market evolution in the traditional PLC model are found to correspond closely to the kind of market evolution one would expect when market and technology change are mediated through *closed-system integrated architectures.* This analysis suggests:

- that *the traditional PLC model is not a general model of product evolution*, as commonly thought, but rather is a model of a special architectural case in market evolution
- that *new models of product market evolution are needed* to represent markets that are mediated by the three other kinds of architectures.

This paper's analysis of the distinctive ways in which open-system modular architectures mediate market and technology change is proposed as the basis for defining a new Open-System Modular Platform Life Cycle (OMPLC) model describing the evolution of product markets based on open-system modular architectures.

Some concluding comments draw on this paper's analyses to suggest that the increasing use of open-system modular architectures in many industries calls for a fundamental rethinking of some current notions about the role of modularity in market evolution. These comments specifically address some current misunderstandings about the so-called modularity trap and the emergence of modularity at a late stage in the evolution of a product market.

2 Product architectures, process architectures and platforms

A *system* is a set of interacting elements that work together in some coordinated way (Simon, 1962; Morecroft *et al.*, 2002). An *architecture* defines the technical structure of a system design, whether the design is for a product, a process, an organisation, or any other kind of system in which the constituent elements are intended to work together in a coherent way (Sanchez, 1995; 2004b).

As illustrated in Figure 1, a product architecture consists of:

- the *functional decomposition* of the overall functionalities desired in a product into specific kinds of *functional components*
- the *specification of the interfaces* between the functional components that will govern how the components interact in the product design and enable the components to work together as a system. Interfaces in product architectures are of six basic types (Sanchez, 1999; 2000), as shown in Table 1.

Figure 1 Product and process architectures and their interactions define a product market 'platform'

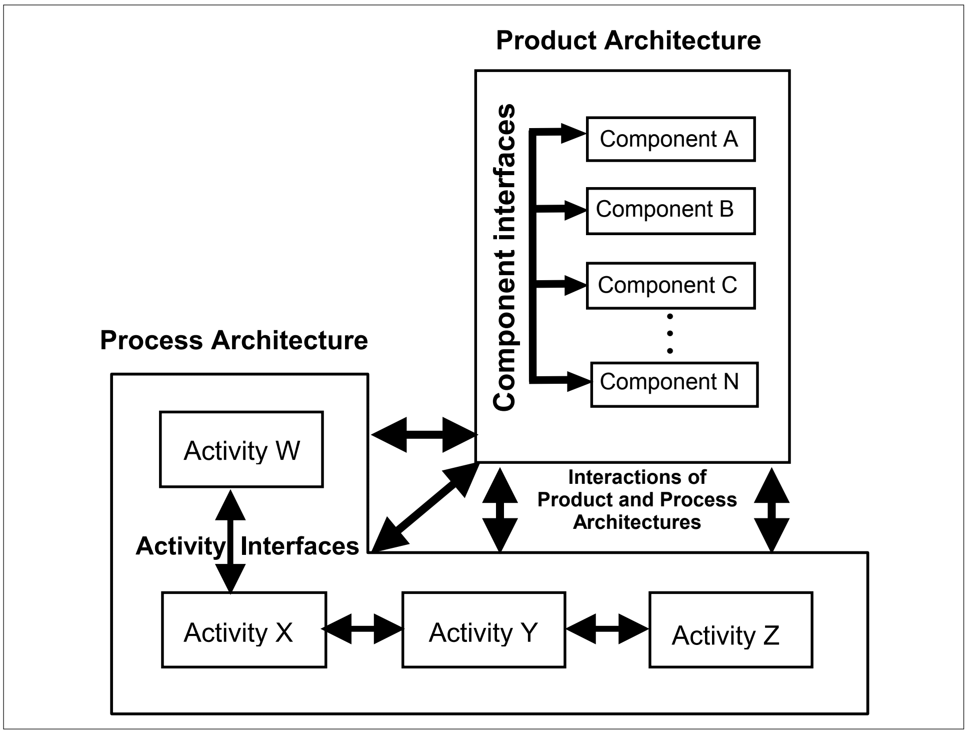


Table 1 Types of component interfaces in a product architecture

Type of interface	*Characteristics of the interface*
Attachment interface	Defines how physical components will attach to each other (*e.g.*, bolt hole sizes and locations)
Spatial (or volumetric) interface	Defines the location and shape of the space that a physical component will occupy in the overall design (*e.g.*, a specified space for an alternator within an automobile's engine compartment)
Transfer interface	Defines the input that a component will transform into a specified kind of output (*e.g.*, an electrical input to a motor of specified voltage and amperage, and an output of rotary mechanical power of specified rotational speed and torque)
Control interface	Defines how one component signals to another component what state it is in, and how the second component signals back to the first component (or a controlling component) whether to stay in that state or change to another state (*e.g.*, a data processor module in a computer programme may signal to a controller that it is ready to receive more data, and the controller may signal that the data file may send more data and activate the data processor)
User interface	Takes two forms: 1 The way in which the user is intended to interact directly with the component in using the product (*e.g.*, the 'human factors' or ergonomic aspects of a product design) 2 The way in which the component must enable the use of the product in the user's macrosystem context (*e.g.*, the kind of electrical power or fuel the user is expected to have available)
Environmental interface	Takes two forms: 1 The ambient environmental interface that specifies the environmental conditions (temperature, humidity, *etc.*) in which a component is intended to function reliably 2 The internal environmental interface that defines and controls the ways in which the functioning of one component can affect the functioning of other components (*e.g.*, a heat interface that limits a component's heat output when heat can affect other components' functioning)

As Figure 1 also suggests, a process architecture defines:

- the *functional decomposition* of the overall functionalities desired from a process into *specific activities (or process components)* that will compose the process
- the *specification of the activity interfaces* between the process components that will govern how each process component interacts with the others to enable to work together as a system. The activity interfaces in a process architecture are of six types, as indicated in Table 2, and are analogous in basic respects to the six types of product component interfaces listed in Table 1.

Table 2 Types of activity interfaces in a process architecture

Type of interface	*Characteristics of the interface*
Attachment interface	Defines how one activity may be physically connected to another (*e.g.*, how machines in a production line will be connected)
Spatial (or volumetric) interface	Defines the location and shape of the space that a physical activity will occupy in the overall design (*e.g.*, a specified space for a production or shipping activity)
Transfer interface	Defines the input that an activity will transform into a specified kind of output (*e.g.*, an input of a vendor invoice into an accounts payable activity will be transformed into a payment of the invoice)
Control interface	Defines how one activity signals to another activity what state it is in, and how the second activity signals back to the first activity (or a coordinating activity) whether to stay in that state or change to another state (*e.g.*, an activity signals to a supply activity that it is ready to receive more inputs, and the supply activity signals that it is sending more inputs to be processed)
User interface	Takes two forms: 1 The way in which users of a process are expected to interact with the activity (*e.g.*, the 'human factors' or ergonomic aspects of a process design) 2 The way in which the activity must enable its use in the user's macrosystem context (*e.g.*, the way the user is expected to access an activity)
Environmental interface	Takes two forms: 1 Ambient environmental interfaces that specify the environmental conditions in which an activity is designed to function (*e.g.*, regulatory and safety constraints) 2 Internal environmental interfaces that define and control the ways in which the functioning of one activity may affect the functioning of other activities (*e.g.*, a buffer inventory to prevent interruptions in one activity from disrupting a downstream activity)

Creating and sustaining a product market requires both product architectures and supporting process architectures. The technologically determined *strategic flexibilities* of existing product architectures (*i.e.*, their ability to support the configuration of product variations and the upgrading of products to improve performance) both enable and constrain the range of product variations that can be offered to customers in a product market at any point in time (Sanchez, 1995; 1999). In addition, the process architectures that firms use in a product market determine the different ways in which products may be developed, produced, distributed and supported in the market. In this regard, product architectures both enable and constrain the range of product variations and upgrades that may be leveraged from a product architecture.[1] Thus, as suggested in Figure 1, there are strategically important *interactions* between a product architecture and its supporting process architecture(s). These interactions must be managed – either by individual firms or by collectivities of firms – to assure the technical compatibility of their product and process architectures. As we discuss in later sections of this paper, these interactions between product and process architectures significantly influence the ways in which market and technology change are mediated in a product market.

As suggested in Figure 1, taken together, a product architecture and its supporting process architecture(s) define a *platform* (Sanchez, 2004a) on which one or more firms may undertake to create products for a product market, and on which firms may interact with resource markets (Sanchez and Heene, 2004) to configure specific processes or "resource chains" (Sanchez, 1995; 2004b) for developing, producing, delivering and supporting products in a product market.

3 Integrated *versus* modular architectures

The product and process architectures that make up a product market platform may be either *integrated* or *modular* in their respective designs. The basic design differences between integrated and modular architectures concern the ways in which each kind of architecture is decomposed into functional components – *i.e.*, its *strategic partitioning* (Sanchez, 2000; 2002b) – and the ways in which the interfaces between functional components are specified.

3.1 Integrated architectures

An integrated architecture is one that has been strategically partitioned so that at least some functions that could be provided by technically separate components are instead combined into aggregated multifunctional components or subsystems to create an *optimised design*. The most common basis for design optimisation leading to an integrated architecture is the effort to maximise performance subject to a cost constraint, or to minimise cost subject to a defined performance constraint. Given either a performance or cost optimisation goal for an architecture, the functional components in the architecture will be grouped and interrelated technically in ways intended to help maximise performance or minimise cost (subject to the specified cost or performance constraints, respectively).

A common assumption motivating the creation of performance- or cost-optimised designs is that a given architecture needs only to meet performance and cost criteria that can be defined at the beginning of the design process and that will not change during the expected lifetime of the resulting architecture in its product market. This assumption directly affects the way interfaces are specified within and between the integrated functional components in the integrated architecture. Because it is assumed that there will be no need to configure different kinds of product or process variations in the future (*i.e.*, new designs offering different performance and cost combinations), the interfaces that define how the various components of the integrated design will actually fit and work together are often highly idiosyncratic to each integrated design, because the interfaces are also optimised to enhance performance or reduce cost. The consequence of adopting such interfaces, however, is that the substitution of new parts or components into an integrated architecture (Garud and Kumaraswamy, 1995) to enable new performance and cost combinations would entail a major redesign effort to integrate the new parts or components into the product architecture.

In sum, the salient characteristics of an integrated architecture for the purposes of this paper's analyses are:

- its (intended) ability to deliver optimised performance or cost according to a *fixed set* of performance and cost criteria
- its use of integrated component designs and idiosyncratic interfaces that are intended to achieve optimised performance or cost
- the second characteristic thereby makes it time-consuming and costly (or sometimes infeasible) to accommodate changes in the performance or cost parameters to be delivered by the architecture.

On this basis, a 'moderately integrated architecture' would be one in which relatively few of the overall functionalities of an architecture are delivered through integrated component or subsystem designs, so that modifying the architecture involves a relatively moderate component or subsystem redesign and reintegration task. A 'highly integrated architecture' would be one in which most or all functionalities are delivered through integrated components or subsystems, which may themselves be interrelated in ways that are difficult to change, so that modifying the architecture requires a lengthy and costly redesign effort.

3.1.1 Integrated product architectures and process architectures

A common motive for the use of integrated product architectures is to create an optimised design (sometimes referred to as a 'peak' design) in which specific product performance parameters are maximised subject to an overall product cost constraint, or in which the production cost of a product is minimised subject to a set of constraints for certain aspects of product performance thought necessary to meet market expectations. For example, to improve driving performance, designers of the first Porsche 911 engine architecture sought to reduce both vehicle weight and the engine power consumed in generating electrical power for the car. As a result, early Porsche 911s were designed with an alternator that was integrated into the cooling fan assembly, so that only one fan belt was needed to cool the engine and generate electricity. The result of integrating these two technically separable functions into one component assembly was both a reduction in the weight of the 911 and an increase in the net power available from the engine to propel the car, both of which helped to increase the acceleration and top speed of the car.[2]

Analogously, an integrated process architecture is a process design in which process functions that could be delivered through separate activities are instead integrated into a single activity (or process component) in the process design. As with integrated product architectures, a common motive for creating integrated process designs is either performance optimisation (*e.g.*, maximising quality levels and yield rates) or cost optimisation (*e.g.*, using integrated processes to lower production costs). In the production of steel, for example, slabs of steel may be poured and rolled into commercial shapes in separate process steps, but doing so involves cooling a just-poured slab of steel so it can be moved to a rolling mill and then reheating the slab to make it malleable enough to be rolled into desired shapes. The cooling of a glowing-hot steel slab takes time, storage space and a heat extraction system, while reheating a slab to a malleable temperature for rolling incurs a significant energy cost. Thus, in steel mills that try to minimise costs, the pouring and rolling of a steel slab is generally combined into one continuous process step, even though they are technically separable activities.

When the activities that constitute a process architecture are combined into integrated process components, the activity interfaces within process components will typically also be performance or cost optimised, resulting in activity interfaces that are idiosyncratic to that process architecture. Subsequently, changing the process to emphasise new performance parameters instead of cost, or cost instead of prior performance parameters, or simply new targets for existing performance or cost parameters, is likely to entail a substantial redesign of the process architecture.

3.1.2 Integrated platforms

An integrated product architecture may be supported by an integrated process architecture in ways that require tight coordination between the two, in effect creating an *integrated product and process architecture.* For example, deep production process knowledge and tight process control may be required in order to create high-performing product architectures. Alternatively, in an effort to minimise production costs, a process architecture may be designed with large-scale, integrated production equipment capable of producing a given product architecture at low cost – but only that product architecture. In such cases, the critical interactions between the integrated product and process architectures result in an *integrated platform* for participating in a product market. In order to achieve the necessary level of control and coordination of the two architectures composing an integrated platform, it may be necessary for both architectures to be owned and directly managed by a single firm (Funk, 2008).

3.2 Modular architectures

The use of modularity in product and process architectures may be motivated by either technical or strategic objectives, each of which results in different levels and intensities of the use of modularity in an architecture.

Technical modularity is created when an interface between product or process components is specified to allow some different versions of the components to be used in various combinations without having to redesign the components or the interfaces to accommodate each combination of component variations. The motive for technical modularity is usually a simple rationalisation of designs to reduce unnecessary complexity and cost in design and production. In this regard, technically modular designs or parts of designs are often adopted in the engineering process, where modularity is introduced at the detailed design stage in ways that are often not requested or even noticed by a firm's management.

Strategic modularity, by contrast, explicitly seeks to use modularity to improve the configurability, upgradeability and other strategic flexibilities of an architecture in ways that elevate modularity to the status of key driver of product and process strategies (Sanchez and Mahoney, 1996; Sanchez, 1995; 1999). To elevate modularity from the technical domain to a driver of firm strategy, three steps must be taken in the design process to explicitly align the technical design aspects of an architecture with the intended strategic uses of a product or process architecture in a product market:

Step 1 First, an architecture must be strategically partitioned, to achieve *a one-to-one mapping* of the functions that are the basis of product differentiation in a product market, into technically separate components within the architecture (Sanchez, 1999; 2000). In a product architecture, all the individual functions or features of a product that are perceived by the intended customers as sources of significant differences between products should be 'contained' in technically separate, individual components, each of which ideally delivers a single function or feature that is an important basis of product differentiation in the eyes of the intended customers. Similarly, the activities in a process architecture that are significant sources of perceived variety in the eyes of targeted customers (*e.g.*, alternative shipping processes) are contained in individual process activity components. When an architecture is strategically partitioned in this way, the substitution of component variations into the architecture can result in the generation or 'leveraging' of product and process variations that will be regarded as significantly different (*i.e.*, clearly differentiated) by the intended customers (Garud and Kumaraswamy, 1995; Sanchez, 1995; 1999). Specific component variations can then be used to refresh product designs, improve the features of products and processes, or upgrade performance as higher-performing component variations become available. At the same time, an important second effect of this kind of strategic partitioning is that the remaining components in the architecture that are *not* sources of perceived variety and change can be designed as *standard components* that can be used in common ('common components') across many product or process variations, or reused ('reusable components') in successive generations of product and process architectures (Sanchez and Sudharshan, 1993; Sanchez, 1996c; 2000; 2004a).

Step 2 The second design step in creating strategic modularity is to *specify the interfaces* for components that are sources of product differentiation *to allow the substitution of an intended range of component variations* into the architecture. Such interfaces enable the ready introduction of component variations to configure a strategically desired range of product and process variations within the same architectures.

Step 3 The third step in creating strategically modular architectures is to *standardise – i.e.*, to freeze – *the interface specifications* in the architecture to create a *technically stable environment* within the architecture. The technical stability of the architecture that results from freezing interfaces makes it feasible and more attractive for firms to develop modular component variations that will 'plug and play' in the architecture,[3] thereby extending the range of product and process variations and upgrades that can be leveraged from the same architectures (Sanchez, 1996c; 2000; Sanchez and Mahoney, 1996; Sanchez and Collins, 2001).

3.2.1 Modular product and process architectures

There are numerous possible motivations for creating strategically modular product architectures, each of which can lead to modular architectures whose strategic partitioning and interface specifications are intended to support different kinds of strategic objectives. Compared to creating integrated architectures, a firm that creates strategically modular architectures may be able to obtain many more product variations from one design and development effort by including components developed by other firms that can plug and play in the firm's modular architecture, resulting in *improved* *development productivity* and a *greater product variety* offered to markets (Sanchez, 1999). Modular architectures may also be designed to enable *fast technological upgrading of components* to improve product performance more rapidly (Sanchez, 2000). In markets with uncertainty about which product variations or upgrades will be most appreciated in the future, the ability to leverage more product variety and upgrades into its markets gives a firm using modular architectures more *strategic options,* and in this sense modularity can become a strategically important tool for *managing market and technology uncertainty* (Sanchez, 1993; 1996c; 2003; Asan *et al.*, 2008).

Strategically important benefits can also be derived from a *modular product development process* (Sanchez and Mahoney, 1996; Sanchez, 2000). Freezing interface specifications *before* beginning the development of specific components enables the *concurrent development of components,* with a resulting substantial reduction in development time and an increase in speed to market (Sanchez and Collins, 2001; Sanchez, 2000). Because a modular product development process can often be performed much faster and more efficiently than a traditional product development process, sometimes even a 'one-off' product design intended to be used for a single purpose (*e.g.*, a NASA moon rocket) may be executed as a modular architecture to accelerate or improve the coordination of the product development process (Sanchez and Mahoney, 1996; Sanchez, 2000).

Finally, as will be discussed more fully in later sections of this paper, modular architectures (especially open-system modular architectures) may create significant positive externalities for participants in a product market. These *modular externalities* may offer benefits to individual firms that 'open' their architectures to other firms, and may create incentives for market participants to engage in cooperative, collaborative activities to agree on an *industry-standard modular architecture* based on a common approach to strategic partitioning and the adoption of industry-standard interface specifications. When some or all of the participants in a product market believe that the benefits they can derive from modular externalities equal or exceed the benefits they could derive from their individual (closed-system) proprietary architectures, they may seek ways to coordinate with each other to define a common modular architecture that becomes the basis for a 'modular market' (Sanchez and Collins, 2001), in which many firms may benefit in various ways from modular externalities.

Strategically modular process architectures are analogous to strategically modular product architectures in both design and motivation. They will be strategically partitioned to contain important sources of perceived process variety in specific, technically separate activities, a design step that will also clarify which activities can become standard activities that can be used in common across process variations or even reused in successive generations of process architectures. Activity interfaces will be specified to support the introduction of some range of variations in process activities, and the activity interfaces will be standardised to create a technically stable environment for performing and coordinating an overall process. For example, the standardised interfaces in a common Computer-assisted Design (CAD) system enable many firms to 'quick connect' into a distributed product development process (Sanchez, 1996b), just as an Electronic Data Integration (EDI) system enables a variety of firms to plug and play in a product market's commercial processes (Sanchez, 1996c). Process variations can then be created within a modular process architecture to serve different user or consumer preferences for product distribution, logistics and support.

Modular process architectures (especially open-system modular process architectures) also create positive modular externalities that give firms incentives to cooperate in defining an *industry-standard modular process architecture*, in which many market participants can plug and play in providing various services (development, production, marketing, distribution, customer support) to other participants in a modular product market (Funk, 2008).

3.2.2 Modular platforms

When the strategic partitioning and interface specifications of one or more modular process architectures are well defined and aligned to support the modular product architecture(s) used in a product market, they jointly define a *modular platform* that becomes the overall basis for the mediation of market and technology change in the product market (Sanchez, 1997; 2004a). When the essential architectural information about strategic partitioning and interface specifications used in the product and process architectures of a modular platform are available to all interested product market participants, this architectural information provides the essential *information structure* (Sanchez, 1996c; Sanchez and Mahoney, 1996) for coordinating the development and commercialisation of products (including components) and activities within the product market, eliminating the need for hierarchical coordination by one firm (Williamson, 1986; Sanchez and Mahoney, 1996). The following discussion will characterise such modular platforms as 'open systems' that enable new kinds of autonomously coordinated, 'disintegrated' industry structures (Funk, 2008), and that lead to new kinds of mediation dynamics that are fundamentally different from the dynamics associated with integrated architectures (Sanchez, 1996c; 1996a; Cebon *et al.*, 2008).

4 Closed-system versus open-system architectures

An architecture defines the technical structure of a *system*, which can in turn be characterised as either a closed system or an open system.

A *closed system* is a system whose architectural properties – specifically, its mode of strategic partitioning and/or (more commonly) its interface specifications – are either not known to or are not able to be used by parties other than the creator and owner of the system. For example, some product or process designs may contain components that are physically hidden (Von Hippel, 1983) or interfaces that are concealed or encrypted so that they cannot be analysed by users or competitors (Baldwin and Clark, 2000). Alternatively, a firm may have intellectual property rights (patents, copyrights, or trade secrets) that foreclose innovation of its components or use of its interface specifications by other firms. For example, both Philips and Braun have patented interfaces between their powered toothbrush handsets and replaceable brush tips, which prevent each firm from competing in the other firm's lucrative market for replacement brushes (Sanchez, 2004a). Finally, a firm may have such advanced design or production knowledge about a component or its interfaces that other firms are simply unable to create equivalent components or use the firm's interface specification in architecting their own components or products. All of these reasons may make it impossible for other firms to create and use a closed-system architecture in a product market.

An *open system*, by contrast, is an architecture whose strategic partitioning and interface specifications are publicly known, are unencumbered by intellectual property rights and are usable technically by at least some (and potentially many) firms interested in developing components, services, products, or processes that are compatible with (plug and play in) the architecture. Because open-system architectures allow firms to access and use an architecture, open-system architectures may create *significant positive externalities,* both for firms that participate in a product market based on an open-system architecture and for users or consumers of products and services leveraged from open-system architectures. For example, 'open innovation' processes like those that continue the development and extensions of the Linux operating system bring benefits not only to users who do not have to pay for the use of another firm's intellectual property, but also to software developers who can readily understand and use the interfaces provided by Linux in developing various kinds of application programmes.

Both integrated and modular architectures may exist as either closed systems or open systems, suggesting that there are *four basic types of architectures*: closed-system integrated architectures, open-system integrated architectures, closed-system modular architectures and open-system modular architectures. For brevity, only the two polar cases of closed-system integrated architectures and open-system modular architectures are analysed here to illustrate the impacts of different kinds of architectures on the mediation of market and technology change in product markets.

A *closed-system integrated architecture* is typically an architecture that a firm intends to keep proprietary, usually as an intended source of competitive advantage in a product market, or that is so advanced technically or so idiosyncratic in other respects that other firms are unable to contribute to or use the architecture, even if invited to do so by the creator or owner of the architecture. Again in the interest of brevity, we will consider only the proprietary intent for creating a closed-system integrated architecture in the analyses to follow, as this is the case of greatest interest in analysing product market evolution.

Finally, an *open-system modular architecture* is often created to support an open innovation development process (Chesbrough, 2003; Christensen *et al.*, 2005), like Linux, or to encourage an 'open' product market with significant modular externalities that invite participation in its open-system modular product and process architectures by many kinds of firms (Funk, 2008). While a 'pure' open-system architecture may be rare (even Linux is exposed to some claims that it uses proprietary components and interfaces), 'mostly open' system architectures can be found in many industries where *interconnectivity based on technical compatibility* is essential for capturing the positive network externalities in a product market. Such product markets include personal computers, consumer electronics (Langlois and Robertson, 1992), financial services (Jacobides, 2005), telecommunications (Galvin and Rice, 2008) and many others.

5 Architectural mediation of market and technology change in the evolution of product markets

We now consider the ways in which the use of closed-system integrated architectures *versus* open-system modular architectures results in distinctive processes for mediating market and technology change in the evolution of a product market. Because the mediation of market and technology change depends on both the product and process architectures in use in a product market, the analysis below compares *closed-system integrated platforms* with *open-system modular platforms*. Each type of platform is characterised by its distinctive ways of enabling or constraining the mediation of market and technology change in a product market. Each platform's resulting impact on the evolution of a product market is analysed in each of the five stages of the traditional PLC model (Levitt, 1965). The Appendix provides a review of the PLC model. The analyses of the two kinds of platforms considered here suggest that the kinds of platforms in use in a product market will significantly affect both the kinds of market changes (market innovations) and the kinds of technology changes (product and process innovations) a product market will undergo as it evolves through the PLC model's five stages.

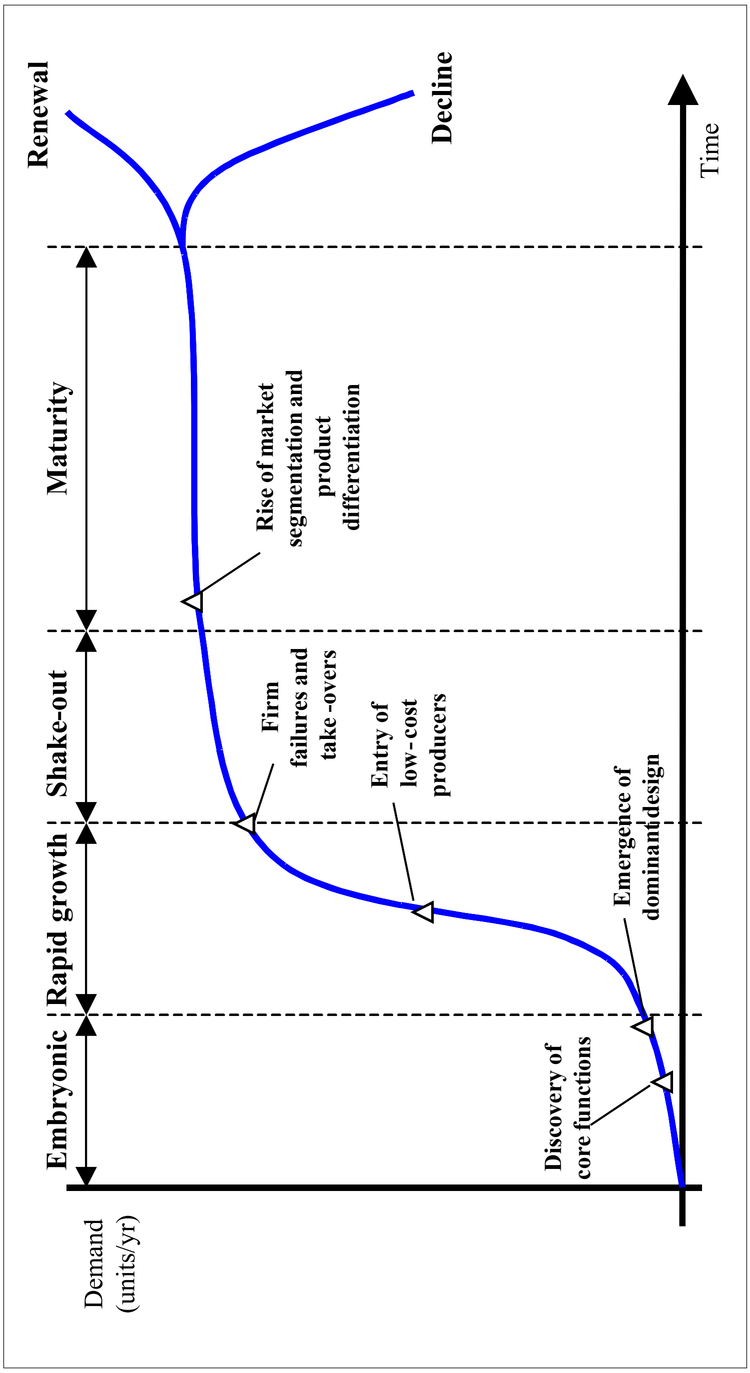
The findings in this section, which reflect important theoretical and empirical findings by other modularity researchers (Sanchez and Mahoney, 1996; Cebon *et al.*, 2008; Funk, 2008), suggest an important new perspective on the traditional PLC model, as illustrated in Figure 2: The kind of market and technology dynamics described in the traditional PLC model are found to resemble most closely the dynamics one would expect to observe in *a product market based on closed-system integrated platforms*. Moreover, the dynamics associated with product markets based on open-system modular architectures are found to differ in fundamental ways from the predictions of the traditional PLC model. These analyses lead to the conclusion that the *traditional* PLC model (as summarised in the Appendix) is not a general model of product market evolution as previously thought, but rather describes well only one – but a historically important – kind of product market evolution mediated through closed-system integrated architectures. The kinds of market and technology dynamics predicted by the analysis of open-system modular platforms are proposed as the basis for the new OMPLC model.

5.1 Market and technology mediation through closed-system integrated platforms

We now consider the product market dynamics that can be predicted and observed in each stage of the PLC model when market and technology change are mediated through closed-system integrated platforms. Such platforms have three defining architectural properties:

1. They consist of product and process architectures that are each closed systems in the sense that they are proprietary to or understood only by a specific firm.
2. The product and process architectures both have significant design integration of optimised multifunctional components or subsystems in their respective designs.
3. The product and process architectures interact in ways that have both important *closed-system properties* (*i.e.*, the ways in which the two architectures interact are proprietary to or understood only by a specific firm) and important *integrated system design properties* (*i.e.*, the successful development and use of each architecture requires significant technical knowledge exchanges, operational coordination, or other kinds of interactions between the architectures).

Figure 2 The five stages in the traditional Product Life Cycle model (see online version for colours)



Source: Sanchez and Heene (2004)

5.1.1 Embryonic (Introduction) stage

In the Embryonic (Introduction) stage of the PLC model, the development of a new product concept is costly and risky. Because individual firms intend to capture the full economic benefits that will accrue to the owner of a closed-system platform that proves to be successful in a new product market, each firm must pay the full costs of designing and developing its integrated product and process architectures, including the costs of developing new technologies or adapting existing technologies for use in the two architectures. Until the *core functions* and *dominant design* for the new product concept are discovered and confirmed through market interactions, however, incurring these costs – which are likely to be substantial for an integrated design – is very risky. For example, a pioneering firm may be mistaken about the core functions the market will want and that should therefore be optimised in its architectures, rendering its initial architectural design and development work of little or no value. Moreover, the 'discovery' of the core functions of a new product concept is not a clearly identifiable discrete event, but rather is a convergence process driven by trial-and-error learning subject to ambiguity and possible costly misdirection of effort. The eventual reworking of initial integrated architectures to incorporate new 'core functions' once they can be identified with confidence also requires extensive redesign time and further costs.

Even if the core functions are unambiguously established in the new market, firms must still bear the risks inherent in competing to see which of their architectural approaches to providing the core functions will become the dominant design in the new product market. Those firms whose architectures fail to become the dominant design will face further redesign time and costs if they wish to continue competing in the product market. The risk inherent in this eventuality is accentuated by the fact that the 'emergence' of a dominant design is the result of a process that is subject to the same kinds of ambiguities and misdirections as the 'discovery' of a new product's core functions. As a consequence, relatively few firms will be willing or able to bear the substantial costs and risks of pioneering or entering early into new product markets. New product markets and the market and technology innovations on which new markets are based will therefore be relatively infrequent events.

5.1.2 Rapid Growth stage

For those firms that persevere through the discovery of the core functions and the (apparent) emergence of a dominant design, the challenge in the Rapid Growth stage is to correctly shift their strategic emphasis from product architecture innovation to process architecture design and implementation – *i.e.*, to putting in place the large-scale production, distribution and customer support infrastructure needed to build and defend a major position in the new market. The need to make this strategic shift will be accentuated by the entry of low-cost producers – firms that have large-scale production and distribution capabilities, but that wait for innovative firms to demonstrate that a large market exists for a new product concept. There are at least two major risks involved in making this strategic shift, both of which involve an important form of *architectural lock-in* in integrated platforms and resulting questions of timing. These risks apply equally to firms hoping to become one of the dominant firms emerging from the Shake-out/Consolidation stage and to firms jockeying for advantages against other firms in serving niche markets.

'Lock in' is the term introduced by Arthur (1989) to describe how customers may become dependent on, and thereby locked in to, a firm's proprietary architecture – a kind of 'outward' locking-in of customers by a firm. An analogous 'inward' form of architectural lock-in can occur, however, when a firm creates an integrated platform in which the design of its process architecture is optimised to support a given product architecture and in which the process architecture is closely integrated technically and operationally with its product architecture. In effect, the process architecture created to optimise the use of a product architecture may thereafter constrain a firm's willingness or ability to change its product architecture, because doing so would entail significant redesign of its process architecture as well.

The first risk posed by this potential for architectural lock-in is that a firm may commit *too early* to creating an integrated process architecture, and may become locked in to an integrated platform based on a product architecture that is not destined to become the dominant design. Committing too early may substantially increase the time and costs required to adopt a different product architecture that later proves to be the dominant design accepted in the market. The second risk associated with an inward lock-in is that a firm may wait *too late* before committing to an integrated process architecture. Waiting too late may result in the loss of the first-mover advantages a firm would otherwise have been able to harvest as a result of its pioneering or early entry into the new market. Further, given that late entrants are often large firms intent on mounting large-scale operations, a firm that waits too late to commit to an integrated process architecture may face a loss of substantial market share to later entrants who have made better judgements about the eventual dominant design in the market and better timing decisions about when to commit to creating and implementing process architectures.

Both of these risks make the Rapid Growth stage a risky rite of passage in a product market, with market pioneers and early entrants making architectural decisions that either give them significant first-mover advantages, or (more commonly) eventually result in their exit or demise. Late entrants, who have waited until both the core functions and dominant designs have been identified, then use their capabilities in architecting products and processes for large-scale, low-cost operations to introduce an aggressive price competition to the market and build market share.

5.1.3 Shake-out (Consolidation) stage

In the Shake-out (Consolidation) stage, the goal of firms hoping to become one of the few dominant players is to use their cost advantages resulting from cost-optimised product architectures and large-scale, cost-optimised process architectures – and their market position advantages resulting from a large market share – to force other firms to exit the market or to be taken over. While the potential rewards for achieving this goal may be large, the prospects for firms that do not achieve this goal are dim (exit or absorption) or much reduced (retreat to a niche market). For firms that have found and become established in niche markets, the potential rewards may be a profitable business on a modest scale – if they prove to be the most capable in identifying and serving the preferences of its niche customers. The prospects for firms that are not able to compete successfully in niches are exit (either voluntarily or in the form of firm collapse) or absorption.

The key aspect of risk in this stage for firms that aspire to use integrated platforms to become either dominant players or entrenched niche players is that by the time the Shake-out stage begins, in effect *les jeux sont faits* ('the bets have been made'). The substantial time and cost required to become a more effective competitor by creating a new integrated platform may preclude the possibility of a second chance, both in the mainstream of the market and in contested market niches. The commonly observed shake-out of firms and the consolidation of the product market into a few large players and a few niche players attest to the high risks that firms with integrated platforms face as the result of their early decisions in creating their integrated product and process architectures.

5.1.4 Maturity stage

In the Maturity stage, the surviving mainstream firms must monitor and respond to an emerging diversity of customer preferences with respect to the product concept, resulting in segmentation of the market. Since their response to the emergence of market segments will be the creation of new or significantly adapted integrated platforms, the key questions firms must try to answer are as follows:

- What are the new product functionalities, features and performance levels required to successfully serve emerging new market preferences?
- Can the emergent market demand for product variations be met with an adaptation of the existing integrated platform, or is a new integrated platform required?
- Is there enough demand and profit potential in identified new market segments to justify the significant costs of creating one or more new or significantly adapted integrated platforms?

In fundamental respects, responding to the perceived emergence of new market segments involves a rerun of the issues, decisions and risks that firms originally faced in the Embryonic, Rapid Growth and Shake-Out stages of a new product market – only this time at the scale of a market segment rather than at the scale of most or the entirety of a product market. A well-recognised hazard in this context is the potential for a firm to become "stuck in the middle" (Porter, 1985) by changing its established integrated platform enough to incur major new costs (and perhaps a loss of cost advantages), but not enough to adequately differentiate its new product to meet the preferences of a given market segment.

5.1.5 Renewal or Decline stage

In Renewal, the level of market demand may be reinvigorated because of fundamental shifts in customer preferences that favour the product market, or because of product or process innovations (within a firm's integrated platforms) that significantly improve the performance-to-price ratio. The key determinant of whether an individual firm participates in the Renewal stage or not is whether feasible adaptations of the firm's existing product and process architectures can adequately accommodate the market and/or technological changes that are precipitating a renewal of market demand. Given the time and cost required to design a new integrated platform or to make significant adaptations or extensions within an existing integrated platform, there is a risk that a firm may not be able to respond to the changes in time or with adequate differentiation of its prior products to participate in the market's new growth.

In the event of a Decline stage, the key issues are whether a firm can adapt its existing integrated architecture to improve its product's performance or lower its costs enough to slow the flight of customers to substitute products, prolonging the decline and eventual phasing out of its product market. Firms that have fully amortised the costs of their integrated platforms may have some ability to engage in aggressive pricing to retain customers, but will generally be constrained in their ability to improve performance by the high costs of modifying their integrated platforms.

5.2 Market and technology mediation through open-system modular platforms

We now consider the product market evolution that can be predicted and observed in each stage of the PLC model when market and technology change are mediated through open-system modular platforms. Such platforms have five defining architectural properties:

1 They consist of product and process architectures that are each *open systems* in the sense that the strategic partitioning and interface specifications used in the architectures are known and understood by many firms and available for use by any interested firms.

2 The product and process architectures have been *strategically partitioned* to achieve a one-to-one mapping of significant sources of product and process differentiation into technically separate individual components.

3 The interfaces between both product components and process components have been specified to allow the substitution of an intended range of component variations without having to redesign those or other components in the architectures.

4 The interfaces in the product and process architectures and between the two architectures have been standardised (frozen) to create a technically stable environment within the two architectures.

5 The product and process architectures have been aligned so that the technically separate components in the product architecture can be developed, produced and supported by technically separate process components in the platform's process architecture(s) – and thus by different organisations who may perform any of the process components. The standardised interfaces in the product architecture and between the product and process architectures then provide an *information structure* that is the basis for autonomous coordination of the development, production and support processes in the process architecture(s). When these two conditions are met, the product and process architectures become *decoupled* – in the sense that they no longer need direct managerial control for the process architecture(s) to work in a coordinated manner in performing development, production, or customer support activities for the product architecture (Sanchez and Mahoney, 1996; Funk, 2008).

The emergence of an open-system modular architecture as the basis for a product market may come about in at least two ways. First, a firm competing in an established product market may decide to 'open up' its architectures in an effort to improve its ability to compete against firms using closed-system architectures. For example, Sun Microsystems (Garud and Kumaraswamy, 1993) and GE Fanuc Automation (Sanchez and Collins, 2001) adopted 'open-system' architectural strategies with considerable success in competing against closed-system rivals. Second, collaboration among firms may launch a new product market as an open-system product market, or may launch a new open-system product architecture in an existing product market. The early personal computer market (*i.e.*, before the dominance of Microsoft and Intel) and the market for stereo components were in many respects launched by collaboration as open-system product markets (Langlois and Robertson, 1992), and Linux was collaboratively launched and developed as an overtly open-system alternative to Microsoft or Apple closed-system architectures in the market for computer operating systems.

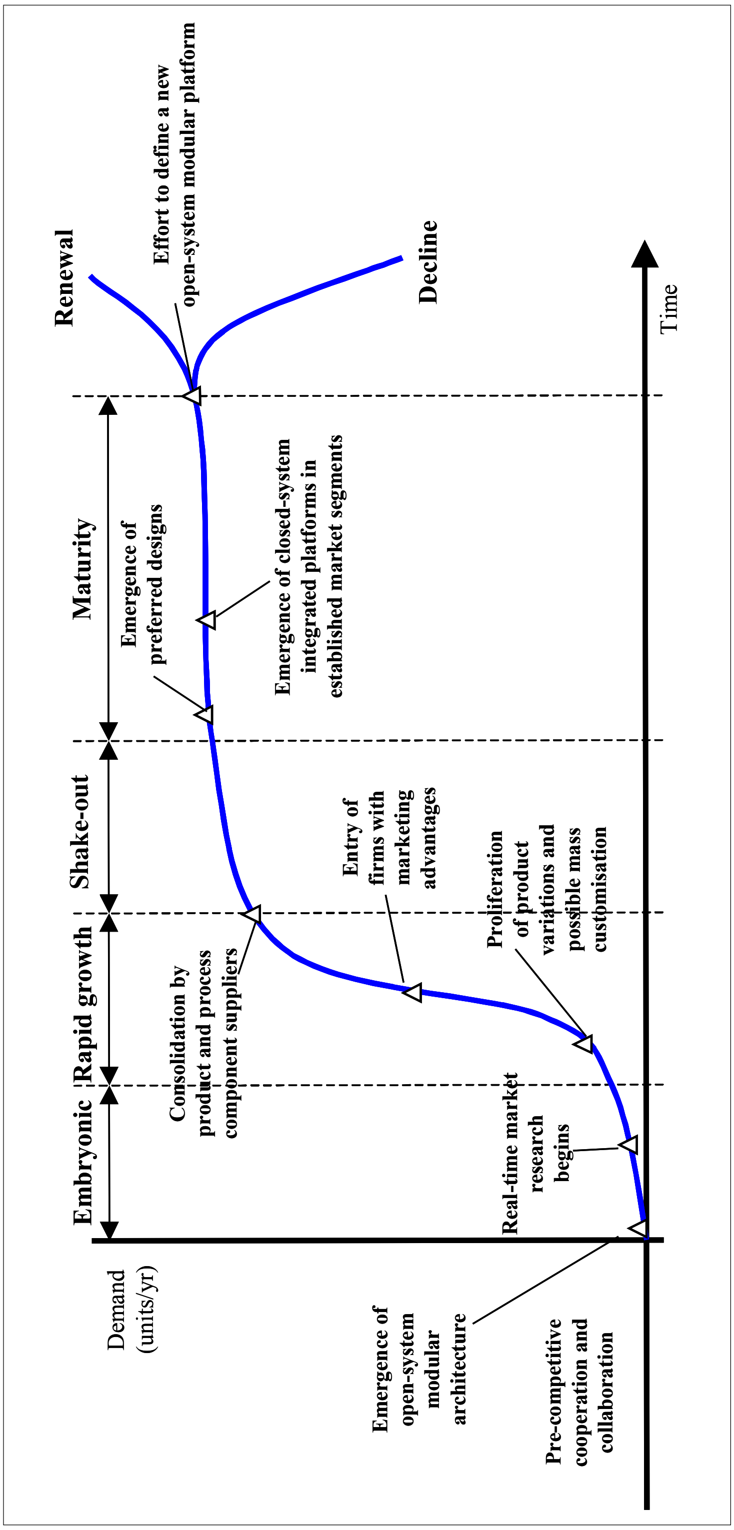
In the latter case, creating the five characteristics of an open-system modular architecture as described above requires considerable cooperation and collaboration among a potentially large number of firms and possibly other institutions *before* an open-system product market is launched or an open-system product is launched in an otherwise closed-system market. To address this important case, the following discussion of the OMPLC includes a new PLC stage, 'Precompetitive Cooperation and Collaboration' as illustrated in Figure 3. Subsequent discussion elaborates the dynamics of market and technology mediated by open-system modular platforms through stages of market evolution that somewhat correspond to (but differ in important respects from) the five stages of the traditional PLC model. This analysis suggests that the ways in which open-system modular architectures mediate market and technology change differ significantly from mediation by closed-system integrated architectures, leading to new patterns of market evolution in product markets based on open-system modular platforms.

5.2.1 Precompetitive Cooperation and Collaboration stage

Unlike new product markets that may be pioneered by a single firm or a small number of firms who create their own proprietary architectures, creating new product markets based on open-system modular platforms meeting the five requirements defined above requires significant effort and coordination among a potentially large number of firms interested in participating in a new market. Thus a central question in analysing product markets based on open-system modular platforms is, How does an open-system modular platform get established as the basis for a new product market?

Research into the early stages of 'open innovation' initiatives have identified a number of institutional contexts and processes that facilitate communication among parties interested in creating open-system modular platforms, provide models for the establishment of collaborations in various forms, and establish forums for defining an industry-standard strategic partitioning of architectures and interface specifications needed to achieve autonomous technical coordination among participants in a new product market (Chesbrough, 2003; Christensen *et al.*, 2005). More directly relevant to this analysis, however, is an understanding of the *incentives* that firms may perceive to engage in such activities. Sanchez (2002a) has identified a number of incentives for firms to collaborate in defining industry standards, modular architectures and common components. These incentives are derived from a number of *positive modular externalities* – benefits that firms can realise by engaging in activities for creating, using and supporting open-system modular platforms as the basis for a new product market or as an alternative to proprietary platforms in existing markets. We therefore briefly consider the nature and sources of these modular externalities and the specific benefits that firms can derive from these externalities by collaborating in various ways to create open-system modular platforms.

Figure 3 Stages in an Open-System Modular Platform Life Cycle model (see online version for colours)



For new product concepts that will be based on new enabling technologies, the first arena for collaboration includes laying the basic technical foundations of a new product. Firms, universities and research institutes must first agree on a standard scientific language for describing the physical phenomena that will be the basis for new technologies and derived product functions. Agreeing on standard measures for physical phenomena of interest and standard tests for making such measurements are the next essential steps in establishing a coherent scientific basis for creating new technologies. The creation of standard technical vocabulary, measures and tests enables firms to capture research network externalities, because they will be able to understand and compare basic research that is conducted and described in a standard way.

As progress in basic research enables a 'second wave' of applied development leading to usable technologies and designs of derived components, collaboration is required to define and promulgate standard materials specifications for any new materials to be used in designing components. The standardisation of material specifications removes technical uncertainty about the kinds of materials a new product market will use, thereby helping to induce material suppliers to develop and produce appropriate materials. In effect, the adoption of standard material specifications in a product market makes it possible for interested firms to become suppliers to the market and for developers and producers of the new product to access the capabilities of material suppliers.

The next level of technological cooperation involves establishing technical standards for components, the new product and complementary goods (*e.g.*, consumables) to be used with a new product. In particular, standards for measuring the performance of components and products may be critical to the formation of a market for a new product. When potential customers are uncertain about how to assess the benefits they would derive from a new product, industry standards that define relevant measures of performance and minimum levels of performance to be maintained by products in a market help to overcome such uncertainties and the resulting hesitations of potential customers.

Once these basic aspects of a new market's technological infrastructure are in place, important incentives exist for cooperating in defining open-system modular platforms as the basis for product development, production and customer support in the new market. These incentives may be grouped into incentives derived from *demand-side modular externalities* and incentives derived from *supply-side modular externalities* (Sanchez, 2002a, pp.672–680). Demand-side incentives for firms to cooperate in creating and using open-system modular architectures include the ability to configure greater product variety (by accessing a wide range of components developed by suppliers), the resulting ability to test and serve multiple market segments using one architecture, more rapid upgrading of product performance by substituting higher-performing components into product designs, and using modular platforms as the basis for building long-term customer relationships by offering product designs that are scalable, upgradeable, extensible (when new functions or features may be added) and interconnectible. Supply-side incentives include the reduction of product development costs when other firms' components can be used, lower component costs as suppliers consolidate the demand for components and achieve economies of scale, reduced investment in production facilities and reduced complexity in managing product creation when development can be distributed among capable suppliers.

5.2.2 Embryonic (Introduction) stage

Once an industry-standard open-system modular platform is available to participants in a new product market, a *real-time market research* approach to exploring market preferences for the new product concept can begin (Sanchez and Sudharshan, 1993; Sanchez, 1999). As component suppliers begin to develop modular component variations for the new product architecture, assemblers and marketers of products are able to configure a growing number of product variations to offer to potential customers. Firms may then configure and test a range of product variations to let potential customers ‘vote with their dollars’ for the combinations of the functions, features, performance levels and price points they most prefer, leading to accelerated learning about market preferences.

Rather than converging towards a single set of core functions that has the widest appeal in the new market, as predicted in the traditional PLC model, firms in OMPLC markets may identify several areas of product space that can be served with different combinations of functions based on different combinations of modular components (Sanderson and Uzumeri, 1997). For example, the mobile phone market has generated many product variations based on different combinations of functions (voice communication, internet access, digital photos, digital video, digital music, automated payment, *etc.*) that have become viable product concepts within the market, not just a single product concept based on a single set of ‘core functions’.

Similarly, although a dominant design in terms of the physical configuration of modular components may emerge as the most preferred version of a modular product (*e.g.*, the laptop computer), the ability of firms to configure modular components into a number of product arrangements may lead to the coexistence of several distinct physical arrangements of components in the market, rather than the emergence of a single dominant design. In mobile phones, again, several different kinds of phone designs representing different physical arrangements of components persist in the marketplace: the ‘clamshell’ design, the open-face design, the sliding cover design, *etc.*

Because modular architectures may offer the strategic flexibility to configure many combinations of component-based functions, features and performance levels in a number of alternative physical arrangements, and because market preferences may support more than one set of functions and physical design arrangements, there is a much reduced risk that a firm will fail to emerge from the Rapid Growth stage as a result of wrong guesses about the core functions it must provide or the dominant design for providing those functions. Rather, early firm exits and failures are more likely to result from more ordinary reasons for poor business performance (an inability to establish distribution, build a brand, maintain operational control, *etc.*) than from inappropriate architectural choices.

Production during the Embryonic stage may be accomplished through a firm’s own assembly processes, but may also use the services of contract assemblers whose assembly skills are compatible with the new open-system modular process architecture. In general, as contract process suppliers become available in the market, they allow product firms to convert process costs to variable costs rather than incurring major investments in process assets, thereby both reducing the risk of entering the new market and allowing product firms to focus on investing in product innovation within the modular architecture (*i.e.*, developing new component variations or component arrangements). Pioneers and early entrants are therefore likely to practice *fixed-asset parsimony* (Sanchez, 1996c) by minimising investments in plant and equipment whenever contract-based variable cost process solutions are available. Process innovations may be undertaken by process service providers, however, who may benefit from spill-over effects from the process development work they are doing for product markets requiring related process capabilities.

5.2.3 Rapid Growth stage

The Rapid Growth stage of an open-system modular platform market is likely to differ in important respects from the same stage in a traditional PLC model based on closed-system integrated platforms. Rather than market growth being fuelled by the discovery of core functions and the emergence of a dominant design reflecting a convergence of market preferences, rapid growth in an OMPLC market is likely to be driven by a proliferation of product varieties that encourages and serves the *increasing diversity* of market preferences at an early stage in the evolution of a market. As market familiarity with the product concept and the range of possible product variations increases, some firms may begin to offer *mass customisation* of products, further driving growth in both market demand and the diversity of preferences in the market.

Unlike the momentous entry of low-cost producers of final products in the traditional PLC model, large firms with relevant *marketing advantage*s in brands and distribution may enter the market and compete on brand reputation and/or wider availability of their products. Firms with strong brands relevant to the new market are likely to try to use their brands to charge premium prices in the market, rather than to engage in price competition. Firms with strong distribution and customer support capabilities that are relevant to the new market may begin to use their scale advantages to put a price pressure on competing firms to gain market share. However, firms that do not have those scale advantages may be able to deflect competitive pressure from larger firms by configuring and offering product variations and sales and service options that are intended to appeal to market preferences that are different from those targeted by the larger firms.

Low-cost producers may emerge in the Rapid Growth stage *at the component level* of the industry as some component suppliers begin to invest in the large-scale production of common components. To the extent that such components are technically stable and that large numbers of component variations are not needed in the market, some component suppliers may start to develop cost-minimised integrated platforms for the production of 'industry-standard' components.

Given these developments, the rapid growth of an open-system modular platform market will be driven by:

- increasing product variety, as more suppliers capable of producing plug-and-play components for the open-system modular architecture are attracted to the product market
- ongoing product innovation as product firms direct investments to developing better components and more diverse product variations
- falling product costs (and prices) as suppliers of technically stable common components achieve greater economies of scale.

5.2.4 Shake-out (Consolidation) stage

In an open-system modular market, any shake out or consolidation that may occur will happen for reasons quite different from those described in the traditional PLC model. Firms configuring and marketing finished products are unlikely to be forced to exit or to be absorbed by competitive pressures from low-cost producers, as in the traditional PLC model. Rather, a shake-out is more likely to occur because finished-product firms fail to develop branding, marketing, distribution, and customer service and support capabilities adequate to compete against late entrants with strengths in those activities.

A shake-out due to scale advantages and the resulting price competition may occur, however, at the component level of the market, as some component firms are able to build component market share and achieve economies of scale that give them cost and pricing advantages in component markets. Some component suppliers with dominant positions or strong niche positions may then try to vertically integrate downstream into production and possibly the marketing of assembled product variations in which their components are a major cost factor.

Shake-out and consolidation may also take place in various scale-sensitive activities in the modular process architecture, as some process specialist firms invest in expanding their facilities for production, distribution, or customer support. Their cost advantages may then enable finished-product firms who use their services to lower their overall costs, improve quality levels in product assembly, distribution and customer support activities, and reach more of the market with even more product variations – all without making significant investments of their own in process assets.

5.2.5 Maturity stage

In the traditional PLC model, a few large low-cost producers will dominate the market at the beginning of the Maturity stage, and must then switch from a strategic emphasis on the low-cost production of a dominant design to identifying and serving emergent market segments. At the beginning of the Maturity stage in an open-system modular market, however, the largest and most successful firms are likely to be those firms that have used their marketing capabilities to build up strong brand and distribution positions in the market. Further, the market will be founded not on one dominant design, as in the traditional PLC model, but more likely on a number of *preferred designs* that serve clusters of similar preferences in a market now likely to be characterised by a significant diversity of preferences.

To the extent that the market segments served by preferred designs are large and are thought to have stable preferences, some firms with leading positions in market segments may begin to vertically integrate to consolidate their positions in their market segments. Such firms may acquire smaller producers of components that provide important differentiation in their products, as well as providers of production, distribution and customer support activities that are critical in their overall process architectures. If the preferences in their market segments are thought to be stable well into the future, such firms may begin a process of redesigning the open-system modular architecture to optimise performance or cost parameters that are critical in serving their market segments. The outcome of this process may be the *emergence of some proprietary closed-system integrated architectures* in large and stable market segments.

To the extent that new market segments continue to emerge in the market and that established market segments continue to evolve in their preferences (for example, by demanding and rewarding higher product performance), firms will continue to serve such market segments by using the strategic flexibilities of the open-system modular architecture to configure new product variations, including higher-performing products that can be leveraged within the technical limits of the architectures.

5.2.6 Renewal or Decline stage

Renewal or Decline may occur because of fundamental shifts in customer preferences that either favour or disadvantage the product market, respectively. Either Renewal or Decline may also be influenced, however, by the potential for effecting technological changes within the current modular platform.

In the case of Renewal, market demand may be reinvigorated because of innovations in product or process components that significantly improve the performance-to-price ratio available in products provided by the platform. However, as the technical limits of the product or process architectures are approached, firms may recognise a need to define a new open-system modular platform to continue the development of the market. Thus, in the latter part of the Maturity stage, firms may begin to seek a basis for creating a new industry-standard open-system modular platform that will reinvigorate the market demand. As with the original launch of the product market, an individual firm may define and launch an open-system modular platform in an effort to gain strategic advantage by precipitating the Renewal stage, or a collective of firms may start a collaborative process of defining a next-generation open-system modular platform as the foundation for market renewal. In either case, the incentives firms face in seeking renewal are similar to the incentives for cooperation and collaboration in the Precompetitive Cooperation and Collaboration stage and the Embryonic stage.

Decline may occur because of fundamental shifts in customer preferences, the rise of more attractive substitute products, or government regulations affecting the product or its supporting processes. Decline will follow if firms cannot respond effectively to these challenges by configuring new product or process variations within the existing modular platform, or by defining a new open-system modular platform in time to preserve the market.

6 Conclusions: towards a broader understanding of modularity

The foregoing discussion of the relative abilities of integrated versus modular architectures to mediate market and technology change provides a basis for addressing some current misunderstandings about modularity in the evolutions of firms and product markets. We focus here on three of those misunderstandings that have gained some currency in the literature.

6.1 'The Modularity Trap'

Some researchers into modularity have described what has come to be known as "The Modularity Trap" (Chesbrough and Kusunoki, 2001). The basic idea here is that a firm may become 'trapped' within a modular architecture in the sense that the firm is unable to innovate in desirable ways because of the technical limits imposed by the standardised interfaces in its current modular architecture. In the more extreme promulgations of this idea (Ernst, 2005), standardised interfaces are asserted to block virtually all forms of innovations and to lock firms and industries into insignificant incremental improvements and eventual technological obsolesence.

What is typically overlooked in these arguments is the fact that managerial decision-making – including the decision as to the kind of architecture a firm will develop and use – is a comparative discrete choice process. In effect, managers must choose between defined possibilities by comparing their relative advantages and disadvantages. In this choice process, there are no perfect solutions – only alternatives that have their distinctive sets of advantages and disadvantages. When firms choose a modular architecture over an integrated architecture, they are not getting a perfect means to unlimited innovation, and in fact no such means has been imagined yet (and may never be). Rather, what managers and researchers alike should consider is the relative difficulty of innovating within the standardised interfaces of a modular platform compared to the difficulty of innovating within the much more significant cost and effort constraints imposed by an integrated platform.

It is simply naïve to condemn modular architectures because their interfaces impose *some* constraints on innovation, when the other alternative is an integrated architecture that imposes even more serious constraints on innovation because of the severe architectural lock-in inherent in integrated designs. In effect, the inherent technical limits of a modular architecture's interfaces may pose a 'modularity trap' of some importance, but there are many reasons to think that the 'integrated architecture trap' imposes much more costly and difficult constraints on innovation (cf. Cebon *et al.*, 2008). That these reasons are conveniently ignored in typical modularity trap arguments belies the incompleteness of such reasoning.

Some uninformed firms may indeed choose a modular architecture that unnecessarily limits potential innovations. More knowledgeable and thoughtful firms, however, will define interfaces in a modular architecture to support anticipated innovations in components and configurability. In particular, when the collective understanding of a host of industry participants is involved in defining an open-system modular platform for a new product market, such a deliberative process should lead to a modular platform that is well posed to support an extensive run of innovations that plug and play in its architectures.

6.2 The need for process and product integration

An argument widely espoused by proponents of manufacturing as a critical national competence in the 1980s was that firms must have intimate knowledge of manufacturing processes in order to create product designs that can be manufactured at high quality and competitive costs (Hayes *et al.*, 1990; Wheelwright and Clark, 1992). A later incarnation of this view is the idea that firms that do not manufacture a product will lack the knowledge and information necessary to define and design good architectures. In the extreme extensions of this argument in discussions of modularity (cf. Ernst, 2005), it is claimed that firms that do not produce their own products will not understand the process technology advances underway in an industry and will not be able to define new product architectures that can take advantage of those advances.

An important but erroneous assumption underlying such arguments is that it is just not possible to extract and make explicit the process architectural knowledge needed by other firms to define and design product architectures that are compatible with existing or future process architectures. While it is always possible that a given product firm may lack such knowledge or that a process firm may fail to provide such knowledge, there is ample evidence to establish that process firms may communicate to interested product firms sufficient architectural information about their processes to enable product firms to define and design architectures compatible with current and future process architectures. As Funk (2008) has documented, product and process specialist firms in the open-system modular semiconductor industry have learned how to coordinate their respective architectures autonomously through the exchange, publishing, or other forms of dissemination of essential information about their respective architectures and interfaces. In effect, the claim that firms that lack process capabilities will fail in their design of product architectures is refuted by the existence of this and other highly dynamic and innovative industries in which separate ownership ('vertical disintegration') and autonomous coordination of product and process architectural development and innovations are the norm.

6.3 Modularity as a mature technology phenomenon

A final misunderstanding about modularity is the claim that modular architectures will only emerge at later stages in a product market – *i.e.*, the Shake-Out or Maturity stages – when technologies have stabilised, because it is not possible to specify and standardise interfaces in an architecture when technologies are still evolving and uncertain. This argument also rests on a failure to compare alternatives – in this case, the difficulty of defining interfaces in modular architectures *versus* integrated architectures when technologies are evolving.

Technology change occurs at the component level of product architectures and takes one of three forms:

1. improvements to existing technologies used in existing kinds of components
2. the development of new technologies as the basis for implementing existing kinds of components
3. the invention of new kinds of components based on new or existing technologies.

Interfaces in a modular architecture can be – and indeed often are – defined to allow the introduction of some defined range of technologically upgraded components or even new kinds of components in the future. For example, the original SCSI interface and more contemporary USB and Firewire interfaces have supported more than two decades of rapidly evolving, technologically innovative peripheral components for open-system modular computers and other electronic products.

By comparison, designing an integrated architecture intended to optimise some defined performance or cost parameters is highly problematic when component designs that have to be integrated and optimised in the architecture are technically uncertain or evolving rapidly. Thus, *on a comparative basis*, while defining modular architectures that can accommodate some defined range of technological change and uncertainty may not be easy (but usually at least possible), the alternative of creating integrated architectures when component technologies are uncertain or evolving rapidly is even more difficult, if not unattainable.

Perhaps the most persuasive argument against the claim that modular architectures cannot be created when technologies are uncertain and evolving, however, is the fact that product markets anticipating high levels of technology change and uncertainty (*e.g.*, telecommunications devices and personal computing products) are increasingly adopting open-system modular architectures in which relevant component interfaces are being specified (successfully) to support significant technological change and even alternative technology outcomes.

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Notes

1 A product architecture in a product market may be supported by more than one process architecture, as would be the case when two firms create products using the same product architecture, but vary in the process architectures they use to develop, produce, deliver and support their respective products. For example, the range and rate of product variations and upgrades that each firm can bring to market may vary with the number of firms (and their capabilities) involved in the component development for each firm's product architecture, as well as with the nature of their interactions with each firm in its product creation process.

2 However, the integrated design for the alternator and cooling fan eventually proved to be too costly to produce, maintain and repair. The integrated alternator and fan assembly lasted only one year (1965–1966) and was subsequently replaced by separate components in later-model 911s.

3 More formally, a component variation that can 'plug and play' in an architecture (whether product or process) is one that can be introduced directly into and perform well within an architecture without modification of the design of the component or of the architecture. We may then define a *modular component* as a component whose function and interfaces have been defined to enable the component to plug and play in at least one modular architecture.

Appendix

The five stages in the traditional product life cycle model

The five stages in the traditional PLC model of the evolution of a product market – Embryonic (Introduction), Rapid Growth, Shake-out (Consolidation), Maturity, and Renewal or Decline – are illustrated in Figure 3 (Levitt, 1965). Each stage in the traditional PLC model is characterised by specific kinds of changes in market conditions, marketing activities, product designs, product technologies, component development processes and supporting process technologies (Sanchez and Heene, 2004). These changes are summarised below for each of the five stages.

Embryonic (Introduction) stage

The initial stage of a product market begins when a *new product concept* is introduced for the first time. A product concept is a unique bundle of functions that are not otherwise available in that exact combination, and a new product concept offers a new unique bundle of functions. In this sense, for example, upon their market introduction the laptop computer was a new product concept, even though desktop personal computers had existed for several years before the introduction of laptop computers, because laptop computers added the function of portability to create a new unique bundle of functions.

In the Embryonic stage, there is considerable uncertainty about how potential users will react to a new product concept. Since intended users have no prior experience (by definition) with the new product concept, they typically have difficulty imagining how they would use the new product in their lifestyles or business processes. Firms may try to identify 'lead users' (Von Hippel, 1983) thought to have particular appreciation for the new product concept, and to learn from them how the refine or revise the new product concept. Marketing activities in the Introduction stage are therefore likely to be focused on interacting with potential customers, especially lead users, in ways intended to discover the exact 'bundle' of 'core functions' – and their necessary performance levels – that will become the basis for a successful new product market.

Based on the feedback they are gathering from their interactions with potential customers (or not), inventors and early entrants will introduce product designs based on different combinations of functions, features and performance levels, and different physical arrangements of components providing the functions, features and performance levels. This process is very risky, however, as most new product designs and their firms typically fail to survive the early market exploration and testing process. Eventually, however, a "dominant design" (Clark, 1985) may emerge which appears to offer the most successful combination of user satisfaction and production economies. Firms that remain in the new product market must be able to provide their own versions of the emergent dominant design.

The most important form of technological change at this stage is the development of enabling product technologies capable of delivering the 'core' product functionalities at performance and price levels that will induce widespread adoption of the new product concept. Although some new product-enabling technologies may need to be developed, some firms entering the Introduction stage may try to adapt their existing technological capabilities in developing and producing versions of the new product concept. Relatively little new process technology is developed in this early stage of the market, and many firms will try to use or adapt existing production technologies in producing the new product concept. Only when the core functions and dominant design arrangement of components for providing those functions are discovered will firms begin to invest in developing new process technologies best suited to the production of the new product concept.

The development of product technologies is carried out by creating product designs and developing components which are capable of delivering the functionalities, features and performance levels required to induce broad adoption of the product concept. Appropriate processes for producing and assembling the component parts of the new product must also be considered as product and component designs are developed. In the Introduction stage, many variations in product designs may appear in the market as various firms draw on their distinctive technological, engineering and production capabilities in creating early versions of a new product concept.

Rapid Growth stage

Once firms understand the core functions and dominant design for the new product concept preferred by the market, and once growing market acceptance establishes the commercial viability of the new product concept, the basic market uncertainty about the new product is essentially resolved. Firms then begin to compete by refining their early versions of the dominant design, often imitating the product designs of the most successful firms when possible. Product design and technology development shift to a focus on improving product and component designs to reduce the costs of manufacture.

Once market uncertainty about core functions and dominant designs is resolved, and once product costs begin to fall as revised product designs result in lower product costs, market demand starts to grow rapidly. Once market demand reaches a certain size, ‘low-cost producers’ will enter the new market. These firms are not risk-takers like the market pioneers that launched the Introduction stage; rather, they are firms with proven capabilities in the efficient large-scale production and distribution of similar or related kinds of products. These firms wait until market and product design uncertainties have been resolved and until a new market is shown to be large enough to enable them to use their large-scale, low-cost production and distribution capabilities. They will then enter the new market using product designs similar to those that have proven most successful in the market, supported by aggressive pricing strategies that often reflect their anticipated long-term production costs rather than initial costs. Although falling price levels initially stimulate further growth in demand, eventually the demand growth levels off, often precipitating an even more intense price competition as the large firms scramble to maintain growth and increase market share.

Shake-out (Consolidation) stage

Price competition precipitated by the entry of low-cost producers and slowing market growth leads to the failures or takeovers of most or all market pioneers and early entrants. Although occasionally such firms may manage to transform themselves into large-scale, low-cost producers, most early firms will not be able to develop the process technologies, production facilities and management skills required to become efficient large-scale producers and price competitors. The resulting ‘shake-out’ of early firms leads to the consolidation of the industry in the hands of a few large-scale, cost-efficient firms that have invested in large-scale production and distribution facilities for the new product. These firms will emphasise the production and marketing of *de facto* 'standard' product designs produced using large-scale process technologies.

During the rapid growth of the market, however, at least some customers for the new product concept will have imagined specific ways of using the new product concept that would better suit their lifestyles and/or business processes, and some of these customers will begin to demand product versions that are better adapted to their situations and preferences. Some early market participants who do not mange to become large-scale, cost-efficient producers may manage to survive as smaller firms by identifying and serving the resulting *niche markets* for specific kinds of product variations. Such niche firms may continue specialised product technology and component development until their product designs are adequately adapted to their niche customers' needs and preferences, at which time they will adopt process technologies best suited to the specific kind of product variations they have developed to serve their niche customers' needs and preferences.

Maturity stage

As demand stabilises at its long-term level in the maturity stage, different kinds of customers begin to imagine product variations that could serve their individual preferences better than the standard products offered by mass-production firms. Thus begins the long-term process of *market segmentation*, in which firms try to detect diverging customer preferences and identify which emerging market segments are large enough to justify developing *differentiated products* to serve them. Although some firms may continue to offer low-priced undifferentiated products, and niche players will continue to focus on their niche customers' evolving needs, eventually larger firms in the market will try to avoid price-based competition in favour of differentiating products for several or many market segments, as selling an undifferentiated product to increasingly sophisticated and demanding customers becomes progressively more difficult and less profitable. Firms will try to differentiate their products by developing existing and new product technologies and derived components that can help them differentiate their products through superior performance, increasing features and distinctive styling, as well as by distinctive service, distribution and customer support.

Renewal or Decline stage

The renewal of a product market in the Maturity stage occurs when demand levels in the product market undergo a significant increase. Demand levels may increase for a number of reasons (Sanchez and Heene, 2004): fundamental changes in sociocultural or demographic factors that shift market preferences in favour of the product concept (*i.e.*, more people start to see the product concept as useful and desirable in their evolving lifestyles or business processes), geographic expansion of the product market, technological advances that improve product performance or lower costs or both, design refinements that improve ease of use, favourable changes in complementary product markets, and the decline or demise of substitute products, among others. Significant increases in demand may precipitate new Shake-out/Consolidation and Maturity stages as market participants try to respond to the changes that have precipitated the increased demand in the market.

Decline occurs when demand begins a significant and permanent fall, possibly ending in the extinction of the market. Decline may be precipitated by fundamental shifts in market preferences that are unfavourable to the product concept, technological advances that give rise to more attractive substitute products, unfavourable changes in complementary product markets and new government regulations unfavourable to the product market, among others.