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Modularity and the Product Lifecycle

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Summary:

In this paper we argue that product lifecycle theory, which underlies theories of technical innovation across the social sciences, is undermined if products are modular.

Abstract:

Product lifecycle theory, which underlies theories of technical innovation in economics, strategy, marketing, and operations management, is based implicitly on the assumption that products are integrated wholes. The modularization of products undermines the specific synergies which drive the product lifecycle, and this undermining has impacts spanning from the structure of individual organizations to the structure of economies and the definition of industries. (62 words)

Modularity and the product lifecycle

In the first decade of the 20th century the three-way competition between gasoline-powered, steam-powered, and battery-powered electric vehicles was won by gasoline. This led to a massive shakeout in the world automobile industry and the gasoline-powered vehicle became the dominant design (*1*). A century later, a similar competition is emerging, but this time between fuel-cell-powered electric vehicles, gasoline-powered electric vehicles (hybrids), and gasoline-powered vehicles. While fuel-cell-powered vehicles will most likely win the competition, there is no sign this victory will cause any shakeout whatsoever.

The product lifecycle model, with its premise about the synchronicity of innovation and market development is one of the most widely accepted frameworks for research on the management of technological innovation and pervades research in management strategy (e.g. *2, 3-6*) industrial economics (e.g. *7, 8-11*), marketing (e.g. *12, 13*) and operations management (e.g. *14*). The idea of an industry being built around a core product (e.g. automobiles, computers) is implicit within the theory and pervades research throughout the social sciences.

Authors in this tradition would explain the shakeout in the first instance, but not in the second, by labeling the first technological change as "competence destroying" (5, 6) and the second as "competence enhancing" (5, 6). However, given that the changes are technically homologous, this explanation seems hollow. In this paper we will argue that in the second instance, the automobile technology has become highly modular (15, 16), and as such, notions of competence destruction, competence enhancement, and the product lifecycle have declining relevance. We will elaborate this basic thesis – that modularization undermines the product lifecycle – with examples from the automobile, personal computer, and construction industries.

Products on a continuum from integrated to modular

An end-product is a set of components that are linked together so as to be useable as a relatively stand-alone unit by an end-user.[2] Products vary on a continuum from integrated to modular (*17, 18*).

In essence, a modular system is built of parts so that their internal complexity is hidden from other parts and from the environment external to the system (*19, 20*). A module is a component of a modular system, and an interface is a set of formal well-codified rules

[2] This definition has high heuristic value, but surprisingly little analytical value. For instance, while we think of a printer as being a "product", a printer has very limited use unless attached to a computer.

that define how modules interact with each other. The set of interfaces that make up a modular system is its architecture. A system is modular in as far as its architecture supports the substitutability of modules (*18, 21-23*), with more modular systems supporting more substitutions. Domestic construction is highly modular in that virtually all of the components can be used across architectures with no modification (bricks, nuts, bolts, refrigerators, cisterns, windows), or minimal modification (beams, plasterboard, wires, floorboards), and can be substituted for each other (steel beams for wood, carpet for linoleum, wooden windows for Aluminum etc.)

While modular products are non-specifically synergistic, integrated products have synergistically specific interfaces (*18*). In integrated systems, the functionality of the system declines if one substitutes one component for another. In contrast, modular products can achieve equivalent or alternative levels of performance if the various components are either arranged differently or are substituted. For example, a user can replace the Cathode Ray Tube (CRT) screen on her computer with a Liquid Crystal Diode (LCD) display with essentially no change in utility. Because the CRT screen performs as well as it would if it were integrated into the computer, the CRT screen and the computer are synergistic. However, because the user can swap the CRT screen for the LCD display, the synergy is not specific to the CRT screen. The computer is equally synergistic with the LCD display. The CRT screen and the computer are non-specifically synergistic.

Innovation in modular systems

The non-specific synergies allow four types of innovation in modular systems. Designers can modify a module incrementally (*24*). In incremental innovations, neither the core-concepts which define the way the technology within the module is constructed nor the nature of the interface between this module and other modules changes significantly (*24*). In storage devices for personal computers, most of the 12,000-fold increase in hard drive capacity from 5MB in the mid-1980's to 60 GB today was achieved by progressive refinement of the parts or components within the modules, and the way they interact with each other.

Alternatively, designers can replace one module with another – a modular innovation (*24, 25*). This is an innovation in which the internal content of the module changes, but the interface standard stays the same. Examples include substituting the second floppy drive on the original *IBM* PC for a hard drive, a record player with a CD player, or a VCR with a DVD player (*26*).

Third, designers can create an architectural innovation – in which the interface standard changes although the core concepts within the modules are preserved (*24*). Obvious examples include changes in the size of hard drives from 8" to 5.25" to 3.5" to 1.75" which have allowed the drives to be used in different ways, changes in the interface between the drive and the rest of the computer (e.g. MFM, IDE, SCSI), and the adoption of the Universal Serial Bus (USB) which allowed many peripherals (e.g. printers, personal organizers) to move from the nine-pin serial port with minimal internal changes.

Finally, designers can develop new products. The laptop computer, like the *Sparcstation* and the *Macintosh,* is a product with a different architecture but functional modules that are nearly identical to those in a personal computer. New products are likely to involve new architectures, some new modules, and a number of old modules, some of which have been incrementally improved or modified.

The implications of modularity on the product lifecycle can be derived using an ideal type analysis, in which it is assumed that an integrated product obeys product lifecycle theory and then the impact of modularization is considered, with the full knowledge that real products are neither fully integrated nor fully modular. We start by summarizing contemporary theory of the product lifecycle and showing how it rests on the assumption of increasing synergistic specificity, not only between the components of the product, but also between the product, the organization which designs it, and the market which consumes it. We then consider how the possibility for modular and architectural innovation in modular systems undermines the core predictions of product life cycle theory.

The Product Lifecycle Model

The product lifecycle and patterns of innovation

All elaborations of the product lifecycle model (e.g. *3, 4, 6-12*) and industry evolution models which are based upon it (e.g. *5, 13, 14, 27*) rest on the core idea that there is a temporal and causal connection between the nature of the market for a product and the evolution of the technologies that it embodies (product technologies) and the technologies that support and enable it (process technologies). While the connection between product technologies is predicated upon experimentation and learning by and about customers and users necessary for the diffusion of a new product, the connection with the process technologies is based upon the economics of innovation, from novelty products to mass production and commoditization. The transition from novelty products to mass production is marked by the emergence of a dominant design.

A representative model (*3*), can be summarized as follows: The evolution of an industry begins with the introduction of a novel product by a firm. The innovation creates a new market, so there are no pre-existing links to customers, or it completely reorganizes the value chain. This innovation also requires the firm to master technical competencies that did not previously exist in that market space. This is called an architectural innovation, because it "lays down the architecture of the new industry." (*3: 60*).[3] Because the technical capabilities are new, the players in this nascent industry are either all start-ups or are players in related industries. At this stage, the product is still evolving and numerous firms participate in its refinement and production, experimenting with features, materials and design with a view to creating product configurations that might appeal to the market. The industry is quite attractive economically, with numerous firms sharing in the high returns and growing demand.

Eventually, one player develops a product which integrates technologies and features in such a way that it is attractive to a large segment of the market (the dominant design). This company is able to achieve a dominant market share (*28*) and to derive profit advantages on the basis of economies of scale. During the shakeout that follows, companies that are able to imitate the dominant design survive and succeed as participants in an oligopolistic market (*29*), while the rest deteriorate and exit the industry, retreat to market niches not serviced by the dominant product, or perish. The

[3] Note that the term "Architectural innovation" has two meanings within the literature. In this case, it refers to the creation of a new industry. For most of this article, an architectural innovation refers to a change in the relationship between the modules in a product.

remaining players produce essentially the same configuration (*30-33*) and compete on the basis of price and performance (*34*).

As competition moves from between-configuration competition to within-configuration competition, the locus of innovation moves from product innovation to process innovation (*2, 35*). Manufacturers become more rigid (*36*), and price and reliability become the main factors that separate winners from losers (e.g. *34*).

Over time, the dominant design is refined in two ways. Along one dimension, new platform innovations are developed out of it, creating channels to new customers (niche innovations). On the other, the main design itself gets progressively refined (regular innovation), and new product offerings are clustered around it (*37*). The act of regular innovation, through means such as specialist machinery, economies of scale, and the development of closed communities of practice within and between firms (*38*), erects barriers that prevent the owner of the dominant design from detecting novel or emergent designs and/or implementing them even if detected. Thus, core competencies become core rigidities (*36*). The market sits wide open for a new entrant to bring a radical innovation that, once again, transforms the industry and the competencies that underpin it (*5, 6, 27, 37*). These processes are summarized in Figure 1.

Insert Figure 1 about here.

The dominant design and synergistic specificity

The product lifecycle model hinges on the concept of dominant design, or “a specific path, along an industry’s design hierarchy, which establishes dominance among competing design paths” (*39: 49*) which drives both the beginning and the end of the product lifecycle. The adoption of such a design can dramatically affect the nature and direction of competition, and the structure and evolution of the industry (*2, 39*). At the top of the cycle, the emergence of the dominant design leads to the shakeout that rationalizes the industry and enables its owners to both build their skills and market position (*39*). Early authors emphasized the role of specialization, scale economies (*3*), and embedded competencies (*24, 36*), in locking in a dominant design. All three of these correspond to increases in synergistic specificity (*18*). In the first case, the skills of the product designers and production engineers become specific to the particular design. In the second, the entire production system becomes specific to that design. In the third, the cognitive systems of the people involved with the product become aligned with the dominant design (*24, 36, 37*). Later authors also see a role for network externalities built around ties to specific complementary assets (*40*), such as videotapes (*30*), typing schools (*41*), or the *Unix* operation system (*42*).

The dominant design permits more stable and reliable relations with suppliers, vendors, and customers, and from the customer's perspective, a dominant design reduces product-class confusion and promises dramatic decreases in product cost (*6*). All of these correspond, once again, to increased synergistic specificity. In this case, it is between the product and suppliers and customers.

Specific synergies are also the fundamental source of the core rigidities that prevent firms from responding to competitive threats posed by radically new technologies at the end of the cycle. These rigidities might reside in the production system (*6, 43*) or in channels to customers (*33*). After the radical new technology has broken through and transformed the industry however, the system is re-stabilized by the reintroduction of specific synergies between the cognitive systems of product designers, skills and production systems of manufacturers, market channels, and the expectations of the market.

The impact of modularity on drivers of the product lifecycle

As we saw in the section above, the central assumption of product lifecycle theory is that systems evolve towards and are stabilized (or re-stabilized after radical innovations) by increasing synergistic specificity between the product, organization, competencies, production technology, suppliers, and customers, locked in by specialization, scale economies, embedded competencies, and network externalities. In modular products, specific synergies between product elements have been eliminated. In this section we examine how this affects specialization, scale economies, embedded competencies, and network externalities in the production system.

With regard to specialization, there is considerable evidence that companies which pursue a modular strategy develop tremendous specialist expertise, both in the design and manufacturing of particular modules, and in the design of product architectures (*44*). However, that expertise does not lead to specific synergies between the organization and its competencies and production technology, but the opposite. Because the product is modular, it becomes possible for the organization to modularize the group which either designs or manufactures it, even to the point of out-sourcing it. Consequently, entire parts of the organization or its production technology can be substituted in and out without disrupting the rest of the organization.

Modularization reduces the minimum efficient scale of production, and hence the specific synergies in two ways. First, suppose an integrated product with a certain minimum efficient scale was subsequently separated into two modules. Each of those modules would have a minimum efficient scale that is smaller than or equal to that of the integrated product. Consequently, the modular product has a minimum efficient scale less than or equal to that of the equivalent integrated product. Second, because our integrated product is now modularized, it becomes possible to use the two modules in other products. For instance, a flat-screen display can be attached to a television tuner as easily as to a computer. Therefore, the minimum efficient scale for our production system may be quite different from the minimum production run for our product. Therefore, the scale of production is much more loosely coupled to the size of the market for a given product for modular products, and so specific synergies are much weaker.

Modularization also undermines embedded competencies. As a general rule, modularization forces organizations to make tacit knowledge explicit (*44*) in as far as that tacit knowledge is relevant to the interactions between modules. Furthermore, the remaining embedded knowledge and associated competencies are confined within the boundaries of individual modules. As such, they cannot pervade the entire organization. As a result, there is a much lower likelihood of specific synergies forming between particular sets of embedded knowledge and competencies and larger organizational, technological, and market systems.

Finally, lock-in associated with network externalities results from specific synergies between particular products and complimentary assets in the marketplace (*41*). In as far as those complimentary assets are substitutable; the extent of the lock-in is reduced. Modularization enhances substitutability. For instance, VHS and *Betamax* could have co-existed just like electric and gas stoves (or 5.25” and 3.5” floppy drives) if people had only used video-cassette recorders to play back home videos and to record and replay television shows (*31*). VHS only triumphed decisively over *Betamax* when video rentals took off. Among other things, the need for store-owners to manage inventories meant that the specific synergies between the tape format and the VCR become much more important (*31*). If the VCRs were modular however, and so manufacturers could simply substitute the VHS playing module for the *Betamax* playing module, while leaving the rest of the machine as it was, even that specific synergy would have become irrelevant.

In summary, modularization serves to reduce, and in some cases eliminate the four principal drivers of lock-in for dominant designs -- scale economies, specialization, embedded competencies, and network externalities. In the next section we examine how this undermining affects patterns of innovation and the dynamics of the product lifecycle.

Innovations in Modular Systems and the Product Lifecycle

The above sources of lock-in drive the progressive increases in synergistic specificity, through increasingly incremental and component-based innovation, which stabilize the entire value chain, notwithstanding occasional punctuations (4, 5) which are quickly stabilized. If the sources of lock-in are removed, innovation can occur in both architectures and modules at once, and so we can expect a much more chaotic process (see Figure 2). Innovation no longer stabilizes the system, but rather destabilizes it. Architectural, modular, and incremental innovations to either modules or architectures can happen in any order (see Figure 3). Products might start with an architectural innovation, in which pre-existing modules are organized in a different architecture. This may create demand for many new modules. For instance, the creation of a high-speed data port on personal computers opened up the market for external devices that could process audio and video, and software to manage the content. Skyscrapers facilitated the development of pads to isolate buildings from seismic forces (*45*). Similarly, the creation of specific modules to fit these new architectures is likely to drive the creation of new products that can use those new modules. For instance, the development of small motors and high-fidelity headphones for personal cassette players facilitated the invention of the personal radio, the personal CD-player, the personal MP3 player and the personal mini-disc player. Elevators facilitated skyscrapers (*46*). Alternatively, products might start with a modular innovation in which a new module is inserted into an existing architecture, as with CD players being added to Audio systems (25), and then find their way into a multitude of products, such as computers, as components. They may also begin as a combination of both modular and architectural innovations, where a few modules are combined with old ones into a partially new architecture, as with the transition from analogue to digital home-video cameras.

Insert Figure 2 about here

Insert Figure 3 about here

Undermining the product lifecycle

We saw above how modularization undermines the drivers of lock-in and creates possibilities for multiple types of innovation simultaneously. We also saw how the product lifecycle model hinges on the establishment of the dominant design at the top of the product lifecycle and its dislodgement at the end. We will now consider the impact of increased modularity on the establishment and dislodgement of the dominant design.

The "era of experimentation" leading to the establishment of a dominant design will decline in importance as products become more modular. Because consumers and manufacturers can swap modules in a given architecture, experimentation can be relatively cheap. If customers eschew certain features in a VCR, the manufacturer can stop including them. If their voice recognition software does not work properly, customers can buy another package at low cost. Meanwhile, their poor choice of program has not affected the rest of the functionality of their computer. From this it follows that potential adopters are much less likely to await the emergence of an industry standard before purchasing a new product or installing a new process technology. It also follows that the emergence of an industry standard will not be a prerequisite to mass adoption and volume production of a new generation of technology (see *6*).

The establishment of a dominant design marks a transition from competition between technical regimes to competition within a technical regime (*6*). The more modular product systems become, the less likely such a transition will occur. The innovative technology can simply be inserted, as a new module, in an existing architecture, such as a "Zip" drive inserted into a PC. In addition to avoiding the transition, this increases the number of niches occupied by the given technology because it can be embedded into a number of different architectures. For example, "Zip" drives can be incorporated in PC's, laptops, workstations, and industrial robots. It also makes the host architecture more flexible, and therefore able to occupy more niches (*47*). As a consequence, a given design can dominate more spatial niches (*48, 49*) and more temporal niches. A PC of the near future -- a very high-powered machine, possibly with a photonic processor, embedded in a network with input by voice and graphical manipulation, output to a flatpanel screen or the Internet, and storage on an optical disk – will have no parts in common, no physical resemblance, and few uses in common with the product from which it has evolved, the original *IBM* PC. Notwithstanding, the same "product" will have dominated the same "niche" for about 20 product generations.

As products become more modular, dominant products will become less entrenched at the end of the cycle. Because the dominant product is modular, it is possible for a new entrant to adopt many of the attributes of the existing product by purchasing modules from existing suppliers. *Dell* entered the PC market with an innovation in logistics and supply chain management but purchased all its hardware and components.

In the conventional model, discontinuities can be driven by competence-enhancing or competence-destroying discontinuities, where "A competence enhancing discontinuity builds on know-how embodied in the technology that it replaces," (*6: 11*) and strengthens the position of the incumbent, while a competence-destroying discontinuity does the opposite. With modular and architectural innovations, competence enhancement stops being as clear a concept. The car example which opened this paper illustrates this. Vehicle manufacturers may well end up outsourcing their fuel cells to new companies, but this will enhance their ability, as manufacturers, to compete in the face of new environmental regulations. Consequently, whether or not an innovation is competence enhancing or competence destroying depends on the role of the actor in the innovation network.[4]

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[4] In a recent article, Tushman and Murmann (*37*) argued that the advent of modularization did not change the logic of the product lifecycle. Instead, they argued, the "product lifecycle logic" would be observed at a different level of analysis, namely within the module. If they were correct, then all of the lock-ins associated with the product lifecycle could be destroyed simply by modularizing the module. This

It is important to note that the above paragraphs speak of more and less modular products. There are no perfectly modular products because there will always be a cost of substituting modules, and the brands associated with particular products have value, among other reasons. These will serve to maintain a weak semblance of a product lifecycle. Notwithstanding, a recent study of the Japanese domestic construction industry (*50*) provides an example of a mass-produced product which is close to the modular ideal. About 20% of Japanese luxury single occupancy dwellings (houses) are produced in factories and assembled on site. Interestingly, Toyota, the world leader in modular vehicle design and manufacturing, is one of the leading manufacturers, so we can assume that these manufacturers are very sophisticated. In short, the market has rejected all attempts to produce standardized architectures (potential dominant designs) for houses. In fact, two of the three most successful manufacturers use architects as salespeople who customize the design with the client by modifying room-level modules. None of the lock-ins which make the product lifecycle model theoretically useful are observed. Product lifecycles at the level of the components (if they exist) lead neither to product lifecycles at the level of the modules (room units) nor the product (houses).

Discussion

We have shown how modularization removes the synergistic specificity between components and this undermines the logic of the product lifecycle. We discuss one key implication, that for the design of organizations and the configuration of industries.

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undermines their argument. Put differently, such an argument assumes that all important innovation occurs within the modules, and that innovations between them are irrelevant.

The optimal form of organization according to product lifecycle theory is the ambidextrous organization (*37, 43*). Such an organization has discipline and rigidity to produce regular innovation during the convergent phases of the product lifecycle, and is able to reinvent itself and its products during the discontinuities.

In contrast, if the fundamental driver of organization is interdependence (*51*), and modularization enables components to be decoupled, then efficient forms of organization for the design of modular systems will involve a meta-level organization to design the architecture and divide it into modules and decoupled units which design the modules (*44*). Organizations which control the architectures of their products and produce them efficiently tend to adopt such a form and oscillate temporally between phases of architecture development and phases of module development for products, processes, and knowledge (*44, 52-54*).

If products involve modules produced by different manufacturers, these two roles can involve two types of organization, one specializing in modules (module manufacturers) and the other specializing in aggregating modules and assembling them into final products (assemblers). Each module manufacturer might supply a number of assemblers. Those assemblers might be in completely different markets, and so might interact with fundamentally different sets of module manufacturers. In such a situation, the optimal form of industrial organization becomes a network of small firms, rather than a dominant manufacturer with subservient suppliers (*25, 55-57*). Hence, we hypothesize that the Silicon Valley phenomenon would be strongest in industrial domains where modularization is practiced extensively.

In such an environment, we expect to see extensive entrainment of firms (*58*). Consider two computer assemblers "D" and "C". Suppose that D pressures its module suppliers to produce new models by June and December, so it can release its new products at trade shows in September and March. Because C will have access to the same new modules in June and December, it will then schedule its product releases for the same trade shows, and put pressure on its suppliers who don't supply to D to deliver in June and December as well. Those suppliers will put similar demands on third tier suppliers, and will make modules available to other assemblers, possibly outside the narrow sectors in which "C' and "D" operate, e.g. "A", pressuring them to release their products on the same schedule. Once the market (e.g., the computer magazines) gets used to this schedule, it will build its own expectations. Consequently, we can expect an entire complex of firms to be entrained into the same timing schedule.

Finally, we are led to consider the definition of an industry. If organizations, technologies, and markets are synergistically specific, then an industry can be defined as a group of companies "hanging off" a dominant design through particular market linkages and technical competencies (*3, 59, 60*)[5]. So, for example, the "automobile industry" comprises vehicle manufacturers, their suppliers, and their distribution channels. Once modules start to appear across significantly different architectures, technologies and markets become decoupled. Whereas technology once defined industries, in a modular world, an industry has to be defined exclusively in terms of the product market. This means that an industry is, at least to some extent, independent of a particular knowledge

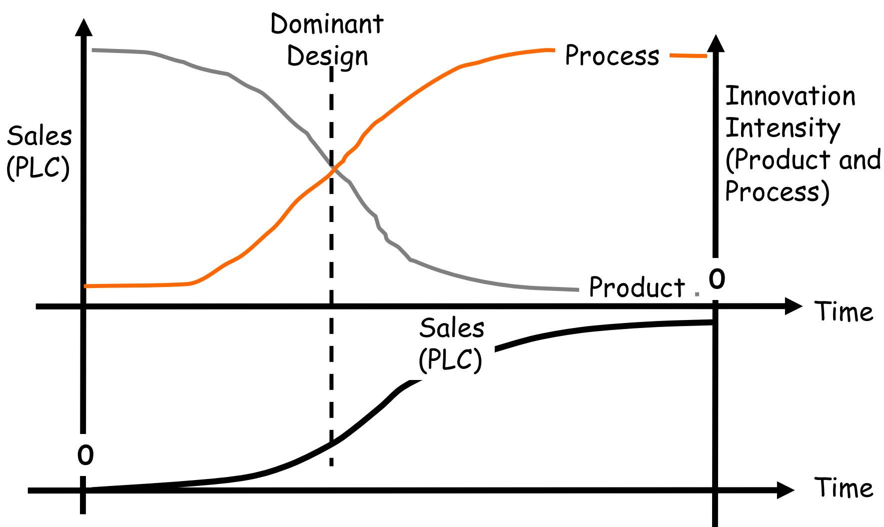
[5] It should be noted here that all the above show the conjunction of markets and technologies in industries with data that clearly predates modularization of product technology, Abernathy with mainly data from *Ford*, circa 1900-1935, Kogut et al. and Teece et al with pre-1970 data.

base of the manufacturers, but is dependent on the cognitive categorization systems (*61, 62*) of consumers. Industries move from being "in the making" to being "in the market".

(4407 words)

Figures

Figure 1: Product lifecycle and patterns of technological innovation for integrated products



Source: Adapted from Abernathy (1978)

Figure 2: Innovation rates for modular and integrated products

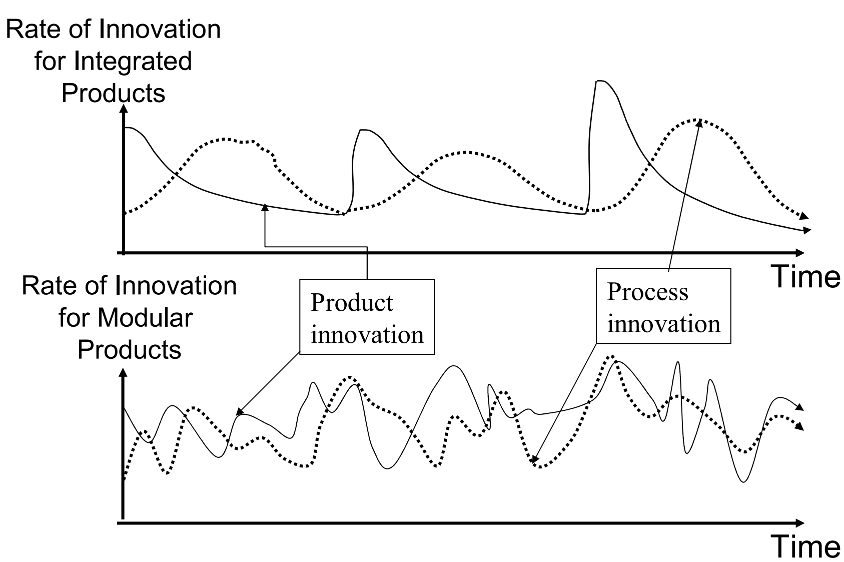
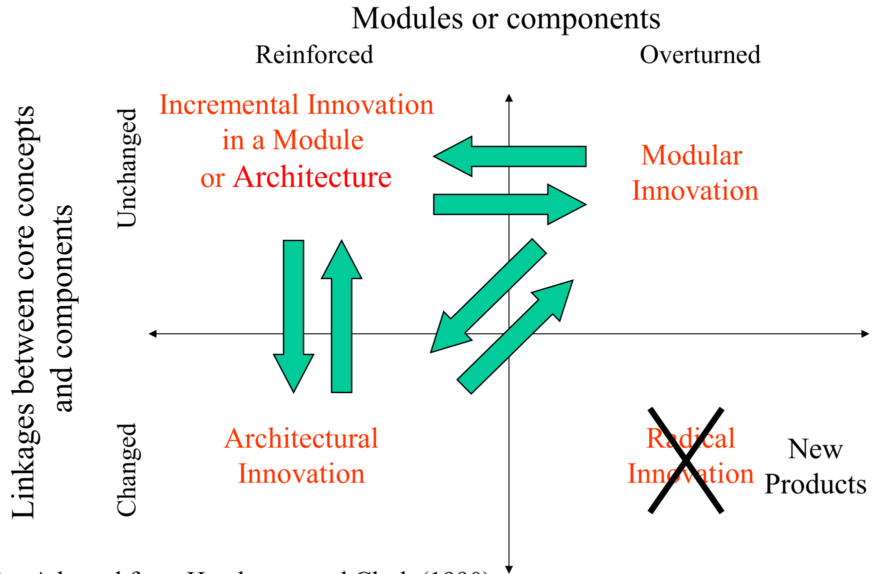


Figure 3: Innovation dynamics for modular products



Note: Adapted from Henderson and Clark (1990).

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