Paper to be presented at
the DRUID16 20th Anniversary Conference
Copenhagen, June 13-15, 2016

When do Industries Modularize? Firm Actions and the Role of Product and Organization Architecture

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Abstract

When industries modularize, the degree to which firms capture value can shift. This paper develops a conceptual framework to understand when industries modularize, and how firm actions influence such modularization. To do so, we first outline how modularity increases at the product and organizational level. We argue that industry modularity increases when product interfaces and organizational practices disseminate beyond the focal organization. Next, we highlight several moderating factors that influence this dissemination process. Overall, the paper attempts to contribute to the existing literature as follows. First, the framework highlights strategic actions at the product and organizational architecture level to understand changes in industry modularity, attempting to "endogenize" the structure of a given industry. Second, the conceptual framework suggests how industry architectures become more modular through dissemination of interfaces and practices, and proposes several moderating factors that influence this diffusion process. Third, the contingent perspective developed in the framework may reconcile diverging perspectives on the role of modularity and inter-firm coordination, in particular existing work on systems integration.

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INTRODUCTION

Modularity generally refers to a design property focused on managing complexity by containing interdependencies within rather than across subsystems (Ulrich, 1995; Baldwin and Clark, 2000; Schilling, 2000). We can distinguish at least two theoretical antecedents to the concept of modularity. First, Simon's work on complexity and nearly-decomposable systems (Simon, 1962, 2002) has proved foundational to an emerging line of work focusing on e.g. organizational architecture (Galunic and Eisenhardt, 2001; Ethiraj and Levinthal, 2004), imitation (Rivkin, 2000), and innovation (Von Hippel, 1990; Pil and Cohen, 2006; Staudenmayer et al., 2006). Second, the idea of organizations as loosely coupled systems (Weick, 1976) has inspired work on a range of topics including e.g. systems integration (Brusoni et al., 2001; Prencipe et al., 2003), organizational redesign (Mitchell and Zmud, 1999; Karim, 2006); and cooperative alliances (Luo, 2005).

The emerging literature on modularity has conceptualized its properties at multiple levels, including product and organizational architecture and how the two relate (Baldwin and Colfer, 2010). More recent work has also looked at modularity at the industry level, i.e. where standardized modules allows firms (or sometimes even consumers) to mix and match components across firm boundaries (Staudenmayer et al., 2006; Jacobides et al., 2006; MacDuffie, 2013). The clearest example of a sector marked by a high degree of modularity is the PC industry; here, a variety of firms specialize in different components of the overall system – the PC industry is noteworthy as integration of the various components can (at least in the desktop computing segment) be done by individual consumers[1]. At the same time, research has highlighted how industry modularity has generally not increased, despite analyst predications and expectations of industry participants (see e.g. the automotive industry, cf. MacDuffie, 2006; Zirpoli and Becker, 2011). While several studies have investigated how industries become more modular (Jacobides, 2005), there appears to be little consensus about the conditions that influence the degree to which industries modularize. For instance, some studies have suggested that modularity represents a new mode of production (Sturgeon, 2002;

[1] Other examples include stereo components (Langlois and Robertson) and, at one stage, the bicycle industry (Fixson and Park, 2008).

Langlois, 2003), whereas others have pointed to persistent "integrality" of certain industries (Prencipe et al., 2003). By synthesizing and building on existing work in this area (Christensen et al,, 2003; Fine, 1998), our study attempts to provide a more contingent perspective to understand the degree to which industries modularize, focusing in particular on the actions firms might take to influence modularization at the industry level.

Understanding changes in industry modularity is a key topic for several reasons.

1) First, existing work has shown how changes in the degree of industry modularity can have important strategic implications, e.g. in terms of industry-wide value capture (Jacobides et al., 2006; Teece and Pisano, 2007; Brusoni et al., 2009). For instance, increases in industry modularity in computing had widespread ramifications for incumbent firms such as IBM, which have since exited the industry. By contrast, value and profit has, for long periods, been concentrated among developers of key components, in particular the operating system (Microsoft) and chipsets (Intel).[2] Industries might also become less modular over time, as shown in a study of the bicycle industry (Fixson and Park, 2008), with important implications in terms of profitability and survival.

2) Second, though the PC industry has frequently been taken as a template for understanding industry modularity (MacDuffie, 2013), we have increasing evidence that such a high degree of modularity may be the exception rather than the rule (Jacobides et al., 2012). Furthermore, current trends in computing show an intriguing trend away from industry modularity; instead, in segments related to personal computing (e.g. mobile telephony and tablet computing) we see increasing evidence of decreasing industry modularity. A better understanding of what drives changes in industry modularity may help us better explain such changes.

3) Third, industry modularity may also have important socio-economic implications. Phenomena such as offshoring and outsourcing depend on increasing industry modularity. Beyond labor market considerations, such practices also have long-term implications for regional competencies for innovation (Pisano and Shih, 2009). Furthermore, service-based industries might also become more

[2] Interestingly, among the systems integrator firms, the only device maker that has remained profitable is Apple, the most integrated firm among device makers.

modular, as shown in a study of mortgage banking (Jacobides, 2005) – the latter example also illustrates the potential vulnerabilities caused by such changes when regulatory oversight is lacking (Jacobides and Winter, 2010).

Drawing on the growing literature on modularity and architectural change, the key contributions of this paper are as follows. First, the study underlines the role of product and organizational architecture in driving changes in industry modularity. The conceptual framework we introduce draws on processes at the product and organizational architecture to explain differences in industry modularity. In particular, we highlight the role of dissemination of product interfaces and organizational practices as ways to increase modularity at the industry architecture level. As such, this paper builds on recent work that has examined modularity and architecture at different levels (e.g. Sako, 2003; Brusoni and Prencipe, 2006; Colfer and Baldwin, 2010) especially work that has focused on industry level changes (Langlois, 2002; Jacobides and Winter, 2005; Jacobides et al., 2006; Fixson and Park, 2008). Particularly, we extend existing research that has addressed industry level differences due to "technological" variations (e.g. Luo et al., 2012). We focus especially on the role firm actions play in relation to product and organizational level choices. As such, we pay attention to the influence firms might have in shaping the degree of industry modularity. Therefore this perspective ties in with recent work that has "endogenized" the structure of existing sectors in terms of their strategic implications, e.g. recent work on industry architecture (Jacobides et al., 2006) and business and innovation ecosystems (Adner and Kapoor 2010).

Second, the conceptual framework proposes several moderating factors (focusing on firm actions) that influence industry-wide diffusion. Regarding dissemination of product interfaces, these moderators are strategic factors related to standardization and capability trajectories. In relation to the dissemination of organizational practices, moderating factors constitute informational mechanisms and complexity surrounding technological breakthroughs. As such, the framework presents a contingent perspective to understand differences in industry modularity. This ties into recent work that has examined how architectures at different levels are related, most explicitly in research examining "the mirroring hypothesis" (Colfer and Baldwin, 2010), and related empirical work addressing modularity at different levels (Brusoni and Prencipe, 2006). It adds to recent studies in this area (MacCormack et al., 2008; Cabigiuso and Camuffo, 2012) by highlighting strategic contingencies that indicate how changes at the product and organizational architecture level relate to changes in industry architecture.

Third, the contingent nature of the conceptual framework sheds light on recent debate in relation to the "vanishing hand" hypothesis, emphasized in particular by Langlois (2003; see also Sturgeon, 2002). Work in this area has pointed to the increasing prevalence of coordination via modular interfaces, as opposed to coordination through large organizations.[3] The idea of the vanishing hand can be contrasted with other studies, in particular work on systems integration, which has suggested that these modular interfaces often pose an imperfect substitute for coordination. Therefore, firm coordination remains important, reflected in the role of systems integrators, whose primary purpose comprises the integration of different technological subsystems (Brusoni, Prencipe and Pavitt, 2001; Prencipe, Davies and Hobday, 2003; Hobday, Davies and Prencipe, 2005). The framework introduced in this paper suggests why these phenomena need not be contradictory. For example, differences in degrees of product interface codification, or their dissemination across firms may explain heterogeneity of industry modularity across sectors. Overall, our paper introduces a more contingent perspective to understand changes in industry modularity, focusing in particular on the role of strategic firm actions to influence the extent to which industries become more (or less) modular.

This paper is built up as follows. In the next section we examine background literature relating to the overall question of what drives changes in industry modularity, and the role of product and organizational architecture herein. We then move on to the conceptual framework, defining architecture and modularity generally, specifying how modularity might increase at different levels,

[3] The phrase "vanishing hand" responds to Chandler's (1977) work on the "visible hand" and the role of large corporations vis-à-vis market-based exchanges.

and the role of industry-wide diffusion. After this, several moderating factors are highlighted that influence the dissemination process, followed by concluding remarks.

BACKGROUND LITERATURE

Existing research on modularity and architectural change has often studied these concepts at multiple levels of analysis, examining e.g. the relation between products and organizations (Henderson and Clark, 1990; Sanchez and Mahoney, 1996) and how product and industry architecture interact (Baldwin and Clark, 2000; Sako, 2003; Fixson and Park, 2008). Building on emerging work that analyzes architectural change at different levels (Brusoni and Prencipe, 2006; Colfer and Baldwin, 2010), this paper attempts to understand what drives changes in industry modularity, drawing on strategic factors in relation to product and organzation architecture.

Simon's (1962) seminal work on complex systems underlines the prevalence of hierarchical organization and near decomposability in these architectures. In particular, he emphasizes that systems characterized by stronger interdependencies within (rather than across) subsystems appear to be more robust from an evolutionary perspective. Drawing on this, research on modularity has used a variety of typologies to highlight different facets of modular systems. For example, in their influential work on design evolution and industry change, Baldwin and Clark (2000: 78) distinguish between modularity-in-use, modularity-in-production, and modularity-in-design, focusing on the latter and its associated task structures. Modularity-in-production allows firms to divide production into process modules, which may induce outsourcing. Modularity-in-use lets users and manufacturers mix and match independent modules into an overall system. Similarly, Takeishi and Fujimoto (2003: 254) distinguish modularization in product architecture, -production, and -interfirm system. Based on this typology, they refer to modularity in the automobile industry as "closed modularization", which can be distinguished from "open modularity" observed in e.g. the personal computer industry. This distinction between open and closed organization is similar to work by Farrell, Hunter and Saloner (1998: 144) who use the terms components and systems organization.

Further conceptualizations of modularity include Langlois' (2002) study of a modularity-based theory of the firm. Contrasting market-based from firm-based organizations, here he provides an illustration of how in the 1970s and 1980s vertically integrated firms produced personal computers in a non-modular (or internally modular) fashion. This can be constrasted with the subsequent industry trajectory, characterized by external modularity. Similarly, Chesbrough (2003) distinguishes between internal modularity and market modularity. The former refers to modularity within the firm, whereas the latter refers to modularity at the industry level. He proposes that technological advance is marked by cycles of interdependence and modularity, which correspond with firm and market-based organizational form respectively.

Insert Table 2.1 about here

As illustrated in Table 2.1, current work shows how existing conceptualizations of modularity can be applied to different levels of analysis. Further, existing studies display overlaps in conceptualizing modularity, different terms notwithstanding. For example, Takeishi and Fujimoto's (2003) notion of closed and open modularity appears to be similar to what Langlois (2002) refers to as non-modular (or internallly modular) vs. externally modular, and what Chesbrough distinguishes as internal vs. market modularity. However, these studies generally do not address what drives changes within or across these dimensions. The conceptual framework developed in this paper distinguishes between architectural change at the product, organization, and industry level, which partially correspond to typologies introduced by Baldwin and Clark (2000) and Takeishi and Fujimoto (2003).[4] I expect that formulating a framework that more explicitly distinguishes between multiple levels can help better

[4] The point of specifying these particular levels is not that other levels of analysis (e.g. communities, institutions, geographic regions) are unimportant. For example, other researchers have specified modularity at a finer-grained level of analysis (e.g. modularity in intellectual property, cf. Henkel and Baldwin, 2009). Rather, I have chosen these particular levels as they appear most prevalent in current research.

understand the processes underlying architectural change. Most importantly, I use the framework to highlight the role of changes in product and organization architecture and moderating factors that drive differences in industry modularity.

The framework builds on several recent studies that has focused on architectural change at or across different levels of analysis. In particular, recent work on the notion of the "mirroring hypothesis" (Colfer and Baldwin, 2010) examines existing work to understand when product and organizational architecture mirror each other. Woodard and West (2009) provide a framework to understand dualities between components and interfaces in the product and organizational domains. Further, Padgett's (2001) notion of "cross-domain rewirings" provides another important conceptual precursor of how different levels might interact. His study on the transformation of banking in Renaissance Florence, as well as related work by Padgett and Powell (2003), highlights the role of various network ties (e.g. relational or transactional) and their role across different types of domains (economic, family or political) in changing regimes. Adopting the conceptual apparatus of Padgett and Powell (2003), a study by Brusoni and Prencipe (2006) analyzes how different domains affect each other, focusing on changes in design rules. Their study, based on an in-depth examination of a firm's tire design and manufacturing process, highlights the key role of knowledge, and how it mediates between the product-level (referred to as the technology domain) and the organizational level.

Finally, a number of studies have examined changes in industry modularity and their underlying drivers. Several authors have highlighted the interplay between transaction costs and capabilities as drivers of industry change (Jacobides and Winter, 2005; Langlois, 2006). Wolter and Veloso (2008) build on Henderson and Clark's (1990) innovation typology to understand changes in industry structure. Baldwin (2008) synthesizes the literature on transaction costs, knowledge-based theories of the firm and modularity to understand the location of transactions. The study suggests that transactions will occur in locations characterized by "thin crossing points" (i.e. where interdependencies between modules are low), emphasizing the role of knowledge, strategies and technology in driving the modularization process.

Overall, existing research on modularity and architectural change shows that these concepts can be, and have been, applied at different levels of analysis. Drawing on existing typologies of modularity, the product, organization, and industry levels appear to be most salient in existing work. However, few studies have addressed how changes across levels are related, in particular in relation to changes in industry modularity. It is important to distinguish a modular product architecture (e.g. mobile telephony, video gaming) from a modular industry architecture. Many complex, high-tech industries share some degree of modular product architectures. Yet, many do not have a modular industry architecture. Therefore, I first distinguish how modularity may operate in different domains (in particular products and organizations) and then move on to their relation to changes in industry modularity. Building on recent studies that have examined changes in industry modularity, I develop a conceptual framework that attempts to analyze what drives differences in industry modularity. To do so, I first describe processes underlying changes in modularity at the product and organizational level. Drawing on these processes, I then highlight several moderating factors that drive changes in industry modularity.

CONCEPTUAL FRAMEWORK

In this section I develop a conceptual framework to understand architectural change at different levels, in particular to understand differences in industry modularity. Due to variety in definitions of modularity and architecture, I will define relevant constructs upfront. First, architecture (or "systems architecture") here refers to "an abstract description of the entities of a system and the relationships between those entities" (Whitney et al., 2004). Second, modularity is defined as a design principle that advocates designing structures based on minimizing interdependence between subsystems and maximizing interdependence within subsystems (Ethiraj and Levinthal, 2004). Drawing on existing work, I suggest that, at each level, knowledge about interdependencies is crucial to increase modularity. For product architecture I adopt Ulrich's (1995) definition, i.e. "the scheme by which the function of a product is allocated to physical components". Modularity of product architectures can increase as knowledge about interdependencies between functions and components accumulates. Organizational architecture is defined as "the scheme by which tasks are allocated to organizational units (...)" (Sako 2003: 235). Organizational modularity can increase as knowledge about interdependencies between tasks and organizational units accumulates. Industry architecture has been defined as "templates that emerge in a sector and circumscribe the division of labor among a set of co-specialized firms" (Jacobides et al., 2006: 1201). This might be rephrased as "the scheme by which labor (i.e. bundles of tasks) is divided among industry participants (i.e. firms and other organizations)." Industry modularity can increase as knowledge about interdependencies between labor and industry participants accumulates. An overview of these concepts is given in Table 2.2.

Insert Table 2.2 about here

Product architecture: increasing modularity through interface codification

This section shows how modularity of product architectures increases as knowledge about interdependencies between functions and components accumulates. I suggest that, at this level, a key mechanism towards increasing modularity is codification. Here, codification refers to the degree to which knowledge about function-to-component interdependencies (hereafter shortened to "functional interdependencies") becomes stabilized in standardized interfaces. These interfaces can be defined when knowledge about relationships between functions and components increases. I distinguish three steps in this codification process: functional partitioning, articulation of functional interdependencies, and interface standardization. Figure 2.1 provides a visual illustration of this process.[5]

Insert Figure 2.1 about here

[5] In practice these stages will, of course, partly overlap. The feedback arrows in figures 2.1 and 2.2 highlight the iterative nature of this process.

Partitioning of functional interdependencies. The first step towards codifying functional interdependencies involves decomposition. Complex products are, by definition, characterized by various types of interdependencies (Thompson, 1967). One way to manage this complexity is decomposition (Simon, 1962), which involves specifying sub-functions, also referred to as task partitioning (Von Hippel, 1990). A key motivation in doing so is that partitioning can reduce the cognitive complexity associated with understanding the various functional interdependencies (Ulrich, 1995). Also, Simon (1962) has argued that systems, which are typically nearly-decomposable as opposed to fully decomposable, are more evolutionary robust when they are decomposed into subsystems.

Following the generic definition of modularity, the aim in this partitioning stage is to maximize functional interdependencies within subsystems, whilst minimizing interdependence between subsystems. Successful partitioning can usually be characterized as a trial-and-error process (Nonaka, 1994), as initial ideas about how functions and components interact might be partially or wholly inaccurate (Bucciarelli, 1994). However, over time, the team or individual will typically develop a greater understanding of an appropriate partitioning.[6] Also, due to heterogeneity in team size, competencies and so forth, functional partitioning may well vary depending on firm, even for the same product type. This will be reflected in differences in the way interdependencies between functions and components are specified, resulting in differences regarding performance, price and so forth.

[6] We cannot assume a priori that partitioning will take place in the form of a project. However, in many firms, and certainly in most technologically complex systems, projects are the main way in which work is organized. See Prencipe and Tell (2001) on knowledge replication in projects; for analysis on project-based organizations in the context of capital-intensive complex systems (see Davies, 1997; Hobday, 1998, 2000; Gann and Salter, 2000; Brady and Davies, 2004; Davies and Hobday, 2005; Davies, Gann and Douglas, 2009).

Articulation of functional interdependencies. The next phase constitutes knowledge articulation. Accumulating knowledge of the relevant functional interdependencies involves articulation, as previously argued in the context of organizational learning. It is important to explicitly distinguish articulation before codification, since the latter cannot occur without the former (Kogut and Zander, 1992; Nonaka, 1994; Zollo and Winter, 2002).

Articulation involves specifying more explicitly how functional interdependencies play out, as opposed to tacit beliefs internal to the individual (or even internal to an organization, in the case of organizational norms or values). It is therefore likely that feedback loops will occur between articulation and decomposition. As knowledge about the relevant functional interdependencies accumulates, partitioning will be adjusted accordingly, which in turn may further affect the stock of knowledge of functional interdependencies. In the context of modular systems development, Chuma (2006) has referred to this process of knowledge accumulation as “interim modularity”. Here it is suggested that, in the case of product innovations, knowledge about the relevant interdependencies can never be fully specified ex ante. Rather, they only become clear during the development of the innovation itself. Following existing work on the knowledge articulation process (Hakanson 2007), we can expect that the amount of knowledge about functional interdependencies an organization or individual possesses will be greater than the amount of knowledge that becomes codified. In other words, the tacit component surrounding certain functional interdependencies limit the degree to which these can be codified, elaborated on next.

Codification into standardized interfaces. The final step towards increasing product architecture modularity constitutes standardization. In this context standardization focuses on codifying knowledge about functional interdependencies in standardized interfaces. A wide range of studies have emphasized the importance of standardized interfaces in enhancing product modularity (e.g. Langlois and Robertson, 1992; Ulrich, 1995; Chesbrough and Kusunoki, 1999; Baldwin and Clark, 2000; Schilling, 2000; Sturgeon, 2002; Chesbrough, 2003; Chesbrough and Prencipe, 2008).

Generally, interfaces specify how subsystems "fit together, connect, and communicate" (Baldwin and Clark, 2000). In fact, it probably not much of an exaggeration to state that the importance of standardized interfaces provides one of the key axioms of the modularity literature. However, less emphasis has been given to the process of how these standardized interfaces might emerge. This framework suggests that codification plays a key role here.

In this context, codification involves the explication of knowledge about functional interdependencies that was previously tacit, i.e. embodied in the minds of the people involved in understanding the various interdependencies.[7] There are multiple ways in which knowledge can be codified. In the case of knowledge about functional interdependencies, it might take the form of e.g. manuals, databases, software, intellectual property (e.g. patents), knowledge management systems, and other repositories. Once knowledge about functional interdependencies has been codified, tools such as a Design Structure Matrix (DSM, see Eppinger, 1991; Baldwin and Clark, 2000; MacCormack, Rusnak and Baldwin, 2008) may be used to plot the various interdependencies.

Some authors have suggested that advances in information technology (IT) have eased the ability to codify knowledge (Arora and Gambardella, 1994) and may facilitate inter-firm exchanges (Chesbrough and Teece, 1996). At the same time, there may be 'natural' limits to the extent that relevant knowledge of interdependencies can be successfully codified. These might be related to the intrinsic nature of the system, such as the physical mechanics underlying the functional interdependencies, e.g. in the case of the automobile (Whitney, 1996; Sako, 2003; Gereffi, Humphrey and Sturgeon, 2005; MacDuffie, 2006; Luo, 2010). There might also be broader factors that limit codification. For example, in Dunbar, Garud and Kotha's (1995) study on Steinway pianos, customer expectations regarding product "performance" (e.g. warmth of the sound, physical touch of the keys)

[7] For a broader discussion on the distinction between tacit and explicit knowledge, see Polayni (1966) and Winter (1987); further analysis on knowledge codification can be found in Prencipe and Tell (2001) and Zollo and Winter (2002).

set limits on the extent to which relevant interdependencies can be fully codified. In this case, a more modular design could likely be created but would lead to unacceptable performance limitations.

Organizational architecture: increasing modularity through stabilization of organizational practices

This section discusses how organizational architectures become more modular. As specified earlier, modularity at this level focuses on knowledge of interdependencies between tasks and organizational units (i.e. task interdependencies). Here, this process consists of organizational partitioning (or divisionalization); build-up of systemic knowledge; and emergence of stabilized organizational practices. Overall, this process is referred to as "task stabilization", which I argue is a key mechanism in increasing modularity at the organizational level. This process is visually illustrated in figure 2.2.

Insert Figure 2.2 about here

Organizational partitioning (e.g. divisionalization). In this context, organizational subsystems refer to teams, departments and other organizational units (Sako 2003).[8] Here, the aim is to maximize task interdependencies within organizational units, and (where possible) minimize task interdependencies between units. The organization design literature has outlined various formal organizational structures to achieve this, including well known examples such as the multidivisional form (or M-form, cf. Chandler, 1962, 1977). Linking mechanisms include instruments such as matrix reporting and cross-unit liaisons (Nadler and Tushman, 1996).[9] In organizational theory, finding a balance between independence and interdependence has been discussed in terms of different degrees of "coupling"

[8] In the case of inter-firm organizations (such as an alliance or joint venture), the units can also refer to entire firms (Schilling and Steensma, 2001).
[9] At the product level I noted that even though most complex systems will be developed by teams, there are also instances where complex systems are developed by individuals. Organizational partitioning of course only makes sense when the organization outnumbers a single individual.

(Weick, 1976; Orton and Weick, 1990). One way organizations might achieve effective coupling is to group units based on functional similarity. However, despite these advances, how exactly to divisionalize remains a complex process, as emphasized by e.g. Ethiraj and Levinthal (2004) and Jacobides (2006, 2007).[10] Furthermore, similar to the product architecture level, there is no reason to expect equifinality in terms of decomposition. In fact, while technological and scientific boundaries enforce a degree of homogeneity at the product level, at the organizational level these 'natural' limitations do not apply. Though institutional isomorphism (DiMaggio and Powell, 1983) might impose some limitations on decompositional variety, organization design is a design problem exactly because organizations have many degrees of freedom in setting up different organizational structures. Recent work on "landscape design" (Levinthal and Warglien, 1999) underpins this view, suggesting that task interdependencies are not just "discovered", but that organizations can actively manipulate them.

Accumulation of systemic knowledge. As organizations gain experience in decomposition, they build their stock of systemic knowledge i.e. "the underlying patterns of interdependence between tasks" (Puranam and Jacobides, 2006; see also Sako, 2003; Brusoni and Prencipe, 2001, 2006). Systemic knowledge allows the organization to divide tasks based on standardized procedures, as opposed to having to rely on rich, ongoing coordination, e.g. via continuous communication. Creating systemic knowledge may require an initial stage of rich communication (Puranam and Jacobides, 2006), also referred to as integrated problem solving (Von Hippel, 1998) or technical dialog (Monteverde, 1995).

Related to the notion of systemic knowledge is the concept of common ground, defined as "the sum of their mutual, common or joint knowledge, beliefs and suppositions" (Clark, 1996). Common ground can be regarded as both a by-product of accumulating systemic knowledge and a pre-requisite for coordination. In particular, several studies by Srikanth and Puranam (2008a, 2008b, 2010) have

[10] Witness e.g. Jacobides' (2007) intriguing study of the damaging consequences of how excessive divisionalization might drive behaviour that is understandable at the unit level, but highly undesirable at the aggregate level. See Knudsen and Levinthal (2007) for a discussion on the broader challenges of evaluating organizational alternatives.

shown the importance of establishing and maintaining common ground when organizational units rely on standardized practices. In their work on software services offshoring, they demonstrate that various ICT based tools can help to establish and maintain such common ground. Based on an insightful literature review, Colfer and Baldwin's (2010) notion of "actionable transparency" also emphasizes the importance of such tools to facilitate coordination across organizational boundaries.

It is likely that there will be feedback loops between the organizational partitioning stage and build-up of systemic knowledge. As organizations learn, through trial and error, about which divisionalization works best (Ethiraj and Levinthal, 2004), their stock of systemic knowledge accumulates and certain practices stabilize (Fujimoto, 2007). This in turn will affect organizational divisionalization, which influences accumulation of systemic knowledge.

Emergence of stabilized organizational practices. The final step towards increasing organizational modularity involves standardization. In this context standardization refers to the establishment of stabilized operating procedures (March and Simon, 1958; Cyert and March 1963), or standardized practices. In this context, these practices can be regarded as codified procedural knowledge (Argyris 1991).[11] Various studies have argued that organizations become more modular when they interact based on simple, standardized exchanges (Schilling and Steensma, 2001; Galunic and Eisenhardt, 2001). In these situations, organizational units are specialized and operate with a narrow focus (Ulrich 1995). To achieve this, organizations need to formulate standard operating procedures, which might be articulated in design rules, plans or schedules which specify what each unit has to do to achieve coordination, as argued in the classic organization design literature (Tushman and Nadler, 1978; Galbraith, 1977). These standardized practices act as the organizational equivalent of interfaces (Woodard and West, 2009). Importantly, once these are formulated, they minimize the need for ongoing communication, as well as the amount of knowledge that needs to be shared among organizational units. However, organizations need not only select a particular operating procedure,

[11] Therefore, in this paper, these practices refers to a specific subset of organizational routines, as coined by Nelson and Winter (1982); for a review on organizational routines in the general sense, see Becker (2004).

they also need to maintain and enforce them, as otherwise the interface might be compromised (Srikanth and Puranam, 2010).

An important consequence of this non-technical standardization[12] is that it regularizes expectations among organizational actors (Langlois and Savage 2000). This notion of task stabilization is similar to the analysis of Padgett and Powell (2003), in their study of Renaissance Florence, of how socially standardized models or protocols induce reproduction across levels. A further effect is that it allows a coherent division of labor to be established (Narduzzo, Rocco and Warglien, 2000). It is likely that only a subset of knowledge on task interdependencies becomes standardized, given e.g. complexity or degree of unpredictability of tasks, or the costs associated with effective standardization (Hakanson, 2007).

Industry architecture: increasing modularity via dissemination

The previous section discussed how product and organizational architecture increase in modularity, focusing respectively on codification of product interfaces, and stabilization of organizational practices. However, while these processes are necessary for increasing modularity at the industry level, they are not sufficient. The final level I distinguish is the industry architecture (see Jacobides et al., 2006; Pisano and Teece, 2007; Dietl et al., 2009; Brusoni, Jacobides and Prencipe, 2009). At this level, modularity increases when knowledge about interdependencies between labor (i.e. bundles of tasks) and industry participants (i.e. firms and other organizations) accumulates. I suggest a key mechanism for increasing industry modularity is dissemination of intra-firm product interfaces and organizational practices. An important question then, is which factors influence this dissemination process?

Drawing on existing work, I highlight the following moderating factors: 1) strategic considerations related to standardization; 2) capability trajectories and firm specialization; 3) informational

[12] As opposed to technical interface standards (David, 1987; Shapiro and Varian, 1998), further discussed below.

mechanisms and convergence of cognitive frames; and 4) technological breakthroughs, complexity and interaction of organizational practices. Below I discuss these moderating factors in more detail; table 2.3 summarizes the moderating factors and their effect on industry modularity.

Insert Table 2.3 about here

Increasing industry modularity via dissemination of product interfaces

Moderator 1: Strategic elements of standardization. The first moderating factor constitutes strategic aspects of standardization, in particular the trade-off between value capture and control. As highlighted by e.g. Langlois and Robertson (1992), Macher and Mowery (2004) and Jacobides et al. (2006), standards can have important implications for the way industry-wide value is appropriated among individual firms. Also, Schilling and Steensma's (2001) analysis suggests that when industry standards are present (combined with high heterogeneity of inputs and demands) industry modularity increases. An important question therefore is what drives the dissemination of these standards. A variety of literatures has looked at the process of standards establishment and dissemination (e.g. David, 1987; Shapiro and Varian, 1998). The type of standard most relevant here are "technical interface standards", i.e. the collection of explicit rules that permit components and subsystems to be assembled in larger systems (Greenstein and David 1990).[13] Furthermore, there are a number of varieties of interface standard setting. A key distinction involves standards created by publicly controlled standards organizations (de jure standards) or market based standards (de facto standards) (Funk and Methe, 2001; Steinmueller, 2003).[14]

[13] Other types of standards, as noted by Steinmueller (2003: 134) include reference standards (e.g. the definition of a unit of electrical resistance) and quality standards (related to e.g. health or safety).

[14] This chapter focuses on de facto standards, since "diffusion" beyond the focal organization of de jure standards does not apply in this context. De facto standards may emerge through processes of market leadership,

While in some contexts the extra-organizational standardization of product interfaces is relatively straightforward (as in Argyres' (1999) study of standardizing interfaces in a public defence sector project), more frequently this process can be highly strategic, as shown in several in-depth studies (Gawer and Cusumano, 2002; Gawer and Henderson, 2007; Ballon, 2009). Generally, firms resist adoption of industry wide standards to maintain control over their current suppliers. For example, in the automobile industry, interface standards for electronic data interchange have purposefully been made specific to assemblers, so that firms retain control over this process (Markus et al., 2006). Likewise Sako's (2003) analysis of the automobile industry highlights how, for strategic reasons (e.g. when the subsystem is considered to be differentiating, and therefore of high value to the firm) interfaces remain proprietary to the manufacturer. Further, interface standards might also be kept proprietary, or remain less codified to prevent imitation (Langlois, 2002). On the other hand, standards may be used by firms to shape the industry architecture to their advantage. In particular, firms may attempt to control key parts of the value chain (i.e. a "bottleneck"), to enhance value appropriation (Jacobides et al., 2006; Baldwin, 2010). Similarly, Gawer and Cusumano (2002, 2008) have observed this dynamic in the behavior of platform leaders, i.e. firms that successfully control industry platforms. These firms benefit from inducing competition in complementor markets. However, dissemination of interface standards may also be involuntary, exemplified in IBM's development of the personal computer.[15]

In sum, when deciding whether to disseminate interface standards beyond the focal organization, firms generally trade-off their ability to capture value with control considerations. This trade-off (which, as the IBM case illustrates, may be based on incomplete or inaccurate perceptions) leads to increases in dissemination of interface standards when the benefits of dissemination are higher than

design and problem solving within organizations, or between organizations that lead to 'privately held' technical compatibility standards (Steinmueller, 2003).

[15] IBM's decision to use standards from external suppliers for several key subsystems (particularly the operating system and microprocessor, sourced from Microsoft and Intel respectively), had long term implications on the subsequent trajectory of the PC industry. Whilst IBM thought it was able to maintain control over these subsystems via its proprietary BIOS, reverse engineering of this technology by new entrants, loosened IBM's control of the technology and diminished its ability to capture value (Baldwin and Woodard 2009).

the benefits of maintaining proprietary control. Further, systems might also revert back to private (i.e. proprietary) interfaces, as a result of performance considerations or strategic factors (Fixson and Park, 2008). More generally, strategic considerations may influence whether or not interfaces will be shared with other firms, or where exactly these boundaries will be set (Sako, 2003; Zirpoli and Camuffo, 2009).

Proposition 1: industry modularity increases when value capture considerations promote diffusion of standardized interfaces

Moderator 2: Capability trajectories and degree of specialization. The modularity literature has used various ways to conceptualize the distinction between intra and inter-firm product interfaces; they include internal as opposed to external standardization (Ulrich, 1995), internal vs. external modularity (Langlois, 2002), and open vs. closed architecture (Fujimoto, 2007). However, as mentioned earlier, existing conceptual studies have generally paid little attention to the mechanisms by which firm-specific interfaces exceed the firm boundary. By contrast, several empirical studies have focused on the mechanisms that influence the transition from intra- to inter-firm product interfaces.

In particular, Jacobides (2005) argues that motivating factors to standardize information across firm boundaries include gains from trade, based on an in-depth study on changes in mortgage banking**.** A result of this standardization is that the transactions become "simple, transmissible, universally understood", allowing transactions with other firms (Jacobides, 2005; see also Baldwin 2008). Other studies have looked at a variety of domains (e.g. the bicycle and electronics industries) and argue that gains from specialization, in particular to enhance capability development, constitute an important factor (Sturgeon, 2002; Gereffi et al., 2005; Jacobides and Winter, 2005). Langlois and Robertson (1992) further highlight supply and demand-side benefits of a modular production system. Focusing on the stereo systems and micro computer industries, they identify dissimilarity in firm capabilities along stages of production as a driver towards more modular industry architectures. Finally, Sako

(2003) also emphasizes how an industry's existing distribution of capabilities affects if and how product interfaces cross firm boundaries.

Proposition 2: industry modularity increases when capability trajectories and firm specialization promote diffusion of standardized interfaces

Increasing industry modularity via dissemination of organizational practices

This section focuses on how organizational practices might disseminate beyond the focal firm, thereby increasing modularity at the industry level. Standardized product interfaces are of limited use when organizations do not have suitable partners to transact with. For example, Chesbrough (2003) has emphasized the importance of being able to rely on a credible supplier base. This is further emphasized in a study by Jacobides (2008), who highlights the importance of "institutional modularity". His study demonstrates the importance of differences or similarities in the way activities are partitioned along the value chain. Differences between countries are particularly relevant for firms embarking on international expansion. Below I highlight moderating factors that influence the dissemination process from intra-firm to inter-firm practices. Here I will focus on informational mechanisms and convergence of cognitive frames, and complexity surrounding technological breakthroughs.

Moderator 3: Informational mechanisms and cognitive frames. The third moderating factor concerns informational mechanisms that spread organizational practices, which may be reinforced by convergence of cognitive frames. The notion of common ground discussed earlier plays an important role here too. Several studies have underlined the importance of repeated interactions to develop common ground, which might subsequently be codified in organizational systems based on a shared 'grammar' (Argyres, 1999) or contracts (Mayer and Argyres, 2004). This accumulated knowledge allows organizations to codify roles and responsibilities in more detail (Argyres, Bercovitz and Mayer, 2007). More generally, stabilized practices can be considered as a kind of "public routine", which helps organizations coordinate among what previously constituted "private" practices, as Langlois and Savage (2000) demonstrate in an in-depth study of standardization in the field of medical practice. Dissemination of practices may also be promoted by industry associations and other inter-firm consortia (Zenger and Hesterly, 1997). Information about successful practices may also spread through consulting firms, industry associations, and other informational mechanisms, such as employee mobility and shared board memberships (Shanley and Peteraf, 2004). Institutional isomorphism, the pressure for organizations facing similar environments to adopt similar practices (DiMaggio and Powell, 1983), may also promote dissemination of organizational practices.

Relatedly, work on organizational learning has highlighted how cognitive frames shape organizational practices (Gavetti and Tripsas, 2000; Benner and Tripsas, 2011). Actors, both individually and collectively, are assumed to be boundedly rational (Simon, 1991); through trial and error, knowledge of appropriate practices increases, and over time cognitive frames stabilize, leading to convergence in terms of organizational practices. Problem solving can be conceptualized as a search for (near) optimal solutions (Levinthal, 1997). This search process often involves cognitive reframing, in order to arrive at more powerful representations of both the problem and associated solution (Dosi, Hobday and Marengo, 2003; Gavetti and Levinthal, 2000). A key role of management is to articulate and promote these cognitive frames across the organization (Marengo, 1996; Dosi et al., 2003). Further, conceptual work on technological change proposes that cognitive frames tend to converge over time, thereby disseminating across different organizations (Kaplan and Tripsas, 2008).

Proposition 3: industry modularity increases when informational mechanisms and industry-wide convergence of cognitive frames disseminate standardized organizational practices

Moderator 4: Degree of complexity of organizational practices. The fourth moderating factor that influences industry-wide dissemination of stabilized practices relate to technological breakthroughs, and its effect on the complexity and interaction of practices. In line with the literature on organizational routines (Simon and March, 1958; Cyert and March, 1963; Nelson and Winter 1982; Dosi et al., 2003) firms and other organizations can be conceptualized as a collection, or bundle, of practices. Building on this stream of work, the literature on dynamic capabilities (Teece et al. 1997; Eisenhardt and Martin, 2000; Helfat and Peteraf, 2003) suggests that a firm's competitive advantage may partly be driven by its ability to change its capabilities in turbulent environments.

Technological breakthroughs in particular, driven by new combinations of knowledge, create highly turbulent environments (Galunic and Rodan, 1998). In these settings, organizational practices will initially be limited and idiosyncratic to individual firms. However, once the technology life cycle (Anderson and Tushman, 1990) reaches a more stable phase, knowledge of organizational practices may spread to other firms. If gains from trade are present, the value of specialization increases, promoting dissemination of modular practices (Christensen et al., 2002; Chesbrough, 2003; Jacobides, 2005). However, successful execution of practices may depend on a high degree tacit knowledge, which by definition does not disseminate easily. Further, certain practices may only work in combination (Murmann et al., 2003; Marengo and Dosi, 2005). As such, the complexity of a combination of practices (or specific interactions between them) may hamper successful dissemination (Rivkin, 2000).

Finally, gains from transacting with extra-organizational divisions constitute another factor prompting dissemination of practices outside of firm boundaries. Jacobides (2005), in his study of mortgage banking, illustrates how practices that organizational units initially applied to other divisions subsequently were used to deal with organizations outside the firm boundary. Likewise, MacDuffie (2006) has highlighted the difficulty to contain transactions within a single organization once the practices have become more modular inside an organization.

Proposition 4: industry modularity increases when low complexity promotes dissemination of standardized organizational practices

CONCLUDING REMARKS

This paper has developed a conceptual framework to understand architectural change at different levels, focusing in particular on moderating factors driving changes in industry modularity. To do so, I first outlined how modularity increases at the product and organizational level, focusing on codification of standardized interfaces and stabilization of organizational practices. I then argued that industry modularity increases when product interfaces and organizational practices disseminate beyond the focal organization. Next, I highlighted several moderating factors that influence this dissemination process. At the product level I focused, first, on strategic considerations regarding standardization, and second on capability trajectories and firm specialization. At the organizational level I highlighted informational mechanisms and convergence of cognitive frames, and the role of technological breakthroughs and its influence on the complexity and interaction of organizational practices. The overall framework is visualized in Figure 2.3.

Insert Figure 2.3 about here

Overall, the key contributions of this paper can be summarized as follows. First, the framework highlights processes at the product and organizational architecture level, which serve as building blocks to understand changes in industry architecture. Second, the conceptual framework suggests how industry architectures become more modular through dissemination of interfaces and practices, and proposes several moderating factors that influence this diffusion process. Third, the contingent perspective developed in the framework may reconcile diverging perspectives on the role of modularity and inter-firm coordination. As such, the paper complements recent work that has examined changes in industry modularity, focusing on e.g. the interplay between firm capabilities and transaction costs (Jacobides and Winter, 2005; Langlois, 2006) and the role of technological innovations (Wolter and Veloso, 2008). Further, the framework builds on existing work that has analyzed how modularity at different levels is related. For example, research on the "mirroring hypothesis" (Colfer and Baldwin, 2010; Cabigiosu and Camuffo, forthcoming) has investigated how architecture at the product and organizational level relate. Work by Brusoni and Prencipe (2006), drawing on Padgett (2001) and Padgett and Powell (2003), investigate different domains (knowledge, technology and organization), emphasizing the role of changing knowledge bases in affecting how organizations change over time. Drawing on these studies, this paper emphasizes architectural change at different levels (i.e. product and organization), and their relation to changes in industry modularity.

Several implications can be derived from the framework. At the product level, characteristics of the artefact, as well as broader factors (e.g. usage patterns) affect the extent to which the product can be modularized (i.e. the extent to which knowledge of functional interdependencies can be codified).[16] Likewise, at the organizational level, the extent to which practices can be standardized will differ depending on the system in question. Given heterogeneity in size, resources etc., different firms might choose alternative organizational partitions. Further, the paper has highlighted several moderating factors that influence the extent to which industries become more or less modular. As such, the framework may also shed light on the debate on the impact of modularity in relation inter-firm coordination. Here, several authors have stressed how modular interfaces may substitute for organizational coordination (Sanchez and Mahoney, 1996; Sturgeon, 2002), further exemplified in the "vanishing hand" hypothesis forwarded by Langlois (2003). This can be contrasted with other studies that have emphasized the ongoing importance of firms that need to coordinate disparate knowledge bases and technological subsystems (Pavitt, 2003), in particular in research on the role of systems integrators (Brusoni et al., 2001; Hobday et al., 2005). The framework developed in this paper instead proposes a contingent perspective: both perspectives can be true, but may depend on product or

[16] Notwithstanding the overall costs of codification (Hakanson, 2007), increasing pervasiveness of ICT's may lower these costs, though its effects across sectors is mixed (Steinmueller, 2000; Brusoni, Marsili and Salter, 2005). At the same time, recent advances in visualization and simulation impact on the way firms innovate, and may enhance the degree to which knowledge can be codified (Dodgson, Gann and Salter, 2005, 2007). However, the extent to which this will impact on product modularity needs to be further explored.

industry related characteristics. For example, industries marked by higher degree of interface codification (e.g. information-based industries and electronics-based products such as stereo components) have often been the focus of research underlining increases in modularity (e.g. Langlois and Robertson, 1992; Sturgeon, 2002). This contrasts sharply with settings characterized by lower degrees of both interface codification and stabilized practices, such as the aerospace and automotive sectors, settings investigated in research on systems integration (Prencipe et al., 2003). In these latter cases, mechanical interdependencies - as opposed to informational - also play a key role (see also Luo, 2010).

This paper has several implications for practitioners. While many practitioners may intuitively grasp that there are important sectoral differences in modularity, the framework might give theoretical grounding to understand these industry differences, and predict when (and when not!) these might change. The misapplication of the modularity metaphor in the automobile industry (see MacDuffie, 2006 for an insightful account) might serve as a reminder of misappropriation of theoretical concepts across sectoral boundaries. Likewise, policy makers may also take into consideration that modular changes might differ per industry.

As always, there are limitations to this study, and similar boundary conditions apply to the framework introduced in this paper. First, though we know some of the firm-specific benefits associated with modularity, existing work has also highlighted the costs firms face in achieving modularity, in particular in relation to the product and organizational level (e.g. Brusoni, Marengo, Prencipe and Valente, 2007; Srikanth and Puranam, 2008b). Future work might further expand on these issues, for example to understand the extent to which increasing product and organizational modularity is beneficial in changing environments. Second, the framework has largely ignored public policy and socio-economic implications of modularization. For example, an underlying motivation for increasing modularity at the product or organizational level might be to facilitate outsourcing or offshoring to lower wage countries, which may lead to employee resistance.[17] For example, as noted by Sako (2003), the term modularity was met with great resistance in the automotive industry, since it was perceived by labor unions as a euphemism for offshoring. Further, Pisano and Shih (2009) observed that offshoring may have longer-term implications for the innovative potential of regional clusters, further highlighting potential macro-level policy questions.

[17] However, firms might also modularize organizational processes without relying on external suppliers (Hoetker, 2006).

TABLES AND FIGURES

Table 2.1: Existing research: conceptualizing modularity at different levels of analysis

Concept	Description	Applicable level(s) of analysis		
		Product	Organization	Industry
Modularity in design (Baldwin & Clark, 2000)	Partitioning product design into visible and hidden information, and establishing design rules that determine how different modules work together	X		
Modularization in product (Takeishi & Fujimoto, 2003)	Decreasing interdependence between product-function hierarchy and product-structure hierarchy	X		
Internal modularity (Langlois, 2002; Chesbrough, 2003)	Specification of interfaces that are limited to the organization, precluding supply via market transactions	X	X	
Modularity in production (Baldwin & Clark, 2000)	Simplifying production process by distinguishing organizational process modules and specifying their design ahead of production	X	X	
Modularization of production (Takeishi & Fujimoto, 2003)	Decreasing interdependence between product-structure hierarchy and product-process hierarchy	X	X	
Modularization of inter-firm systems (Takeishi & Fujimoto, 2003)	Inter-firm division of labor in development and production, and degree to which outside suppliers conduct and deliver subassemblies		X	X
Modularity in use (Baldwin & Clark, 2000)	Allows users to mix and match modules from different firms, spurring innovation among firms who focus on specific modules	X		X
External modularity (Langlois, 2002); Market modularity (Chesbrough, 2003)	Publicly disclosed product interfaces, allowing industry-wide supplier interaction via market transactions	X		X

Table 2.2: Existing research: key concepts and definitions

Concept	Description	Key references
Architecture	"An abstract description of the entities of a system and the relationships between those entities"	Simon, 1962; Whitney et al., 2004
Modularity	"A design principle that advocates designing structures based on minimizing interdependence between subsystems and maximizing interdependence within subsystems"	Baldwin & Clark, 2000; Ethiraj & Levinthal, 2004
Product architecture	"The scheme by which the function of a product is allocated to physical components"	Ulrich, 1995
Organization architecture	"The scheme by which tasks are allocated to organizational units"	Sako, 2003
Industry architecture	"The scheme by which labor (i.e. bundles of tasks) is divided among industry participants (firms and other organizations)"	Jacobides et al., 2006

Table 2.3: Conceptual framework: moderating variables and effect on industry modularity

Moderating factor	Underlying process	Effect on industry modularity
Dissemination of product interfaces		
1: Strategic elements of standardization	Strategic factors (in particular value and control of subsystems) moderate standardization of product interfaces, either promoting or inhibiting dissemination across firms	Product interfaces may or may not disseminate, either increasing or decreasing industry modularity (net effect unclear)
2: Capability development and	If capability trajectories induce firm specialization, demand for standardized product	Product interfaces disseminate beyond focal organization,

degree of specialization	interfaces across firms increases	increasing industry modularity
Dissemination of organizational practices		
3: Informational mechanisms and cognitive frames	Informational mechanisms (e.g. shared board memberships, industry consortiums) and convergence of cognitive frames promote dissemination of standardized organizational practices across firms	Organizational practices disseminate across firms, increasing industry modularity
4: Complexity of organizational practices	Technological breakthroughs, and complexity and interaction among procedures, inhibit diffusion of organizational practices across firms	Dissemination of organizational practices to other firms is limited, inhibiting industry modularity

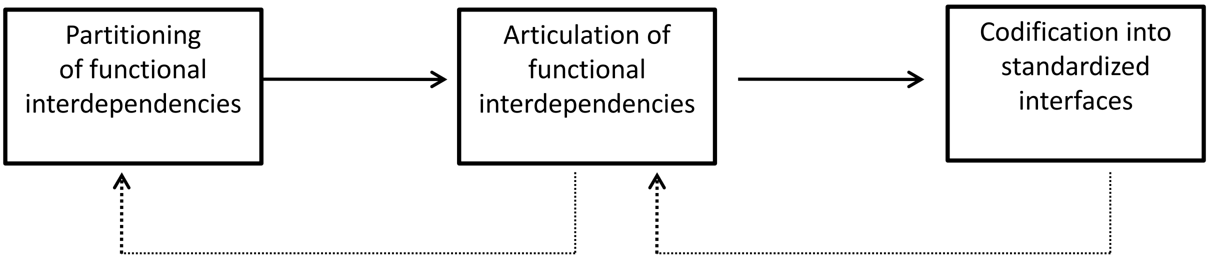

Figure 2.1: product modularity increases through interface stabilization

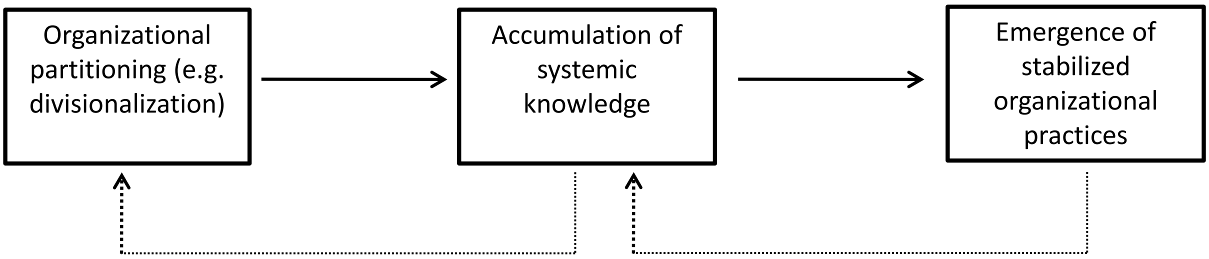

Figure 2.2: organizational modularity increases through task stabilization

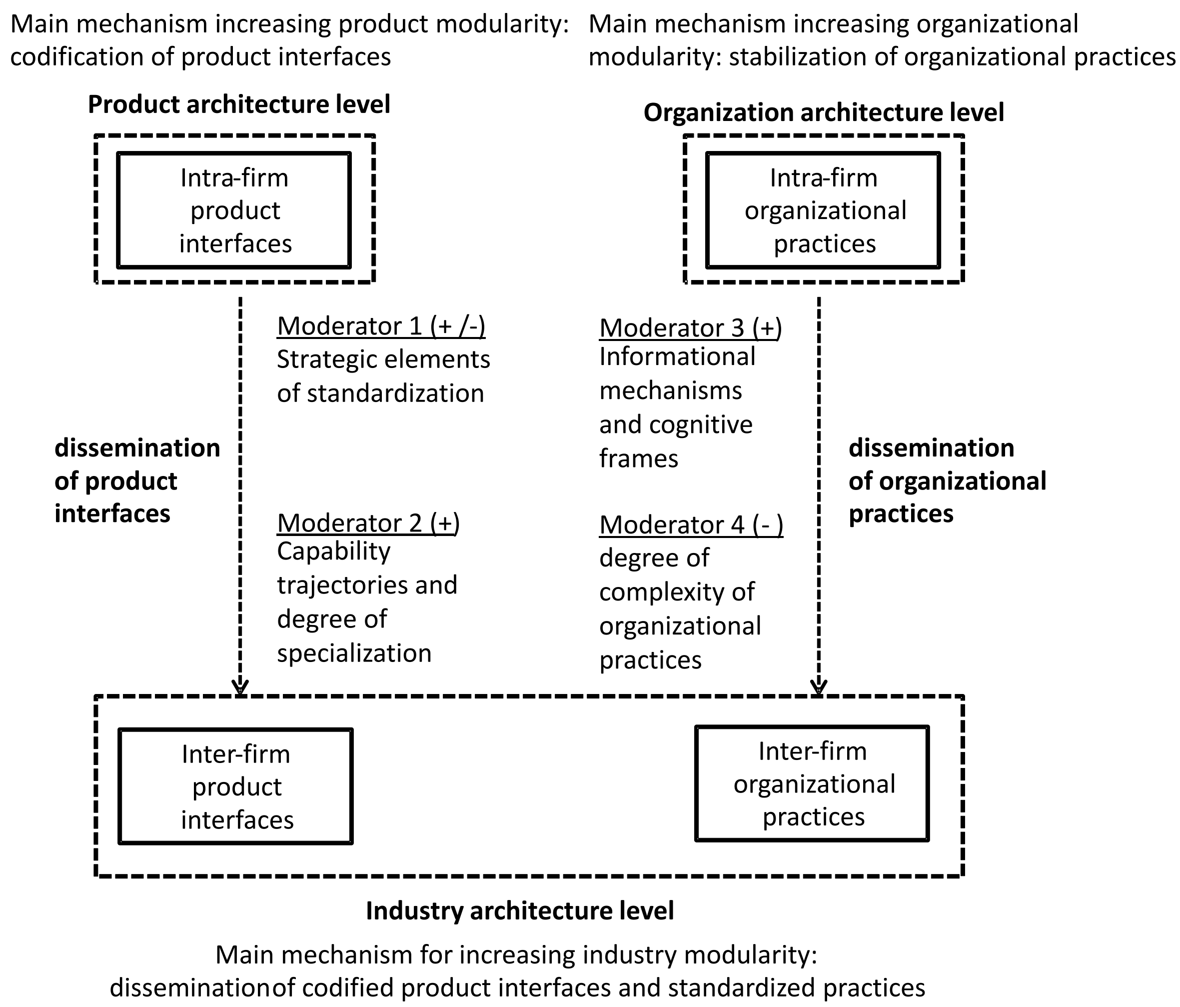

Figure 2.3: Overall conceptual framework

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