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Systems Architectures and Innovation: the Modularity-Integrality Framework

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The architectural investigation of systems generally encountered in management studies – products, processes, organizations – has traditionally focused on the tradeoff between modularity and integrality as alternative, mono-dimensional properties: the first being associated with flexibility and adaptability, the latter with efficiency and control. However, empirical evidence has showed that adopting the modularity-integrality tradeoff can be misleading. In this paper, we reconceptualize modularity and integrality as coexisting and concurring properties of systems, and argue that their interplay along multiple dimensions shapes specific types of system architectures. We then discuss the implications of such reconceptualization for the study and design of systems.

The concepts developed in the paper may provide partners with new principles for product design and engineering, and indications for developing more accurate measures of two fundamental characteristics of technological products: modularity and integrality. In particular, the proposed framework may help IT architects design software and hardware platforms that can be more easily and effectively altered, reconfigured, and upgraded to meet ever changing market and customer needs.

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Systems Architectures and Innovation: the Modularity-Integrality Framework

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The architectural properties of systems of a different nature – physical, biological, social – have been extensively investigated in order to identify and understand the constitutional elements of the world's complexity. In biology, for example, root system architectures are studied in relation to the role they play in plants' nutrition and life (Fitter, Nichols, & Harvey, 1988). In medicine, the architectural characteristics of synthetic implants have been found to heavily influence tissue regeneration (Hollister, 2005). In computer science, appropriate software architectures are critical to system-level evolvability, reliability, and performance (Bass, Clements, & Kazman, 2012). Using a similar approach, a number of management scholars have investigated systems such as products, processes, organizations, markets, and industries in order to understand the relationship between architectural form and system performance, and the possible matching and interplay among system architectures at multiple levels (Chesbrough, 2003; Fixson & Park, 2008; Garud, Kumaraswamy, & Langlois, 2009; Jacobides, Knudsen, & Augier, 2006; Schilling & Steensma, 2001). Such studies have been echoed by practitioner-oriented management literature, which has fruitfully applied architectural thinking to product design and organizational strategies (Morris & Ferguson, 1993; Sauer & Willcocks, 2002).

In this domain, the notion of architecture refers to the overall design of a system, and describes the general form of, and the particular interrelationships between, the whole and its parts – a product and its components, a process and its phases, an organization and its units, and so forth. Since artificial systems behave according to design choices, the architect's first problem is to render a given architecture capable of supporting the intended dynamics and performance. This leads to the notion of *architectural innovation,* defined as a change in the way system components are linked to one another (Henderson & Clark, 1990). As soon as the architecture is formalized, the architect's next goal, in fact, is to experiment with new configurations, in order to understand whether architectural innovations affect the way the system performs, and/or impact the behavior of other, interdependent systems. The characteristics and dynamics of system architectures are interesting to study at multiple levels of analysis. For example, Galunic and Eisenhardt (2001) underline the importance of architectural innovation at organizational level when they talk of "leaders as architects". They explain that in their case study firm "corporate executives played roles that went beyond the traditional ones of managing corporate boundaries and overseeing performance. Perhaps their most important role […] lay in the process of architectural innovation" (p. 1246). Similarly, the study of the effects of changes in the architecture of products, processes, organizations and industries is attracting increasing attention from scholars and practitioners alike (Baldwin & Clark, 2000; Brusoni & Prencipe, 2001; Galunic & Eisenhardt, 2001; Hoetker, 2006; Pil & Cohen, 2006; Schilling, 2000; Schilling & Steensma, 2001).

Central to the cross-disciplinary discussion on architectural innovation and the reconfiguration of products, organizations and industries are the concepts of modularity and integrality (or integration). Both the product design literature and an increasingly coherent body of management studies have been using the *modularity–integrality trade-off* to underpin a conceptual view of architectural problems whose two main cornerstones can be articulated as follows:

1. The architectural evolution of systems involves a bidirectional shift from integrality to modularity (Baldwin & Clark, 2000; MacCormack, Rusnak, & Baldwin, 2006; Schilling, 2000; Shibata, Yano, & Kodama, 2005), and vice versa (Christensen, Verlinden, & Westerman, 2002;

Fine, 2010; Fixson & Park, 2008), which produces performance variations. For example, when the system architecture becomes more modular, it acquires higher flexibility and adaptability. If it becomes more integrated, efficiency and/or effectiveness will be enhanced. Modularity and integrality are conceived, then, as either dichotomous or extremes of a continuum along which system architectures may alternatively evolve by means of *cross-type architectural innovations*. For example, Ulrich (1995) introduces a typology of product architectures based on the distinction between modular and integral. Similarly, in an attempt to lay down the foundations of a general modular systems theory, Schilling (2000) talks of a "bidirectional trajectory" along which systems shift when subject to forces that push for either greater modularity or greater integration. According to this view, modularity is the result of a process of disaggregation of originally integral (or integrated) architectures into non-integral ones. Following the same approach, Schilling and Steensma (2001) carry out an industry-level analysis of organizational forms and oppose modular systems to "integrated, hierarchical structures"; and Ethiraj and Levinthal (2004) tackle the problem of designing and managing complex systems by modeling and simulating the performance of system architectures that range from fully integrated to highly modular.

2. Systems can also evolve independently of migrations toward higher integrality or higher modularity, by means of *within-type architectural innovations*. For example, a system's components can be "mixed and matched" without altering the overall degree of modularity or integrality of the system. In this respect, however, extant literature posits a primacy of modularity over integrality, because it is the modular nature of the system that allows for interchangeability among components, so that new system configurations can be explored. In this view modularity is paired with versatility, flexibility and evolvability, and appears per se sufficient to enhance recombinant innovation (Foray & Freeman, 1993). On the contrary, integrality is paired with efficiency, hierarchy, and control – all features that would hinder architectural recombination and innovation.

Summarizing, a process of modularization entails loss of integrality, while increasing integration means decreasing modularity. Moreover, architectural innovation and system recombination are enhanced by high levels of modularity and correspondingly low levels of integrality.

This interpretation of the structural characteristics and dynamics of systems is so central to the discussion on architectural innovation in management that the vast majority of studies of form, structure, and design of products, organizations, and industries adopt it more or less explicitly. Indeed, the modularity–integrality trade-off has represented a useful conceptual and analytical tool for students of architectural problems within and across systems. However, growing evidence shows that treating modularity and integrality as mutually exclusive properties, and in particular emphasizing modularity as the only precondition for easier and more effective system recombination, is fundamentally wrong. System architectures at all levels show a higher degree of complexity than a linear relationship between modularity and integrality can capture and explain (Brusoni & Prencipe, 2001; Galunic & Eisenhardt, 2001; Hoetker, 2006; Tiwana, 2008). In this paper we tackle the problems associated with the modularity–integrality trade-off, and introduce a new framework, which attempts to overcome such problems.

Problems with the Modularity–Integrality Trade-off

Our study focused on issues arising from the use of the modular–integral trade-off in the product design, engineering, and management literature. In particular, we have reviewed studies of architectural innovation in products and organizations whose analytical and interpretive standpoint hinged on such a trade-off. The scrutiny of contradictory findings provided hints of theoretical inconsistencies affecting the use of both concepts in the management literature, allowing us to locate conceptual sources of misalignment between theory and empirical evidence. Rather than providing a comprehensive review of the relevant literature (an extensive, cross-field review can be drawn from: Campagnolo & Camuffo, 2010; Fixson, 2001; Jose & Tollenaere, 2005; Reijers & Mendling, 2008; Salvador, 2007), for the sake of brevity we will discuss a few selected works that exemplify the problems that have emerged.

The Modularity–Integrality Trade-off

The concepts of modularity and integrality as alternative properties of systems have been used in fields as diverse as industrial engineering, construction, robotics, computer science, mathematics, biology (Andrews, 1998), medicine, cognitive science (Coltheart, 1999; Fodor, 1983), psychology and art (interesting examples from multiple disciplines can be found in Schilling, 2003). The product design and engineering field has carried out pioneering investigation on modularity and integrality as alternative design principles, and contributed important insights into their respective features, advantages, and limits (Baldwin & Clark, 1997; Chang & Ward, 1995; Chen, Rosen, Allen, & Mistree, 1994; Ernst, 2005; Parnas, 1972; Suh, 1984). In particular, it has been determined that, when pursued and implemented strategically, modularity can lead to greater product variety, shorter time-to-market, and lower production costs (Corbett, 1991; Jose & Tollenaere, 2005; Mikkola & Gassmann, 2003; Nevins, Whitney, & De Fazio, 1989; Sanchez, 1999; Thomke & Reinertsen, 1998), whereas the benefits of integral architectures include easier and faster designing, protection of innovation from imitation, and higher entry barriers for component suppliers (Jose & Tollenaere, 2005). In general, designing modular products, as opposed to integral ones, offers firms greater flexibility, agility and adaptability to a changing environment (Thomke & Reinertsen, 1998; Thomke, 1997; Worren, Moore, & Cardona, 2002); however, it also facilitates imitation, impacting negatively on the durability of firms' performance (Ethiraj, Levinthal, & Roy, 2008; Pil & Cohen, 2006).

In the management field, the modular–integral trade-off has been increasingly employed to study the relationship between the architectural forms and systemic performances – such as flexibility, versatility, evolvability, and reconfigurability – of products, processes, and organizations, and has proved a useful conceptualization tool at different levels of analysis (Campagnolo & Camuffo, 2010). Scholars have compared modular and integral organizational forms to understand the different role they played in the dynamics of organizational recombination. Similarly to what happens with products, organizational modularity enhances the reconfiguration of organizational components (Karim, 2006; Lei, Hitt, & Goldhar, 1996; Sanchez, 1995; Sanchez & Mahoney, 1996), and represents an essential prerequisite for leveraging dynamic capabilities, and pursuing innovation, recombination and diversity (Galunic & Eisenhardt, 2001). Furthermore, diversified firms have relied on organizational modularity to facilitate the achievement of economies of scope, and reduce the need for centralized coordination (Helfat & Eisenhardt, 2004). More recently, the modularity–integrality trade-off has been applied to the analysis of processes for the delivery of services (Böhmann & Krcmar, 2006; Pekkarinen, 2008). Voss and Hsuan (2009) argue that the concepts of architecture and architectural modularity are particularly important to service design and innovation. Consistent with this view, Bask, Tinnilä, and Rajahonka (2010) analyze the relationships between modular business processes, business models, and strategic service positioning. Finally, the modular-vs-integral conversation has been enriched by analyses of the cross-level relationships between architectural forms of different kinds of system, with special emphasis on the interplay between product and organizational modularity (Argyres & Bigelow, 2010; Hoetker, 2006; Sako, 2003). On the one hand, a "mirroring hypothesis" has been put forward to explain the empirical evidence of a close matching between product and organizational architectures (Cabigiosu & Camuffo, 2012; Henderson & Clark, 1990; Hoetker, 2006; MacCormack, Baldwin, & Rusnak, 2012). On the other hand, these far-reaching effects of modularity have been contrasted by the fact that fundamental differences between knowledge boundaries and production process boundaries impede an exact correspondence between product and organizational architectures (Brusoni & Prencipe, 2001, 2006; Brusoni, Prencipe, & Pavitt, 2001).

Semantic Inconsistencies and Conceptual Vagueness

Overall, scholars recognize that the study of system architectures in the management field is still immature, and the science behind it is still embryonic (Ethiraj & Levinthal, 2004; Pil & Cohen, 2006). A major issue concerns semantics. There is a variety of different approaches to the use of the modularity construct and its underlying structure of meanings (Campagnolo & Camuffo, 2010; Gershenson, Prasad, & Zhang, 2003, 2004). Let us consider, for example, the conceptual association between modularity and "loose coupling". Orton and Weick (1990) clarify a causal relationship between loose coupling (the antecedent) and modularity (the effect); Schilling and Steensma (2001) treat the two terms as synonyms; Sanchez (1999) and Sanchez and Mahoney (1996) reverse the causal relationship; and finally, Lei et al. (1996) associate loose coupling with increasing integration. Although modularity follows on from the notion of decomposability of a system into subsystems or components (Alexander, 1964; Marples, 1961; Simon, 1962), and indeed is closely associated with this notion, the concept of modularity does not simply designate the property of a system as being made up of components. If that were the case, any system intended as a set of interacting elements (von Bertalanffy, 1950) would be modular by definition, and a general theory of modular systems (Schilling, 2000) would be redundant. Instead, there is something beyond the decomposition of a system into components that makes modularity a property dense with important implications for architectural innovation. Scholars have agreed on the principle of decomposability as a prerequisite of modularity (Campagnolo & Camuffo, 2010; Langlois, 2002), and on its relative nature along a continuum that opposes it to integrality (Schilling, 2000; Ulrich, 1995); and yet, they have then striven to qualify further the idea of relative independence that the concept entails.

The lack of consensus on conceptualizations is hardly surprising if we consider that modularity is a multifaceted concept. The product design and engineering literature has provided the most influential definitions (for an exhaustive review of the definitional efforts, see Gershenson et al., 2003, 2004), and two dominant approaches have emerged that characterize the module's independence from other modules as either *functional* or *structural*. The "functional approach" refers to a module as a system's component that is functionally independent from other components within the same system (Suh, 1984, 1990). Ishii, Juengel, and Eubanks (1995) associate the concept of modularity with the minimization of the number of functions for each component. According to Ulrich (1995: 422): "A modular architecture includes a one-to-one mapping from functional elements in the function structure to the physical components of the product, and specifies de-coupled interfaces between components." Even more neatly, Ulrich and Eppinger (2004) state that a strictly modular architecture requires that all of the components implementing a function reside in the same subsystem with few interactions among subsystems. By contrast, the "structural approach" bases the definition of module on purely structural elements, so that a module is made up of components that are tightly connected among themselves and loosely connected with the components of other modules (Baldwin & Clark, 2000).[1] Studies of modularity in the management field do not demonstrate the same definitional zeal. The only exception (Schilling, 2000) builds on the structural approach that is typical of product design (Baldwin & Clark, 2000), to state that modularity "is a continuum describing the degree to which a system's components can be separated and recombined, and it refers both to the tightness of coupling between components and the degree to which the 'rules' of the system architecture enable (or prohibit) the mixing and matching of components" (Schilling, 2000: 312). This

[1] For completeness, both functional and structural elements are simultaneously contemplated for the definition of modularity in studies that hold a hybrid approach but trade off some analytical sharpness (Allen & Carlson-Skalak, 1998; Pimmler & Eppinger, 1994; Ulrich & Tung, 1991).

definition has the merit of being inclusive of multiple types of constraints to modularity, but does not specify what these "rules" are.

The problems associated with extant conceptualization efforts seem to descend from the fact that systems normally encountered in management research have complex architectures, that is, they are multidimensional (Mitleton-Kelly, 2003). Even very simple systems like products with elementary physical structures present higher degrees of complexity when analyzed in relation to the larger technical, organizational, or social systems of which they are part, and with which they interact (Sako, 2003). For example, when we investigate a product's architecture and try to understand whether it is modular-in-production, modular-in-design, or modular-in-use (Baldwin & Clark, 1997), we are conceptually building a *super-system* that is technical, organizational, and social at the same time, thus encompassing many different dimensions of modularity. Hence, any definition of modularity based on just one dimension – either structural or functional – inevitably fails to harness such complexity (Fixson, 2001). On the other hand, comprehensiveness of dimensions should not lead to vagueness, and theoretical prescriptions aiming to be generic and inclusive (Schilling, 2000) should carefully discern between structural and non-structural factors. Moreover, the degree of modularity as an architectural attribute can vary over time based on what one can possibly do with the system or, within the system, with its components, as component separability and mixing-and-matching possibilities tend to change in line with the advancement of scientific knowledge.

Similar issues affect the other side of the trade-off. To signify the idea of unity of a system as arrangement of parts into a whole, scholars in different areas have mainly employed the concepts of integrality and integration. These have often been used interchangeably (e.g., Ethiraj & Levinthal, 2004; Ethiraj et al., 2008; Fixson & Park, 2008; Krishnan & Ramachandran, 2011; Shibata et al., 2005; Worren et al., 2002), and associated with control, hierarchy, consolidation, and tight coupling (Schilling, 2000; Schilling & Steensma, 2001), but have not been treated as design principles in their own right. In particular, the concept of integrality has been used by students of product architectures without finding an autonomous formalization, so that its definition has been residually obtained from that of modularity: if a system is not modular, it is integral; or, in relative terms, if a system is to some extent modular, it is to the complementary extent integral (Frigant & Talbot, 2005; MacDuffie, 2013; Mikkola, 2006; Mikkola & Gassmann, 2003; Muffatto & Roveda, 2002; Robertson & Ulrich, 1998; Ulrich, 1995). Unlike modularity and integrality, which were borrowed relatively recently by management scholars from technical disciplines, the concept of integration has a much longer history in management studies. It was first used in organizational theory in association with that of *coordination* (Barnard, 1968; Chandler, 1962; Follett, 1987; Lawrence & Lorsch, 1967b, 1967a; Thompson, 1967). Although they referred specifically to organizational systems – not to systems in general – Lawrence and Lorsch (1967b: 4) defined integration in a way that is particularly relevant to this study: "The process of achieving *unity of effort* among the various subsystems in the accomplishment of the organization's task" (emphasis added). This definition captures an aspect of functioning as a whole toward an outcome that plays a central role in any system's design – not just organizational systems – as it refers to each component's ability to contribute to the system's overall performance, or behavior. Such characterization has been largely neglected by studies of system architectures, with the exception of a handful of authors. Clark and Fujimoto (1990) referred to product *integrity* as a multifaceted characteristic of product systems involving two dimensions: one external, "the consistency between a product's performance and customers' expectations"; and one internal, "the consistency between a product's function and its structure: the parts fit smoothly, the components match and work well together" (p. 108). Similarly, in Iansiti (1993) and Iansiti and Clark (1994) the concept of "system focus" expressed how technological choices about a single component fit the product as a whole. Finally, Schilling (2000) used the term "synergistic specificity" to indicate "the degree to which a system achieves greater functionality by its components being specific to one another" (p. 316). Although product integrity, system focus, and synergistic specificity have a number of limitations (i.e. vagueness, challenging formalization, and dimensional limitedness of the first two, and the static and non-relative nature of the third), they represent interesting attempts to capture complex sets of interdependencies among system components, and provide useful hints for a better reconceptualization and precise formalization of integrality as a system property. Table 1 summarizes the extant conceptualizations of modularity and integrality and the related definitions.

Table 1. Extant conceptualizations of modularity and integrality

MODULARITY		
Approach	**Definition(s)**	**Key references**
Functional approach (functions performed *by* the system's modules)	Modules are system components that perform a specific function independently of other components within the same system. A fully modular system presents a one-to-one mapping between components and functions.	Ishii et al. (1995); Suh (1984, 1990); Ulrich (1995); Ulrich & Eppinger (2004)
Functional approach (functions performed *on* the system's modules)	A module is a system's component on which a specific function can be performed independently of other modules – for example, modularity in design, production, use, recycling, and so forth.	Baldwin & Clark (1997)
Structural approach (modularity of the system's structure)	A system is modular when its components can be easily separated and recombined. A module is made of components that are tightly connected among themselves and loosely connected with the components of other modules.	Baldwin & Clark (2000); Schilling (2000)
Mixed approach	Modularity as a bundle of structural and functional characteristics.	Sako (2003)
INTEGRALITY		
Similar concept(s)	**Meaning(s)**	**Key references**
Integration (organizational level)	Intended as *coordination* and *unity of effort* among various parts of a system.	Barnard (1968); Chandler (1962); Follett (1987); Lawrence & Lorsch (1967b, 1967a); Thompson (1967)
Integrity	Multifaceted characteristic of product systems capturing "the consistency between a product's performance and customers' expectations", and "the consistency between a product's function and its structure: the parts fit smoothly, the components match and work well together" (p. 108).	Clark & Fujimoto (1990)
System focus	Describes whether and how the technological choices about a single component fit the product as a whole.	Iansiti (1993); Iansiti & Clark (1994)
Synergistic specificity	The degree to which a system achieves greater functionality by its components being specific to one another.	Schilling (2000)

Examples of Contradictory Empirical Findings

Empirical studies of product and organizational architectures often provide contradictory results that clash with the aforementioned cornerstones of the modularity–integrality trade-off. On the one hand, a large part of the literature describes modularity as a situation whereby "a tightly integrated hierarchy is supplanted by 'loosely coupled' networks of organizational actors" (Schilling & Steensma, 2001: 1149), so that organizational components that are loosely coupled can be easily recombined into many different configurations. On the other hand, several studies have found that hierarchy and modularity can co-exist, and that the two need to be treated as separate and unrelated phenomena. For example, simultaneous evidence of high modularity *and* tight integration within the same organizational architecture was found by Galunic and Eisenhardt (2001: 1232) in what they called the "dynamic community", an organizational form whose dynamism is made possible by "the raw material for recombination – the modular, loosely coupled, yet *related*, business divisions" (emphasis added). This type of corporate structure "displays modularity (generating vital diversity in the corporate 'gene pool'), yet also displays relatedness (facilitating charter recombination)". According to Hoetker (2006), research on whether modular products lead to modular organizations "reveals that the question was overly simplistic and that organizational modularity is a more multiplex phenomenon than previously recognized (p. 502)". Specifically, if the modules are fundamental ingredients for "mixing and matching" strategies, they are not sufficient to explain the whole recipe for architectural recombination innovation. In other words, modularity sustains recombination but cannot act without mechanisms of integration. Hence, there must be other factors that allow highly modular units to work together as a whole. The same conclusion is supported by the literature on product modularity. Exploring the relationship between product and organizational design, Brusoni and Prencipe (2001) find that the overall consistency of large and complex products is guaranteed by pairing modularity with the integrating role of knowledge and organizational coordination. As modularity increases the separation and specialization of modules, a greater effort in terms of organizational integration and coordination is required to ensure fit among modules, and "to search and explore alternative paths of product and process configurations" (Brusoni & Prencipe, 2001: 185). In a nutshell, as Tiwana (2008) puts it, modularity is not a substitute for coordination, or control.

The Need for a Reconceptualization

The above examples show that the modularity–integrality trade-off does not account for modular systems that at the same time show or require high degrees of integrality. The logical consequence is that increasing modularity does not necessarily entail decreasing integrality, and that high levels of modularity are not always a sufficient condition to facilitate system reconfiguration, or architectural innovation. In agreement with other scholars (Fixson, 2001, 2003; Hoetker, 2006; MacDuffie, 2013; Sako, 2003), we note that it is necessary to define modularity and integrality in a way that takes into account bundles of architectural characteristics and captures the context of which the system is part, with special attention paid to the multiple facets of both constructs. Definitional, conceptual, and analytical inconsistencies, as well as controversial empirical evidence (Campagnolo & Camuffo, 2010), strengthen our belief that modularity and integrality cannot be treated as monolithic concepts. The body of studies that we have examined has produced undisputedly valuable insights, but at the same time it has relied, often uncritically, on assumptions, formulations, and approaches typical of the product design and engineering fields, and has applied them to new kinds of system architectures – processes, organizations, industries – that can reveal significantly more complex than the most complex products. Contradictory empirical evidence, lack of consensus on definitions, and the use of meanings that lack rigor undermine the "modular vs integral" thinking, in that they prevent capturing the complexity of systems architectures, fully appreciating the preconditions of architectural innovation and reconfiguration, and drawing comparisons between the findings of different studies. We propose that the starting point of this indispensable reconceptualization be the following question: Can two equally modular architectures have different degrees of integrality? Evidence suggests that they can, and that the modularity–integrality trade-off must be rejected. These two fundamental properties of systems are not simply opposites; they may push system architectures in different directions, but those directions do not necessarily rest on an intuitively simple, linear relationship. Modularity and integrality rather act separately, their determinants are crucially different, and using the two concepts in a trade-off – and the same metrics to measure them invariantly – is evidently misleading.

The Modularity–Integrality Framework

New Definitions

Our goal is to provide renewed conceptual lenses for the analysis of system architectures in general and for a better understanding of the problems of architectural innovation. Therefore, we reconceptualize modularity and integrality as distinct and non-opposite architectural properties of systems. We posit that looking at them in terms of dynamic interplay, rather than mutual exclusion, can help solve the conceptual problems identified, and overcome some of the contradictions that have emerged from empirical studies. The proposed reconceptualization entails the formalization of new, general definitions of modularity and integrality. New, because, unlike previous ones, they separate the two attributes, and take into account their multidimensionality; that is, the fact that they refer to complex, multidimensional systems. General, because they can be applied to whatever kind of systems, not just to systems that are normally the object of management research. Afterwards, we consider the interplay between modularity and integrality within a framework that describes four main types of system. Finally, we discuss the implications of adopting such interplay to study systems' behavior, with special emphasis on the characteristics that facilitate architectural innovation.

Modularity redefined. *Modularity is the systems' property of being made up of modules. A module is a system's element that presents a high, albeit not complete, independence of other elements. Modularity is a relative property in dimension and degree: a system is fully modular along a given dimension when all of its elements behave independently of other elements along the same dimension.*

This definition allows multiple dimensions of modularity to be encompassed. In the analysis of product architectures, for example, specific dimensions can be assigned to the system's physical structure, composition, and types of interface, in order to measure the separability of the system's elements under given circumstances; other dimensions can be assigned to functions performed on or around the system, in order to measure its modularity in design, in production, and in use (Baldwin & Clark, 2000; Sako, 2003); and yet other dimensions can capture the component-function mapping. According to this definition, assessing the degree of modularity of a system makes sense only if one or more dimensions are specifically chosen for the analysis, as the same system can be modular to a certain degree along a specific dimension, to a lower or higher degree along a second dimension, and not modular at all along a third one. As we move across dimensions, the representation of the system architecture can vary, as new elements are included, and/or new interactions among elements are examined. Thus intended, modularity is no more a monolithic property, but an eminently relative one, not only in degree but also in dimension, as it can capture many variable interactions within non-stationary configurations of the architectural elements.

Integrality redefined. *Integrality is the systems' property of being made up of elements that behave consistently as a whole. It is a relative property in dimension and degree. A system is fully integral along a given dimension when all of its elements consistently concur to determine the system's behavior along that dimension*.

This definition allows multiple dimensions of integrality to be encompassed. The dimensions along which a system is integral identify its factors (or mechanisms) of integration; hence, a system can have multiple factors of integration; that is, it can be integrated along different dimensions. For example, in IT product–service systems, different dimensions of integrality can be assigned to the modules' ability to support the overall system behavior in terms of scalability, availability, or performance, in order to counterbalance the limitations of applying modular approaches to the delivery of services (Böhmann & Krcmar, 2006).

Thus defined, modularity and integrality are separate and concurring properties of complex systems. Dimensions of modularity reflect the different traits of independence among modules and describe *component-level interrelationships*. Dimensions of integrality encompass factors that affect the relationship between the component level and the system level, and describe *cross-level interrelationships*. The interplay between modularity and integrality is crucial to the dynamics and evolution of systems, in that effective system reconfiguration cannot take place if both properties do not act simultaneously. On the one hand, modularity facilitates the interchangeability and separability of the modules, enhancing system decomposability and flexibility; this has a direct impact on the ease of architectural innovation and recombination. On the other hand, integrality implies the presence within the system of factors of integration, thanks to which the modules can be recombined effectively without diminishing either their contribution to the overall system behavior or the level of system performance: this directly impacts the effectiveness of architectural innovation and recombination.

A System Typology Based on the Modularity–Integrality Framework

The interplay between modularity and integrality can give rise to variable configurations of system architectures. We identify four ideal types of such configuration, as shown in Figure 1. *Recombinant systems* (or *recombinant architectures*) are characterized simultaneously by high degrees of modularity and integrality, and combine the advantages of both. High modularity provides the system with the building blocks for changes in the architectural configuration, whereas integrality ensures system cohesiveness and consistency toward a given performance, so that recombination can be effectively and successfully implemented. At product level, technological platforms offer, perhaps, the most powerful example of recombinant architectures. Platforms are a special type of modular architecture made of two different types of component: core components, and complements (Gawer & Cusumano, 2008). Core components occupy a central position in the platform architecture, which they hold together and coordinate "by constraining the linkages among the other components" (Baldwin & Woodard, 2009: 19). In other words, they act as factors of integration. Complements are fully modular components with a high degree of reusability and interchangeability, which render the overall architecture highly flexible and variably configurable. Typical examples of technological platforms are mobile handset systems (Mudambi, 2008), wherein the interplay between modular core components (hardware device, and operating system) and modular complements (hardware accessories, and applications) that contribute to the system's functions and performance makes the platform highly integral and highly modular at the same time, and supports rapid and effective architectural recombination.

Figure 1. System typology based on the Modularity–Integrality Framework

Integrality \ Modularity	High	Low
High	**Recombinant Systems** e.g. personal computers, mobile handsets, and technological platforms in general	**Specialized Systems** e.g. specialized software applications such as telecommunications switches
Low	**Bundled Systems** e.g. office automation packages and bundled applications in general	**Chaotic Systems** e.g. stock markets, the Internet

Specialized systems (or *specialized architectures*) are characterized by a high degree of integrality and a low degree of modularity. The system's components have strong mutual interdependencies that condition the behavior of each one within a given configuration, making them relatively difficult to recombine. These systems can enjoy exceptionally high performance (for example, in terms of efficiency), as they can count on easy and fast coordination of components into choral action, but suffer from low levels of flexibility and recombinability (for example, to adapt to exogenous change) in the short run. Highly specialized architectures can be found in software applications whose components contribute altogether to perform distributed functions. For example, Thomke and Reinertsen (1998) discuss the scarce flexibility of large telecommunications switches, in which volatility – perturbing variables present in each component – affects the system performance; they suggest that architectural flexibility can be enhanced by partitioning certain functions into a single module.

Bundled systems (or *bundled architectures*) are characterized by a high degree of modularity and a low degree of integrality. These systems are made of independent, interchangeable, and highly specialized modules, whose contribution to the behavior (or performance) of the overall system is limited. The system is held together by weak, often external, mechanisms of integration. For example, in office automation packages and bundled applications, in general, integration among components is ensured by the user. Despite the high level of modularity (independence along multiple dimensions) effective architectural recombinations of this kind of system are difficult to perform as a result of the limited, and sometimes even detrimental, contribution of the components.

Finally, *chaotic systems* are characterized by low degrees of modularity and integrality. Their components' behavior is conditioned by mutual interdependencies, but the scarce integrality at system level does not translate cross-component interactions into definable and predictable behavior of the overall system. Systems belonging to this type are ubiquitous in nature as well as the artificial world, with stock markets being a typical example.

The above examples facilitate a more concrete representation of the four architectural types identified by the modularity–integrality framework, but their specific characterization as recombinant, specialized, bundled or chaotic systems depends on the scope of the analysis, and on the number and nature of the dimensions of integrality and modularity selected. In reality, few systems will present extremely high or low degrees of modularity and integrality (Christensen et al., 2002), but the four sectors of the modularity–integrality matrix offer ideal types that are useful to the analysis.

Discussion

This work sought to point out conceptual problems and controversial empirical evidence emerging from the "modularity-vs-integrality" way of looking at the design of system architectures, and to the related phenomenon of architectural innovation and recombination. Analysis of the conceptual foundations on which the modularity–integrality trade-off has been built has highlighted inconsistencies and contradictions in the use of the two concepts and the underlying structures of meanings. We have proposed that such problems be overcome through a reconceptualization based on new definitions of modularity and integrality as separate, concurring, and multidimensional properties of systems. To guide our discussion of the solution proposed, we draw a comparison between the extant approach and the new framework (Table 2).

Table 2. Comparison between extant approach and proposed new approach

	Extant approach: Modularity–Integrality Trade-off	**Proposed new approach: Modularity–Integrality Framework**
Definition of key attributes	Modularity is defined as a continuum. Integrality is conceived residually, as opposite or complementary to modularity along the same continuum.	Modularity and integrality are defined as separate, orthogonal attributes of systems. Both encompass multiple dimensions, and can vary in degree along each of those dimensions.
Number of dimensions considered	Monodimensional approach: either structural, or functional – i.e. each of the two dimensions are considered, but one at a time.	Multidimensional approach: multiple dimensions must be considered as a bundle in order to appreciate the complexity of systems.
Underlying rationale and approach	Focused and purposeful approach, oriented toward rapid assessment of architectural problems. Static view, based on monodimensional metrics, generally leading to simplistic measurements. There is no interplay between modularity and integrality.	Comprehensive approach, aiming at a more consistent assessment of architectural problems. Dynamic view, based on multidimensional metrics, to capture system complexity better. The interplay between modularity and integrality affects systems' behavior.
Relationship between the two attributes	Mutually exclusive if considered as discrete attributes, or complementary if considered as extremes of a continuum.	The interplay between the two attributes gives rise to a great number of different combinations in terms of dimensions and degrees.
Implications for within-type architectural innovation	The components of a modular system can be mixed and matched without affecting the system's degree of integrality. Systems that are modular to a degree are also necessarily integral to a complementary degree.	The components of a modular system can be mixed and matched, but different configurations will likely have different degrees of integrality. Systems that are modular to the same degree can be integral to different degrees.
Implications for cross-type architectural innovation	A variation in the degree of modularity entails an opposite and complementary variation in the degree of integrality, and vice versa.	A variation in the degree of modularity does not necessarily entail a variation in the degree of integrality, and vice versa.

The proposed new definitions of modularity and integrality are consistent with a view of systems as "composed of units (or modules) that are designed independently but still function as an integrated whole" (Baldwin & Clark, 1997: 86). However, emphasis on modularity and integrality as concurring – rather than alternative – architectural properties allows factors to be taken into account that explain *how effective* integration among components is; that is, the dimensions that make a modular system function well as a whole. Thus, our framework provides a new conceptual and analytical basis for appreciating the layered nature of modularity and integrality, and seizing the interplay among the multiple dimensions subtended by each of these architectural properties. It offers systems designers broader design choices to better grasp the limits of, and constraints to, modularity (Brusoni, 2005; Ernst, 2005; Fleming & Sorenson, 2001), and to attain deeper insights into the economics of modularization (Thyssen, Israelsen, & Jørgensen, 2006) and the relationship between modularity and system behavior and performance (Antonio, Yam, & Tang, 2007; He & Kusiak, 1996; Worren et al., 2002). These considerations emphasize the role of systems architects and architectural knowledge in management practice (Baldwin, 2010; Sauer & Willcocks, 2002). In particular, they stress the complexity of the managerial choices that are linked to systems design and engineering activities. System architectures result from the purposeful and subjective choices (Gershenson et al., 2004; MacDuffie, 2013) of designers who need to take into account multiple dimensions imposed by the context surrounding a system (MacCormack et al., 2006).

Although we agree with previous studies that modularity can be a design solution to the growing complexity of product and organizational systems (Baldwin & Clark, 1997), we have observed that additional analytical effort is needed to capture such complexity. In that direction, taking modularity and integrality out of a linear relationship shifts the focus of architectural investigation beyond the questions that scholars and practitioners have typically tried to answer so far – whether higher modularity is advantageous or detrimental to a given system, or how much modularity determines an expected system behavior, and so on. Capturing the interplay between dimensions and degrees of modularity on one side, and dimensions and degrees of integrality on the other, may help address new sets of problems. For example, a promising path of investigation could address why systems that are equally modular display different performances in a given context, what dimensions of modularity would explain such differences, what factors of integration foster the effective recombination of modules and the reorientation of the system architecture, and what specific combinations of modularity and integrality guarantee optimal levels of flexibility and efficiency. Reframing architectural problems in these terms makes clear that a mere statement "modularity yes/modularity no", or a simple measure of the "right" degree of modularity can be too partial, as modularity alone is not enough to support system-level flexibility, innovation, and recombination (Thomke & Reinertsen, 1998).

Conceptually, the framework proposed in this paper is an attempt to bring together several conversations on different kinds and levels of system architectures – products, organizations, industries, and so forth – into a common basis (Campagnolo & Camuffo, 2010) underpinned by a general systems approach. As a methodological stance for future studies, the framework encourages the adoption of analytical tools such as hierarchical clustering (AlGeddawy & ElMaraghy, 2013) that are capable of overcoming the flat, monodimensional representations of basic Design Structure Matrixes (Eppinger & Browning, 2012; Steward, 1981). The framework can be employed to study diverse kinds of system, and implies selecting multiple dimensions of modularity and integrality, and carrying out separate sets of observations for each dimension of analysis. Multidimensionality and separateness of observations are expected to lead to more precise and detailed analyses, and to constitute a better reference for cross-system architectural comparisons.

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