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Three Essays on the Relationship Between Product Modularity and Organizational Modularity

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PRODUCT AND ORGANIZATIONAL MODULARITY: A CONTINGENT VIEW OF THE MIRRORING HYPOTHESIS

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ABSTRACT

Our systematic review compares the group of papers ("orthodox") that confirms the mirroring hypothesis with the group of papers ("critique") that assumes a critical position. Although the majority of the papers belong to the second group, we find that the contradiction between the two groups is fairly persistent over time. We also perform a citation network analysis on the "critique" group searching for contingent factors that explain under which circumstances the mirroring hypothesis does not hold. Results show that the mirroring hypothesis is contingent on a set of six distinct, although interdependent, factors: i) component technologic change and diversity, ii) innovativeness of product architecture, iii) complexity of product architecture, iv) capability dispersion along the supply network, v) rivalry among leading firms & among suppliers, vi) and logistics costs. We maintain that a contingent view reconciles the two opposite views on the mirroring hypothesis and enhances its practical implications by helping managers to assess the contingencies under which the mirroring hypothesis does not hold.

Keywords: literature review, product modularity, organizational modularity, modularization, network analysis, mirroring hypothesis.

1. INTRODUCTION

The relationship between product modularity (PM) and organizational modularity (OM) lies at the heart of the modularity theory of the firm that aims to explain the positions of the boundaries of firms and, as a consequence, the vertical contracting structure of industries. The relevance of this relationship dates back to Simon's (1962) ground-breaking study on the architecture of complexity based on hierarchy and near-decomposability. Thanks to the author's intuitions, it is possible to explicitly integrate technology (a variable often considered exogenous in organizational economics) into the analysis of the evolution of organizational design. The seminal paper by Sanchez and Mahoney (1996) has crystalized the effect of PM on OM indicating that the architecture of organizations mirrors the corresponding product design. In other words, modular organizations come from modular products, and integral organizations come from integral products.

A direct and positive relationship between PM and OM has been framed as *the mirroring hypothesis* (Colfer and Baldwin, 2010), which has aroused the interest of many studies so far. The mirroring hypothesis implies a bi-directional positive relationship between PM and OM. One causal relationship that the mirroring hypothesis embeds is from organizations' architectures to product architectures (Henderson and Clark, 1990). This hypothesized causation rests on the argument that problem solving and communication patterns of organizations (OM level) draw the solution space for product design (PM level) (MacCormack et al. 2012). Therefore, modular organizational forms in which loosely coupled organizational units specialize in distinct knowledge domains are more likely to design modular products because no mechanism is available to integrate the dispersed knowledge domains to maximize component synergies that is necessary for the development of integral products.

Our paper focuses on the mirroring effect from products' architectures to organizations' architectures. In other words, we focus on the effects that the architecture of a product has on the organization of the development and production activities of that product. Thus, in the rest of the paper, we refer the term “mirroring hypothesis” to the causal relationship from product modularity (PM) to organizational modularity (OM).

Several studies have empirically supported the mirroring effect from PM to OM at different levels of analyses and in several industries (Schilling and Steensma, 2001; Sturgeon, 2002; Fixson and Park, 2008; Cabigiosu and Camuffo, 2012). Modules are interpreted as market-supporting institutions providing technical design rules that standardize the interfaces between different product components or stages of the production process (Sabel and Zeitlin, 2004). The modularity in product serves as the functional equivalent of coordination mechanisms between firms in a supply chain or among organizational units of the same firm.

As the number of empirical studies have increased and the scope of enquiry has broadened, a considerable number of studies revealed contradictory findings. It is argued that the presumed positive effect of PM on OM conjectured by the mirroring hypothesis is inhibited by inextricable performance interactions among the components of the products (Langlois 2002; Brusoni and Prencipe, 2006; Zirpoli and Becker 2011; Whitford and Zirpoli, 2014). Even if a product is designed modular-wise, the remaining chunks of residual interdependences force organizations to adopt complex and expansive coordination mechanisms in order to assure the performance of the final product.

In the first part of the paper, we carry out a systematic review to compare the group of papers (“orthodox”) that confirms the mirroring hypothesis with the group of papers (“critique”) that assumes a critical position. At the best of our knowledge, this review is the first attempt to compare these two groups. Although the majority of the papers belong to the second group, we find that the contradiction between the two groups is fairly persistent over time. We search for any specific pattern related to the research designs of papers that can explain their different positions. Results show that the differences in the research designs (such as industries, adopted measures, and levels of analyses for PM and OM) are not responsible for the positions of papers in one of the two groups.

Having ruled out the possibility that different research settings might be responsible for the contrasting views on the mirroring hypothesis, we argue that the discrepancy between product and organizational architectures derives from contingent factors "that ultimately impinge on the ability of modular design rules to bring about modular organizations" (D'Adderio and Pollock, 2014; p.1814). However, we lack studies that systematically analyse and discuss these contingent factors.

Therefore, in the second part of the paper, we perform a citation network analysis on the "critique" group searching for contingent factors that explain under which circumstances the mirroring does not hold. Results show that the mirroring hypothesis is contingent on a set of six distinct, although interdependent, factors: i) component technologic change and diversity, ii) innovativeness of product architecture, iii) complexity of product architecture, iv) capability dispersion along the supply network, v) rivalry among leading firms & among suppliers, vi) and logistics costs. We discuss each contingent factor in turn, highlighting theories or approaches that ought to be used in conjunction (not in contrast) with the modularity theory to explain the boundaries of firms and industries. We maintain that a contingent view of the mirroring hypothesis reconciles the two opposite views on the mirroring hypothesis and enhances its practical implications by helping managers to assess the contingencies under which the mirroring hypothesis does not hold true.

2. PM, OM, AND MIRRORING HYPOTHESIS: CONCEPTUAL DEFINITIONS

While a product is composed of different components and sub-systems, an organization can be partitioned into departments, separate firms and vertical industrial layers. Therefore, it is possible to identify both products and organizations as systems whose constituents have interdependencies to implement their system functions. For example while technical, volumetric and aesthetic interdependences exist among components and subsystems of products, there are informational, governmental and resource interdependences among organizational units (Worren, 2012).

We can identify three different levels of PM: the final product level that indicates the modularity degree of a final product; the sub-system level that indicates the modularity degree of a single sub-system; and the component level that indicates the modularity degree of a single component. We use the term PM to cover all these three levels of analyses. Regarding the modularity degree of a final product, Ulrich (1995) puts two criteria, i.e. a) their constituents are coordinated through standardized interfaces and b) each constituent performs only one product function. The subsystems of a final product can also be defined as either modular or non-modular (Simon, 1962) because they can contain complex components' interactions such as in the aircraft engine control system (Brusoni et al.,2001), the exhausting system (Persson and Ahlström, 2013), and the air-conditioning system in automobiles (Cabigiosu et al., 2013). Finally, there are studies (Hsuan, 1999; Cabigiosu et al, 2013; Furlan et al., 2014) assessing whether components are modular or not. The degree of component modularity depends on how many functions the component carries out and on the degree of its interdependency with other components.

OM refers to the degree of decoupling of organizational units regarding various dimensions such as coordination, geography, culture, and electronic connectivity (Fine et al., 2005). Similar to PM, there are different levels of analyses for OM: *intra-firm, inter-firm, supply network, and industry*. We use the term OM to cover all these four levels of analyses. While the intra-firm level refers to the degree of decoupling among organizational units within the same firm, the inter-firm level denotes the decoupling between the buyer-supplier dyads. The supply network level indicates the decoupling degree between firms within the same supply chain. Finally, the industry level refers to the decoupling degree of vertical layers within the same industry.

The mirroring hypothesis proposes that, while modular products (high PM) trigger the adoption of modular organizations (high OM), integral products (low PM) cause the emergence of integral organizations (low OM). First, the standardized interfaces of modular products embed all the information needed to support the coordination of development and production activities (Sanchez and Mahoney, 1996). Second, modules are devised to encapsulate interdependent components within the same technical boundaries (Gershenson et al., 1999), which minimize the interdependencies across modules. Since high PM reduces the need to make relational-specific investments, organizations enjoy flexibility in terms of new product configuration, production volume, and sourcing alternatives (Schilling and Steensma, 2001). On the contrary, the development of integral products (low PM) requires low OM. Ulrich (1995) defines an integral product architecture as the one in which many modules are jointly responsible for each product function. Thus, the joint action of organizational units (low OM) is necessary during both the design and production phases to maximize the product performance (Staudenmayer et al., 2005) and minimize quality problems (Gokpinar et al., 2010).

3. METHODLOGY

To understand the reasons for the contradictory views on the mirroring hypothesis, we sample relevant studies and divide them into two groups (i.e. “orthodox” and “critique”) based on their support. Then, we make a two-stage analysis: i) the preliminary analysis on research settings and ii) the citation network analysis. The first stage reports the frequency of the research setting components such as industries, adopted measures, and levels of analyses for PM and OM in both groups. Subsequently, z-test compares the proportion of these research setting components across "orthodox" and "critique" groups to test whether their proportions are statistically different at 0.05 significance level. Hence, this preliminary analysis shows whether any specific research setting component might cause the contradictory views on the mirroring hypothesis.

In the second stage, our efforts to explore the boundaries of the mirroring hypothesis resume with network analysis. We only focus on the papers of the "critique" group to reveal the contingent factors for which the mirroring hypothesis does not hold. Even if the papers articulate the criticisms with different names and based on different contextual factors, many criticisms point out the same themes. Hence, we track the in-text citations made between the papers of "critique" group to link these criticisms. Then, the network algorithm cluster them thematically based on the links established. After the analysis of the members in each community clustered, we identify 6 different contingent factors for which the mirroring hypothesis does not hold. We will explain our methodological approach more elaborately in Section 6.1.

3.1 Sample selection

The first explicit recognition of the PM's positive effect on OM dates back to the study of Sanchez and Mahoney (1996). Since then, scholars have not reached a consensus whether the mirroring hypothesis can in fact adequately explain the relationship between the architectures of products and organizations. To substantiate this claim, we have conducted a review of all relevant papers published after Sanchez and Mahoney (1996), and classified them into two groups: "orthodox" and "critique" regarding their findings and arguments on the mirroring hypothesis. This review allows us both to weight these two groups and explain why the findings of papers, may indicate opposite arguments on the mirroring hypothesis.

Greenhalgh and Peacock (2005) highlight the risk that a systematic literature review based solely on pre-determined searching rules may not identify some critical sources necessary to fully explore a phenomenon. Considering this precaution, we combined protocol-driven and snowballing searching techniques similar to the recent reviews in management field (Srivastava, 2007; Ravasi and Stigliani, 2012; Marabelli and Newell, 2014; Butler et al., 2015).

To begin with, we conducted Boolean search through the bibliographic database of SciVerse Scopus. We confined our search within two subject areas, "Business, Management and Accounting" and "Social Sciences" for the articles published in peer-reviewed journals and written in English over the period 1996-2015. The choice of the starting period – 1996 - was congruent with the acknowledgement that Sanchez and Mahoney (1996) is the first study that explicitly introduces the mirroring from PM to OM (Campagnolo and Camuffo, 2010; Furlan et al., 2014). In order to identify suitable papers, as of March 2015, we made use of the keyword string (Table 1), which we searched in titles, abstracts and keywords of papers.

Table 1 - The keyword string in Boolean search

The Searched Terms	*The Used Keyword*
Modularity	(Modularity or Modularization) and
Product Modularity	((Product and (Modular* or Architectur* or Design or Develop*)) or
Organizational Modularity	((Design or Structure or Coupl* or Coordinat* or Integra* or Relation* or Cooper* or Modular*) And
Analyses Levels For OM	(Organiz* or Industr* or Supply Chain or Interfirm or Supplier)) or
Mirroring Hypothesis	(Mirror*)

* The operator asterisk in the query returns all words for the given string.

Our search resulted in 311 documents. The main criterion for our including the ones among these 311 papers was whether they discuss the effect of PM on OM either through theoretical conceptualization or based on empirical evidence. Thus, we first excluded the papers whose abstracts were irrelevant. When the abstracts of papers were found insufficient to assess their relevance, we analysed these papers' discussion and conclusion parts for the decision.

All papers in the sample are related to modularity considering that our main inclusion criterion is whether they touch upon the effect of PM on OM. Besides, many keywords in Boolean search contain the word "modularity". Even if the central research question of few sampled papers is not the PM-OM relationship, their analyses and findings have important implications on the mirroring hypothesis. For example, Gadde and Jellbo (2002) examine the dimensions of the firms' system sourcing strategy (OM level). One of these dimensions identified by them is the system definition depending on the modularity degree of components. Alternatively, Srikanth (2007) investigates the factors that provide the coordination in distributed (modular) organizations. One of dimensions they examine is the product modularity degree.

The focus of our review is the "ex-post" effect of the PM level on the OM level. That is to say, the OM level during the product modularization process is not the interest of this research because the term "modularization" is not synonymous of "modularity". Whereas the modularization is a process and an activity through which modular artefacts are created, the modularity is an attribute of a system design (MacDuffie, 2013). Thus, we did not include the studies solely examining the OM level during modularization process. Nevertheless, the papers showing changes of the OM level as a consequence of product modularization were included in the sample since they show the effect of the increased PM level on the OM level.

Few papers resulting from the keyword search both belong to the same authors and are based on the same empirical evidence. Even if those papers address different research questions, they are identical with respect to our research phenomenon. In these cases, we only considered the most cited paper into our sample.

After all these filtering, 52 qualified papers remained. Subsequently, we utilized the snowball technique to inspect the availability of more relevant papers. The search using *"Google Scholar"* into both bibliographies and the citing successors of 52 papers enabled us to add 31 more papers. Despite 2 of these 31 (Puranam and Jacobidies, 2006; Srikanth, 2007) are working papers, we decided to include them because they are highly cited by the following studies. In the end, our final sample consists of 83 papers.

4. PRELIMINARY ANALYSIS

We classified the reviewed studies into two groups: "orthodox" (supporting the mirroring hypothesis), and "critique" (casting doubts on the validity of the mirroring hypothesis). The positions of almost all papers are quite clear, hence, do not leave much room for personal assessment. However, a few papers required some discussion among the authors of this paper and other field experts to determine their positions.

While papers in the "orthodox" group form 31% of the sample, papers in the "critique" group represent 69% of the sample[1]. The comparison of the percentage distribution over time between the two groups (Figure 1) shows that the contradiction is persistent over time.

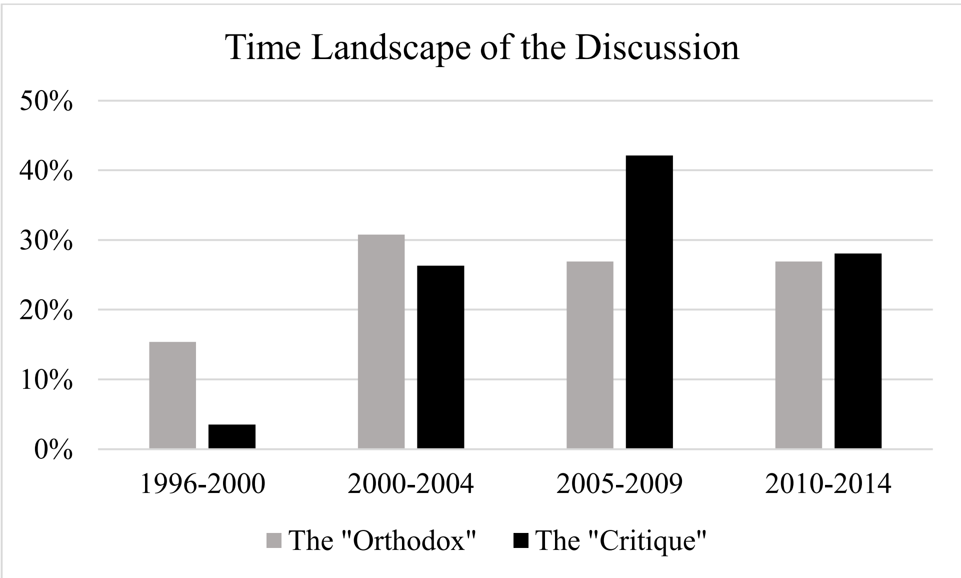

Figure 1 – The percentage distribution of the two groups over time

As a preliminary analysis of the two groups ("orthodox" and "critique), we examine six research setting components that may have a role in explaining the position of each paper.

These are namely: the ratio of empirical papers, the ratio of papers on automotive industry, the adopted PM measure, the adopted OM measure, the level of analysis used for PM, and the level of analysis used for OM. We used z-test to check if the proportions of each component across the "orthodox" and "critique" groups are significantly different. In Tables 2-8 below, unless the subscript letters in the cells of the same row are different, we cannot say that the frequencies of the research setting components examined are statistically different across two groups. In other words, although their percentages in two groups are different, these differences are not large enough to claim a statistical significance that may cause the emergence of contradictory findings on the mirroring hypothesis.

There are both conceptual and empirical papers in our sample but it is chiefly comprised of empirical studies (78%). The distinction between conceptual and empirical papers is relevant for at least two reasons. First, the conceptualization of a phenomenon may not reflect the empirical findings on the same phenomenon. Second, it is possible that the empirical research settings are not adequate to accurately test the conceptualized phenomenon. We looked at the ratio of the empirical research in each of the two groups. The ratio of empirical research is almost equal in both "orthodox" and "critique" groups (Table 2), indicating no significant difference.

Table 2 - Distribution of empirical research among the 2 groups

		Groups		Total
		"Orthodox"	"Critique"	
Research Type	Empirical	19_a (73%)	46_a (81%)	65 (78%)
	Conceptual	7_a (27%)	11_a (19%)	18 (22%)
Total		26 (100%)	57 (100%)	83 (100%)

Different subscript letters in same rows denote that the column proportions differ significantly from each other at the 0.05 level.

The automotive industry is by far the most studied industry in our sample. Thus, the abundant presence of the automotive industry in empirical research (34 out of 65 papers) drew our attention. MacDuffie (2013) maintains that the definition of modules in the automotive industry is different from those in other industries because the modules of a car cannot be developed to perform only one product function. The formation of modules is therefore driven by production concerns rather than design features. Such particularity induced us to control if the papers on the automotive industry mostly gather in one of the two groups. However, Table 3 shows that the ratio of the automotive industry does not significantly differ between the "orthodox" and "critique" groups.

Table 3 - Distribution of the automotive industry among the 2 groups

		Groups		Total
		"Orthodox"	"Critique"	
Industry	Automotive	8_a (31%)	26_a (46%)	34 (41%)
	Others	18_a (69%)	31_a (54%)	49 (59%)
Total		26 (100%)	57 (100%)	83 (100%)

Different subscript letters in same rows denote that the column proportions differ significantly from each other at the 0.05 level.

Our literature review identifies various measures and levels of analyses for both PM and OM.

We classified the wide range of PM measures adopted by papers into five categories. The first, and by far the most adopted PM measure category, is "interface features" that delineates the technical relationships across product modules such as openness, standardization, centralization, and strength. The second PM measure category is "mapping pattern of functions to modules" (Ulrich, 1995) according to which an artefact is modular insofar its constituents carry out only one function. We named the third PM measure category "granted". The papers in this category do not specify the PM level based on any technical criteria. Instead, while some of them postulate the PM level based on previous papers' conjectures, others assume the existence of modular production systems as an evidence for high PM. The fourth PM measure category is "standards in force", the presence of which implies higher PM. These standards may be either the industrial standards set by governmental authorities or the codified practices used across firms within an industry. Finally, the fifth PM measure category, "combinability", considers an artefact as modular to the extent that its design allows to provide high product variety (Salvador et al., 2002; Schilling, 2000).

Table 4 compares the proportion of each PM measure category in the "orthodox" and "critique" groups. Even if the percentages of "granted" and "combinability" are higher in the "critique" group than in the "orthodox" group (respectively 25 % versus 14 %, and 15 % versus 7 %), these differences are not significant.

Table 4 - Distribution of the adopted PM measures among the 2 groups

		Groups		Total
		"Orthodox"	"Critique"	
Adopted PM Measure	Interface Features	14_a (48%)	29_a (47%)	43 (48%)
	Mapping of Functions	4_a (14%)	5_a (8%)	9 (10%)
	Granted	4_a (14%)	15_a (25%)	19 (21%)
	Standards in Force	5_a (17%)	3_a (5%)	8 (9%)
	Combinability	2_a (7%)	9_a (15%)	11 (12%)
Total		29 (100%)	61(100%)	90 (100%)

Different subscript letters in same rows denote that the column proportions differ significantly from each other at the 0.05 level.

There are studies that utilize more than one PM measure.

For OM, we consolidated the wide range of adopted measures into five categories. The three measures introduced by Hieber (2002) cover a substantial number of OM measures in our sample, which are "coordination (the daily operations of transcorporate processes and methods in the logistics network)", "vertical configuration (the modelling of the existing business relationships between the network entities)", and "collaboration (the degree and kind of relationship between participants)". We identified two additional OM measures, which are "geographical proximity" and "autonomy".

The first OM measure, "coordination", contains the following items in our analysis: daily information exchange, joint product development, co-execution of research, cross-organizational teams for design and production processes. Second, "vertical configuration" refers to the size of the supplier base, the form of supply network, or the number of vertical layers in an industry. The third one, "collaboration" covers the ownership structure and relationship features between organizational units such as relational strength, length, and trust. Next, "geographical proximity" regards the geographical distance between buyers and suppliers. Finally, "autonomy" indicates the extent to which each organizational unit makes independent decisions on the design of the components they produce and/or it shows the extent to which organizational units can easily switch their partners that produce the rest of components.

It might be argued that the categories that we specify for the OM measures are not mutually exclusive. According to this argument, the joint activities referring to high coordination might boost collaboration that further limit the autonomy of organizational units. Even if we give some credit to the possibility of such causal relationship between these OM measures, it is difficult to generalize it. For instance, the temporary strategic conjecture may compel organizations to carry out their activities jointly although their relationships are weak. Alternatively, firms may be willing to provide collaboration through joint activities, however, the goal and cultural differences may disable them to establish long and trusty relationships. Similarly, the high level of trust and long relationships (collaboration) may make unnecessary for organizations to monitor and intervene into the decisions of their partners, leading to high autonomy.

As shown by Table 5, while "coordination" is the most adopted OM measure, "vertical configuration" is the least used one. Besides, the distribution of OM measures across the groups of "orthodox" and "critique" does not show any significant difference.

Table 5 - Distribution of the adopted OM measures among the 2 groups

		Groups		Total
		"Orthodox"	"Critique"	
Adopted OM Measure	Coordination	12_a (39%)	35_a (45%)	47 (44%)
	Vertical Configuration	3_a (10%)	7_a (9%)	10 (9%)
	Autonomy	5_a (16%)	9_a (12%)	14 (13%)
	Geographical Proximity	4_a (13%)	12_a (16%)	16 (15%)
	Collaboration	7_a (22%)	14_a (18%)	21(19%)
Total		31 (100%)	77 (100%)	108 (100%)

Different subscript letters in same rows denote that the column proportions differ significantly from each other at the 0.05 level.

There are studies that utilize more than one OM measure.

As argued by Sanchez and Mahoney (1996), the mirroring hypothesis rests on the matching between interface features (the chief measure of PM) and coordination level (the chief measure of OM). We checked if the use of this measure-pair affects the positioning of papers into one of the two groups. Table 6 shows that the proportions of these papers do not differ significantly between the two groups.

Table 6 - The number of papers adopting the PM-OM measure-pair: "interface features - coordination level" among the 2 groups

		Groups		Total
		"Orthodox"	"Critique"	
PM: Interface Features OM: Coordination	Used	8_a (31%)	21_a (38%)	29 (36%)
	Not Used	18_a (69%)	34_a (62%)	52 (64%)
Total		26 (100%)	55 (100%)	81 (100%)

Different subscript letters in same rows denote that the column proportions differ significantly from each other at the 0.05 level.

As shown in Table 7, the papers in our sample analyse PM at the following three levels: final product, sub-system, and component. Among these levels of analyses, "final product" is used the highest number of times (59 out of 79) considering both "orthodox" and "critique" groups. On the other hand, OM is analysed at four levels of analyses as shown in Table 8: "intra-firm", "inter-firm", "supply network", and "industry". Notably, while the percentage of the OM analysis level, "intra-firm", is higher within the "orthodox" group (24 %) than within the "critique" group (13 %), "supply network" is higher within the "critique group" (46 %) than within the "orthodox" group (28 %). We checked if different levels of analyses of PM and OM can explain the different positions of the papers. However, Table 7 and 8 show that there is not any significant difference across the groups.

Table 7 - Distribution of the analysis levels used for PM among the 2 groups

		Groups		Total
		"Orthodox"	"Critique"	
PM Analysis Level	Final Product	19_a (76%)	40_a (74%)	59 (75%)
	Subsystem	2_a (8%)	7_a (13%)	9 (11%)
	Component	4_a (16%)	7_a (13%)	11 (14%)
Total		25 (100%)	54 (100%)	79 (100%)

Different subscript letters in same rows denote that the column proportions differ significantly from each other at the 0.05 level.

While some studies do not use any analysis levels, the few use more than one.

Table 8 - Distribution of the analysis levels used for OM among the 2 groups

		Groups		Total
		"Orthodox"	"Critique"	
OM Analysis Level	Industry	6_a (24%)	8_a (15%)	14 (18%)
	Supply Network	7_a (28%)	25_a (46%)	32 (41%)
	Inter-Firm	6_a (24%)	14_a (26%)	20 (25%)
	Intra-Firm	6_a (24%)	7_a (13%)	13 (16%)
Total		25 (100%)	54 (100%)	79 (100%)

Different subscript letters in same rows denote that the column proportions differ significantly from each other at the 0.05 level.

While some studies do not use any analysis levels, the few use more than one.

All in all, our preliminary analysis shows that there is not any significant difference between "orthodox" and "critique" groups in terms of research design. Therefore, we rule out the possibility that different methodological approaches or research settings are responsible for the existence of contradictory views on the mirroring hypothesis. In the remaining of the section, we review each of the two groups – "orthodox" and "critique" – in detail.

5. DIFFERENT VIEWS ON THE MIRRORING HYPOTHESIS

5.1 The "Orthodox" group

Table 9 lists the papers supporting the mirroring hypothesis along with the PM-OM levels of analyses, and the analysed industry (if applicable).

Most of the papers in this group advocate that modular product leads to modular organization (high PM- high OM). There are mainly three rationales that explain the pair "high PM-high OM", which are low coordination costs, operational benefits, and high strategic flexibility.

The coordination costs may become too high for complex products like those in the aircraft (Argyres, 1999) and automotive (Fine et al., 2005) industries. In order to bring these costs down, many studies suggest adopting modular designs since the standardized interfaces embed the necessary information to coordinate different actors efficiently (O'Sullivan, 2003; Danese and Romano, 2004). Modular product design reduces the need for high coordination by isolating the hardly transferable knowledge, such as the technological knowledge in innovative product developments (Schmickl and Kieser, 2008) and tacit knowledge (Kotabe et al., 2007) within product modules. One-to-one mapping between the components and product functions reduces the interdependency between organizational units, hence curbing coordination costs. Empirical results of studies in the PC and air-conditioning industries (Hoetker, 2006; Cabigiosu and Camuffo 2012) also verify that higher PM lowers the coordination needs thus enabling greater OM.

Many operational benefits are attributed to the pair “high PM-high OM”. For example, the studies (Argyres, 1999; Takeishi and Fujimoto, 2001; Hoetker et al., 2007) highlight that standardized interfaces (high PM) diminish the concern for the quality of the sourced items since buyers do not need to monitor the production processes of their suppliers closely (high OM). Moreover, high PM allows simultaneous engineering (Sanchez, 2013), which shortens the product development lead time.

The third rationale for the pair “high PM-high OM” is the strategic flexibility that it gives. The pre-condition of being responsive under high competition and customization pressures (Christensen et al., 2002; Cheng, 2011) is the flexibility gained through high OM along with high PM (Bush et al., 2010). Firms that source modular components can easily change their suppliers (high OM) to meet the changing market needs because high PM removes the hold-up risks by reducing the specificity of the relational assets (Argyres, 1999; Schilling and Steensma, 2001; Sturgeon, 2002; Hoetker, 2006). Moreover, the existence of visible rules and uniform standards (high PM) increases sourcing alternatives (high OM).

In addition to the papers advocating the pair “high PM-high OM”, there are also studies explaining why low PM drives low OM. First, the intense interdependencies among the components of a product (low PM) increase the coordination efforts that are needed to maximize the synergy between components and minimize product errors (low OM) (Gokpinar et al., 2013). Moreover, a new integral product architecture (low PM) may cause a shift towards coupled supply chains and industries (low OM). For example, Fixson and Park (2008) show how the introduction of an integral architecture with an enhanced performance in the bicycle industry led, in a few years, to a vertically structured and near monopolistic industry dominated by the innovative firm.

Table 9 – The list of papers in the "orthodox" group

Paper	**PM - OM Levels of Analyses**	**Industry**
Sanchez and Mahoney (1996)	Product ==>Intra-Firm Product ==> Supply Network	X
Argyres (1999)	Product ==> Supply Network	Aerospace
Hsuan (1999)	Product ==> Inter-Firm	Automotive
Schilling (2000)	Product ==> Industry	X
Galwin and Morkel (2001)	Product ==> Industry	Bicycle
Schilling and Steensma (2001)	Product ==> Industry	Manufacturing
Takeishi and Fujimoto (2001)	Subsystem ==> Inter-Firm	Automotive
Christensen et al. (2002)	Product ==> Industry	PC
Sturgeon (2002)	Product ==> Industry	Electronics
Mikkola (2003)	Component ==> Inter-Firm	Automotive
O'Sullivan (2003)	Product ==> Supply Network	Aerospace
Danese and Romano (2004)	Product ==> Intra-Firm	Automated bending machines
Fine et al. (2005)	Product ==> Supply Network	Automotive
Hoetker (2006)	Product ==> Intra-Firm Product ==> Supply Network	Notebook manufacturers
Hoetker et al. (2007)	Component ==> Inter-Firm	Automotive
Kotabe et al. (2007)	Product ==> Supply Network	Automotive
Baldwin (2008)	Product ==> Inter-Firm	X
Fixson and Park (2008)	Product ==> Industry	Bicycle
Schmickl and Kieser (2008)	Product ==> Intra-Firm	Electrotechnical
Bush et al. (2010)	Product ==> Supply Network	Manufacturing
Cabigiosu and Camuffo (2012)	Component ==> Inter-Firm	Air conditioning
Gokpinar et al. (2013)	Subsystem ==> Intra-Firm	Automotive
Sanchez (2013)	X	Automotive
Hellström (2014)	Product ==> Intra-Firm	Shipbuilding
Bouncken et al. (2015)	Product ==> Supply Network	X
Hao et al. (2015)	Product ==> Supply Network	High-technology

5.2 The "Critique" group

The criticisms articulated by the papers in the "critique" group are listed in Table 10 which shows for each paper a) the reasons for criticism, b) the levels of analyses for PM and OM, and c) the analysed industry (if applicable).

Many criticisms point out the importance of retaining technologic knowledge. Several studies argue that the knowledge boundaries of firms should be wider than their production sphere (Brusoni et al., 2001). Firms have to couple with their suppliers to keep the component-specific knowledge even if the product is modular. Since complex products are composed of components having different technological evolution paths, the absence of component-specific knowledge by the system integrator may impair the success of the next product configurations and the identification of existing problems during production (Brusoni and Prencipe, 2011). Moreover, even if modular product design is devised to assign each component to different product function, there can be higher-order performance parameters that are the joint outcome of many components regardless of their functional interdependency (e.g. the speed of car depending on many components). Hence, the possession of component-specific knowledge enables the system integrator to achieve performance integration among several systems (Zirpoli and Becker, 2011), avoiding performance bottlenecks (Ethiraj, 2007). Furthermore, as argued by Staudenmayer et al. (2005), most of the interdependencies between components cannot be foreseen ex-ante in the product design phase. This is even more true for innovative artefacts which require high coordination (low OM) across organizational units although the product in question is modular (Sabel and Zeitlin, 2004; Lau and Yam, 2005; Lau, 2011).

Operational efficiency is another frequently used argument that highlights the need for organizational coupling despite the existence of modular products. First, it is argued that modular product design may provide product variety in a cost-effective way. However, this strategy requires geographical proximity, high information-sharing (Van Hoek and Weken, 1998; Salvador et al., 2002), and frequent deliveries of modules to keep low inventory levels, and to shorten lead times (Lau and Yam, 2005; Fredriksson, 2006; Chiu and Okudan, 2011). Total quality management (Gomes and Dahab, 2010), transportation costs (Frigant and Lung 2002; Frigant and Layan, 2009) and scale effects via resource sharing (Fredriksson, 2006; Chesbrough and Prencipe, 2008) are other operational factors which favour organizational coupling even in the presence of modular artefacts. Similarly, both Jacobs et al. (2007) and Nepal et al. (2012) show that the production of modular products through highly coordinated supply chain partners (low OM) gives better performance outcomes.

Another criticism asserts that a modular product design is the result of a modularization process during which organizational units have to coordinate closely. Although the product becomes modular only after the modularization process, Howard and Squire (2007) claim that the investments in specific assets made during the modularization process make impossible for firms to decouple their organizations at the end of the modularization process. Besides, other studies (Campognolo and Camuffo, 2009; Cabigiosu et al., 2013) indicate that the importance of subsystems in terms of their effects on the whole product performance, and on customer perception, is the main determinant of the OM level regardless the PM level. Finally, Lau (2011) remarks that the mechanism may work reversely. That is to say, firms may prefer modular organizations to reduce the risks of knowledge leakages especially for integral products (low PM) that normally require high level of coordination between organizational units.

Table 10 – The list of papers in the "critique" group

Paper	Criticisms (ID number in the network)	PM - OM Levels of Analyses	Industry
Baldwin and Clark (1997)	*Competition level across leading firms (1) *Technologic change rate (2)	Product ==> Supply Network	X
Van Hoek and Weken (1998)	*Getting instant market information to be responsive (3) *Savings in logistics costs (4)	Product ==> Supply Network	Automotive
Brusoni and Prencipe (2001)	*Need for coordination caused by multi-technology and heavy engineered products (5)	Product ==> Industry	Aircraft engines, Chemical engineering
Brusoni et al. (2001)	*Immature and uneven technologic advance of different components (6)	Component ==> Inter-firm	Aircraft engine
Salerno (2001)	*Government incentives (7) *Importance of tacit knowledge (8) *Local factors (9)	Product ==> Supply Network	Automotive
Frigant and Lung (2002)	*Logistical constraints (10) *Commitment mechanism provided by geographical proximity (11) *The secure of quality and innovation processes (12)	Product ==> Supply Network	Automotive
Gadde and Jellbo (2002)	*Negative effect of capability scattering on innovation (13)	Product ==> Supply Network	Automotive
Langlois (2002)	*Dynamic production technology in terms of knowledge change (14)	X	Computer, Automotive, Electronics
Salvador et al. (2002)	*Negative impact of product variety on operational efficiency (15)	Component ==> Inter-Firm	Transportation vehicles Telecom. equipment, Food processing mach.
Takeishi (2002)	*Technological newness of the project (16)	Product ==> Inter-firm	Automotive
Doran (2003)	*Abilities of first-tear suppliers to accommodate the modular production (17)	Product ==> Supply Network	Automotive
Langlois (2003)	*Logistics costs (18)	Product ==> Industry	X
Sturgeon (2003)	*Codification rate of product specifications in standards (19)	Product ==> Industry	Electronics
Ethiraj and Levinthal (2004)	*Negative effect of innovation efforts on module performances (20)	Product ==> X	X
Gerwin (2004)	*Appropriability risk (21) *Lack of socialization and learning (22)	Product ==> Intra-Firm Product ==> Supply Network	X
Sabel and Zeitlin (2004)	*Innovative character of new economy (23) *Vulnerability of current successful product architectures (24)	Product ==> Industry	X
Sosa et al. (2004)	*System modularity (25)	Component ==> Intra-firm	Aircraft engine
Brusoni (2005)	*Cognitive limits to the problem framing and solving (26)	Product ==> Supply Network	Chemical
Ernst (2005)	*Conflicting interests with suppliers (27) *Velocity and predictability of technologic change (28) *Oligopolistic rivalry (29)	Product ==> Supply Network	Semiconductor
Frigant and Talbot (2005)	*Efficient logistics activities (30) *Need for controlling production and processes due to division of competences (31)	Product ==> Industry	Aircraft, Automobile
Fixson et al. (2005)	*Strategic values of the four product development phases (32) (concept, design, engineering, and validation) *The available capabilities from suppliers (33)	Subsystem ==> Supply Network	Automotive
Hobday et al. (2005)	*Technologic change rate shaping strategies to be competitive (34)	Product ==> Supply Network	Automotive, Hard disk drives
Lau and Yam (2005)	*Innovative product (35) *Performance metrics such as quality, inventory level, and delivery speed (36)	Product ==> Supply Network	Electronics
Staudenmayer et al. (2005)	*Performance control (37) *Sporadic hidden interdependencies (38) *Decentralized multiparty networks of relationships (39)	Product ==> Industry	Technology and Telecommunication
Brusoni and Prencipe (2006)	*Changes in engineering know-how (40)	Product ==> Intra-Firm	Tyre
Fredriksson (2006)	*Activity synchronization (41) *Resource sharing (42) *Activity and resource development (43)	Product ==> Intra-Firm	Automotive
Persson and Ahlström (2006)	*Functional interdependencies between different modules (44)	Subsystem ==> Intra-Firm	Automotive
Puranam and Jacobides (2006)	*Existing level of systematic knowledge (45)	X	X
Ethiraj (2007)	*Constraining components that cause bottlenecks for system performance (46)	Component ==> Supply Network	PC
Howard and Squire (2007)	*Build to order supply chains (47) *Aim of having more modular product (48)	Component ==> Inter-Firm	Manufacturing

Jacobs et al. (2007)	*Information leakage risk (49) *Inventory Costs (50)	Component ==> Inter-Firm Product ==> Supply Network	Automotive
Ro et al. (2007)	*Lack of trust in supplier capability (51) *Type of outsourced module (52) *Intellectual property concerns (53)	Product ==> Inter-firm	Automotive
Srikanth (2007)	*Strategic goals of a client (54) *Legacy considerations (55)	Product ==> Inter-Firm	Software
Chesbrough and Prencipe (2008)	*Exploitation of technology for product architecture having limited life-time (56)	Product ==> Supply Network	X
Tiwana (2008)	*The need for outcome control (57)	Product ==> Supply Network	Software
Agrawal (2009)	*Level of product obsolescence (58)	Component ==> Inter-firm	Automotive, Machinery
Benassi (2009)	*The solution of organizational issues (59)	X ==> Intra-Firm	Machinery and Mechanical
Campagnolo and Camuffo (2009)	*Industry and nation specificities (60) *Labour intensity (61) *Technological change (62)	Product ==> Industry	Manufacturing
Frigant and Layan (2009)	*Consideration of logistics costs (63)	Product ==> Inter-Firm	Automotive
Perrow (2009)	*Fight for being the first-tier supplier of leading firms (64)	Product ==> Industry	Electronics
Zirpoli and Camuffo (2009)	*Component specific knowledge (65) *Strategic objectives (66) *Organizational and technological capabilities (67)	Subsystem ==> Inter-Firm	Automotive
Argyres and Bigelow (2010)	*Competitive positioning strategies of firms (68)	Product ==> Supply Network	Automotive
Gokpinar et al. (2010)	*Ambiguity of subsystem complexity (69)	Subsystem ==> Intra-firm	Automotive
Gomes and Dahab (2010)	*Process interdependencies (product development and quality management) (70)	Product ==> Inter-Firm	Plastic Packaging
Lau et al. (2010)	*New module/component development (71) *Technological knowledge leakage and capture (72) *Project team size (73) *Supply chain efficiency (74)	Product ==> Supply Network	Electronics, Plastics
Pero et al. (2010)	*Product innovativeness (75) *Position of firm in supply chain configuration (76)	Product ==> Supply Network	Electronics
Brusoni and Prencipe (2011)	*To perceive the systematic nature of innovation in hand (77)	Subsystem ==> Inter-Firm	Aircraft engines
Chiu and Okudan (2011)	*Operational complexity and costs (78)	Product ==> Supply Network	Bicycle
Lau (2011)	*Integration of customer needs (79) *Knowledge leakage risk (80) *Lower product development time and great coordination requirements (81)	Product ==> Supply Network	Plastics, Electronics, and Toys
Zirpoli and Becker (2011)	*Performance Integration (82)	Product ==> Supply Network	Automotive
Caridi et al. (2012)	*Project innovativeness level (83)	Product ==> Supply Network	Furniture
Nepal et al. (2012)	*The need for more compatible suppliers for modular product (84)	Product ==> Supply Network	Heavy Industry, Automotive
Cabigiosu et al. (2013)	*Buyer's component technological knowledge (85) *Strategic orientation of buyer (86)	Subsystem ==> Inter-Firm	Automotive
MacDuffie (2013)	*Need of retaining the ability for system integration (87)	Product ==> Supply Network	Automotive
Persson and Ahlström (2013)	*Functional interdependencies across modules (88)	Subsystem ==> Intra-Firm	Automotive
Salvador and Villena (2013)	*Product and process innovativeness (89)	Product ==> Inter-firm	Electronics, Machinery, Transportation
Furlan et al. (2014)	*Component technological change rate (90)	Component ==> Inter-firm	Air-conditioning

While some papers listed in Table 10 explicitly reject the mirroring hypothesis, others acknowledge that a positive relationship may exist between PM and OM but only under certain conditions. It is also important to note that the findings and arguments of a considerable number of papers are based on the specific conditions of their studies. For example, Campagnolo and Camuffo (2009) replicate the study of Schilling and Steensma (2001) to examine the effect of industrial standards (high PM) on Italian manufacturing industries. The different characteristics of the Italian industrial system compared to the U.S. lead the authors to deny the role of the industrial standards (high PM) in the formation of modular organizations.

All in all, the reasons behind the criticisms can be interpreted as contextual-specific boundary conditions of the mirroring hypothesis. In other words, each study of the "critique" group tells in which particular context the mirroring hypothesis does not hold. Even if these conditions are highly fragmented, many of them point to the same underlying themes. It is therefore important to identify these common themes to single out the contingent factors of the mirroring hypothesis.

6. CONTINGENT FACTORS: A CITATION NETWORK ANALYSIS

We performed a citation network analysis to thematically cluster the criticisms revealed by the papers in "critique" group. This analysis makes possible to identify the main underlying contingent factors behind the criticisms, advancing a contingent view of the mirroring hypothesis.

6.1 Clustering

A network is a representation of the relationships between a set of nodes. Anything can be a node if the interaction between them is of interest for the researcher. For example, several recent reviews in management (Srivastava, 2007; Peteraf et al., 2013) have conducted network analysis on the bibliographies of papers to explore paths and groups on various phenomena.

While papers are nodes in these networks, citations are edges that represent the relationships between papers.

The criticisms numbered in Table 10 are the nodes of our network instead of whole papers, since many papers have more than one criticism. The aim of this study is to group criticisms whose oppositions to the mirroring hypothesis are based on thematically similar factors. At this point, the citation motives gain importance while linking two criticisms in the network (i.e. two nodes of our network). For example, some citation motives such as *identifying methodology, providing background reading, and alerting to forthcoming work* would not be evidence that the criticisms made by different papers indicate the thematically same factor against the mirroring hypothesis. Therefore, we only took into consideration in-text citations made with the following motives: *the paying homage, the giving credit, and the substantiating claims* (Nanba et al., 2011). These three citation motives show that while papers criticize the mirroring hypothesis due to the specific reason, they get support from other papers' relevant findings and claims.

We used the algorithm of Newman and Girvan (2004) to cluster the criticisms. This algorithm identifies communities, composed of highly interlinked nodes with loose connections with the rest of the network (Leskovec et al., 2008), using the network measure "*betweenness*". There is at least one shortest path across each pair of nodes. The more "*between*" an edge is, the higher number of times it is the part of the network's shortest paths. Accordingly, the absences of those edges are likely to partition the network into well-separated communities. The algorithm of Newman and Girvan (2004) iteratively removes the most "*between*" edge from the network and then recalculates the new betweenneess scores of the remaining edges. This process goes on until the point that another network measure "the modularity" reaches the peak level indicating that the separation of communities is at its maximum. Newman (2006, p. 8578) defines the measure of modularity as following: "Modularity is, up to a multiplicative constant, the number of edges falling within groups minus the expected number in an equivalent network with edges placed at random". Therefore, the value of modularity can be zero or even negative, which implies there is no certainty that all networks contain communities. Newman (2006) states that the network measure, i.e. *modularity,* should be between 0.3 and 0.8 for a meaningful network partition. Our network with a modularity value of 0.442 meets this condition.

6.2 Results: Contingent factors for the mirroring hypothesis

Our review detected 90 criticisms listed in Tables 10. The final network in Figure 2 consists of 49 criticisms having at least one citation link with others. The identity numbers (ID) adjacent to nodes identify each of these criticisms shown in Table 10. Although the edges between nodes of our network should be directed, we set them undirected to better identify communities in accordance with the suggestion of Newman and Girvan (2004). We used the software NodeXL to apply the algorithm, which detected 9 communities.

While five communities are thematically separated, the remaining four communities concern the same theme (i.e. innovativeness of product architecture). Thus, we identified 6 contingent factors shown in Figure 2. Each geographical shape in the network represents a distinct contingent factor. We labelled these 6 contingent factors as follows: i) component technologic change and diversity, ii) innovativeness of product architecture, iii) complexity of product architecture, iv) capability dispersion along the supply network, v) rivalry among leading firms & among suppliers, and vi) logistics costs. We now discuss each contingent factor in turn.

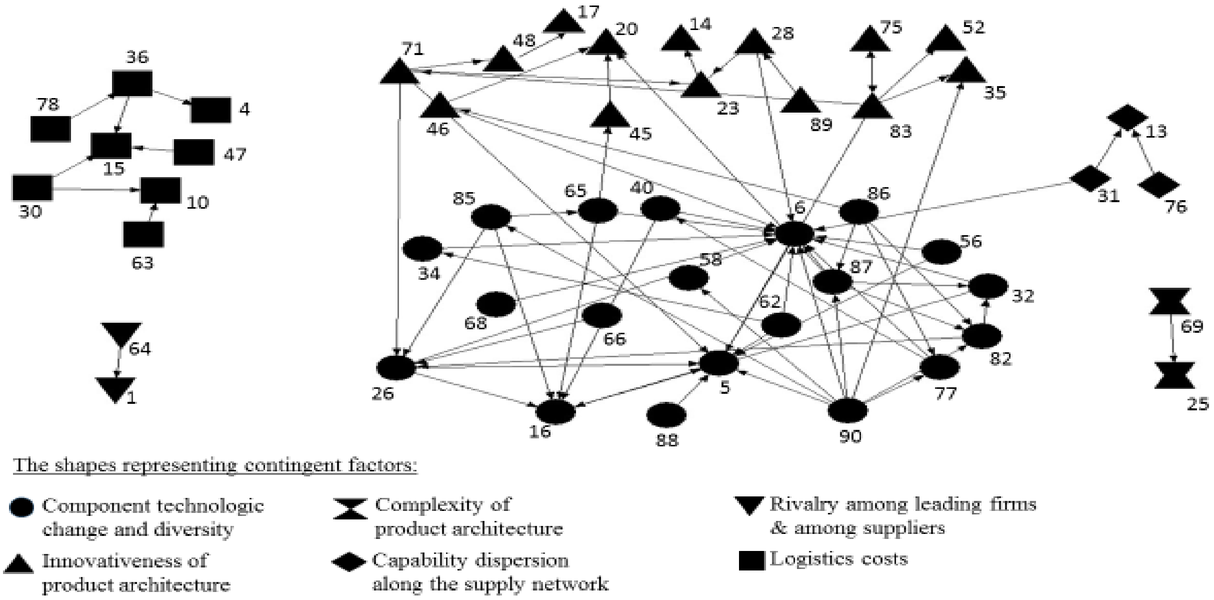

Figure 2 – Contingent factors for the mirroring hypothesis

6.2.1 Component technological change and diversity

The first contingent factor is related to the component technologic change and diversity. The common view of the papers drawing on this contingent factor confirms the mirroring hypothesis when the product's components present even, slow, and predictable technological change. This group emphasises the dysfunctions of organizational decoupling (high OM) in the presence of fast-changing component technologies even for modular products (high PM). Fast changing technologies create the need for system integration (low OM) to maintain the compatibility among all the components (Brusoni et al., 2001; Argyres and Bigelow, 2010). Moreover, it is essential for system integrators to have component-specific knowledge that can only be developed via close relationships with suppliers. As an example, Furlan et al. (2014) focus on the moderating role of the component technological change rate. Their empirical study on the air-conditioning industry reveals that modular components characterized by low component technological change are associated with low information sharing (high OM) between buyers and suppliers. On the other hand, in the presence of high component technological change, buyers and suppliers need to exchange information (low OM) even in the presence of modular components. The authors argue that high component technological change creates interdependencies that cannot be reduced by the modular architecture.

The wide diversity of component technologies in a product is another reason that leads to the coupling of the firms with their suppliers (Brusoni et al., 2001). For technologically complex products, system integrators need to harmonize an architectural knowledge with a wide range of component-specific knowledge maintained by distinct suppliers (Brusoni, 2005). Learning and close relationships with the supplier base are essential for the firms to maintain such architectural knowledge. First, collaboration ensures that firms can manage to cope with the difficulties that may arise from the differences in the technological evolution trajectories of components. Second, it allows system integrators to nurture their capability of new product development.

6.2.2 Innovativeness of product architecture

The innovativeness of product architecture is another contingency of the relationship between PM and OM. There is a fine but conceptually clear distinction between this and the previous contingent factor. While the previous one, i.e. component technologic change and diversity, indicates the technological novelty/diversity of each individual component of the product, innovativeness of product architecture refers to the novelty of the relationships between the components, i.e. the product architecture (Henderson and Clark, 1990). A novel modular architecture of a product may hide interdependencies that are not fully captured by the standardized interfaces between modules. Indeed, in innovative product architectures "the intended modularization and actual modularization do not necessarily match with hidden interdependencies lying side by side with visible ones" (Furlan et al., 2014; p. 791). Problems, unrealized and unpredicted interdependencies, are likely to arise over time (Ernst, 2005; Pero et al., 2010; Salvador and Villena, 2013), causing serious performance penalties (Ethiraj and

Levinthal, 2004). Therefore, uncertainties embedded in innovative architectures of modular products require higher system knowledge and close coordination to manage the resulting interdependencies (Puranam and Jacobides, 2006). This knowledge and coordination can be gained through higher integration between different units within the same organization or between different firms within the same supply network (low OM).

6.2.3 Complexity of product architecture

The complexity of product architecture might create situations with unexpected component interdependencies or intermediate centrality of subsystems. Two papers (Sosa et al., 2004 and Gokpinar et al., 2010) touching upon this contingent factor show how a high complexity of product's architecture inhibits organizational units to grasp the actual component interdependencies, causing lack of coordination, i.e. misalignments between PM and OM.

Sosa et al. (2004) use components' functional dependencies to measure the PM level and consider team interactions to measure the OM level. Their study on the development of an aircraft engine analyses the misalignments between PM and OM levels. Their results show that misalignments occur more frequently for functionally interdependent components that belong to different modules of complex products. For this type of component interactions, modular product architecture increases the ambiguity by creating thick organizational boundaries between teams that develop components of different modules (Sosa et al., 2004). This makes harder to identify functional interdependencies correctly between components (PM level), causing non-adequate team interaction (OM level).

Gokpinar et al. (2010) measure the modularity of subsystems with their centrality degree (how many interdependencies one subsystem has) using network analysis. Low subsystem centrality indicates high PM in congruence with the modular product architecture definition of Ulrich (1995) that a design change in one module does not require changes in others. Gokpinar et al.

(2010) utilize coordination level as the proxy for OM. The findings of this study reveal that the inability of organizations in adopting the necessary coordination level is higher for subsystems with intermediate centrality. Organizations concentrate and devote their coordination efforts to the central subsystems having many functional interdependencies with other subsystems (low PM), while they let the coordination of non-central, i.e. modular subsystems, to be carried out by standardized interfaces. For central and non-central subsystems, no misalignment occurs between PM and OM. The problems occur with the subsystems having an intermediate degree of centrality. For these subsystems, organizations have difficulty in providing the right amount of coordination. Since complex products have often subsystems with intermediate degrees of centrality, they are more likely to generate misalignments between PM and OM.

6.2.4 Capability dispersion along the supply network

This contingent factor emphasizes the potential negative effects of an excessive capability dispersion along the supply network. Such dispersion may in fact reduce the capacity of the firms to sense and seize new market trends. When the firms in a supply network are extremely specialized, they tend to follow completely different knowledge trajectories. The focus of each firm may become too narrow to recognize and seize market trends since they lack inclusive capabilities to align the whole product design with changing market needs (Gadde and Jellbo, 2002). In such a situation, a system integrator is needed to achieve a good environmental fitness of the whole supply network.

The example of the watch-making industry (Jacobides and Winter, 2005) is a case in point. Before the 1970s, Swiss firms specialized in single components (e.g. cases, straps) populated the industry. The emergence of the quartz movement technology caught all these firms unprepared. None of these Swiss firms was in fact able to appreciate and capture the commercial value of the new technology because of their scattered capabilities and excessive specialization. This case shows that system integrators and integration mechanisms (low OM) might be needed to canalize and align dispersed capabilities along the supply network of a modular product (high PM). For example, Airbus adopted integration mechanisms (e.g. joint design tools, project teams, and concurrent engineering) – to develop the model A380 even if it was made of modular subsystems. These integration mechanisms allow Airbus to align a large amount of dispersed capabilities along the supply network (Frigant and Talbot, 2005).

6.2.5 Rivalry among leading firms & among suppliers

Our analysis identifies the market rivalry as another contingent factor of the mirroring hypothesis. High PM may not be a sufficient factor to decouple firms (high OM) because of the high competition that can occur at different layers of the industry especially among leading firms to impose their own standard architecture within an industry and among suppliers to win business with the leading firms.

Consumers give more value to the products for which compatible products are available in a market. These effects are known as “indirect network externalities” (Economides and Himmelberg, 1995), which can be the source of a strong competitive advantage for the leading firms. As argued by Baldwin and Clark (1997), the existence of a race across the leading firms to impose their own standards within an industry urge them to be interested in the developments occurring at the other vertical layers of the industry. The authors suggest that managers of these leading firms should follow the innovations closely (low OM), even if such innovations regard the outsourced modules, in order to keep a tight control over their supply networks.

The competition to be suppliers of the leading firms may have similar effects. Perrow (2009) exemplifies this dynamic within the automotive industry. In order to win the business with large OEMs (original equipment manufacturers), a supplier has to prove that it is better than others in managing the interdependencies embedded in modules outsourced by OEMs. The more competing suppliers there are for a module, the higher incentive there is for the supplier to excel in this effort. To reach this objective, the supplier has to closely cooperate with its upstream suppliers leading to a highly integrated supply chain (low OM).

6.2.6 Logistics costs

The final contingent factor is related to the logistic costs. When transportation and inventory holding costs are significant, firms may choose to locate close to their suppliers (low OM) regardless the product architecture. The geographical proximity provides safe delivery, leanness, and lower transportation costs (Lau and Yam, 2005). Moreover, spatial proximity improves the sharing of demand information (low OM), enabling firms to better foresee demand fluctuations, thus reducing their safety stock level against stock-out risks. Finally, when it is prohibitively expensive to keep stocks of final products, product modularity is used to postpone the final assembly until the receipt of the customer order (Salvador et al, 2002). To successfully adopt these postponement strategies, high coordination and geographic proximity among supply chain partners (low OM) are needed (Howard and Squire, 2007).

7. CONCLUSION

This study contributes in several ways to the ongoing debate on the relationship between products and organizational architectures. First of all, our review provides the current state of the art of the studies dealing with the relationships between PM and OM. The surprising result is that the majority of the reviewed papers (69%) either reject the mirroring hypothesis or advance criticisms. Our review shows that the contrast between the “orthodox” and “critique” groups has been relatively strong since the beginning of 2000. Despite the substantial variability among the studies in terms of research design (levels of analysis, adopted OM and PM measures, and industry), we find that these differences do not have a significant impact on the position of papers in the “orthodox” group or in the “critique” group.

As a consequence, we rule out the possibility that different research settings might be responsible for the contrasting views on the mirroring hypothesis. On the contrary, we maintain that mismatches between product and organization architectures are caused by contingent factors that hinder the ability of modular product to shape modular organizations (D'Adderio and Pollock, 2014). These contingent factors therefore represent additional variables that intervene in the adjustment process between the architectures of products and organizations. As Whitford and Zirpoli (2014) argue, modularity theory (and the mirroring hypothesis) can be useful to explain how firms shape their (internal and external) relations under certain circumstances but not always. Over time, situations change, hence the relations and organizational boundaries of firms can be better explained by other theories (e.g. learning by monitoring, social embeddedness). The authors suggest the adoption of some form of "methodological situationalism". In other words, we need to theorize the contingent factors that may "hinder the translation of modular products into modular organizations" (D'Adderio and Pollock, 2014; p. 1814).

By carrying out a network citation analysis on the "critique" group, this study provides the first attempt to systematically categorize and discuss these contingent factors. We identify six contingent factors: i) component technologic change and diversity, ii) innovativeness of product architecture, iii) complexity of product architecture, iv) capability dispersion along the supply network, v) rivalry among leading firms & among suppliers, and vi) logistics costs.

While we discussed the specific theoretical arguments behind each of these contingent factors in the previous section, here we stress the general implications that a contingent view has for the modular theory of the firm. We follow Baldwin (2008) that defines production systems as networks in which the nodes are the tasks-cum-agents while the linkages are transfers of material, energy and information. Transactions are defined as "mutually agreed-upon transfers with compensation and are located within the task network." (Baldwin, 2008; p.155). Since placing a transaction in a particular location generates costs to define, count, and pay for the transacted objects, the firms tend to locate transactions at the thin crossing points of the task network, i.e. the module boundaries, where these costs are low.

Baldwin's (2008) theory assumes that the structure of the network can be manipulated by the agents' modularization strategy. As the author argues "regardless of their intended purpose, modularizations create new module boundaries with low transaction costs" (p.175). On the contrary, we maintain that the presence of contingent factors identified in this review increases the thickness of the crossing points regardless the modularization efforts of the agents. Our review shows that the contingent factors generate complex (expected or unexpected) interdependencies that make the transfers complex, numerous, and interdependent even at the module's boundaries. An enhanced thickness of the crossing points increases "the advantages of formal and relational contracts over spot transactions and of relational contracts over purely formal contracts" (p.157).

We maintain that, while modularization is a sufficient condition to reduce the task interdependencies between nodes, it might be insufficient to reduce agents' interdependencies (Puranam et al., 2012). Regardless the structure of tasks' interdependencies, the presence of contingent factors might create situations where the rewards of one agent depend on the action of another agent thus generating situations of symmetric or asymmetric inter-agent interdependencies. Using the terminology of Puranam et al. (2012), the contingent factors might generate substantial epistemic interdependencies among agents even at the module's boundaries. To manage these interdependencies, agents have to perform information processing activities such as communication, mutual observation, learning, and (joint) decision making. In other words, they have to couple their organizations even if the transacted artefacts are modular.

We believe that our review might provide some contributions also to practitioners. Knowing under which situations the product design becomes a tool to shape organizations is important for organizational designers. Following the mirroring hypothesis, firms organize their R&D or manufacturing activities as a function of product design placing organizational boundaries at the product' modules boundaries. We caution managers to take into considerations also the contingencies identified in this review. In particular, they should carefully analyse the presence and strength of these contingent factors and their impacts on the optimal organizational design.

8. LIMITATIONS

This review has several limitations although it employs objective techniques both in the phase of sample selection and in the thematic clustering of the contingent factors. First, some authors have more than one paper in the sample. This might have introduced some distortions in the distribution of papers between the "orthodox" and "critique" groups. To minimize this effect, we excluded the same author's studies if their results were based on the same empirical data. Second, our six contingent factors may not be the only ones. Future studies might explore other contingent factors. Finally, even if our contingent factors are conceptually distinct, they are highly interdependent. For example, a high component technological change and diversity is normally associated with a high dispersion of capability along the supply chain. If we assume that contingencies need to be independent, then it might be possible to reduce them after careful empirical verification.

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FOOTNOTES

[1] Our finding indicates a lower support than the finding of Colfer and Baldwin (2010) where 48% of the analysed studies purely supports the mirroring hypothesis. This difference might be due to the fact that while Colfer and Baldwin (2010) focus on the effect of OM on PM, we examine the opposite relationship (the effect of PM on OM).

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THE EFFECT OF PRODUCT MODULARITY ON SUPPLIER RELATIONS: A MULTI-OBJECTIVE APPROACH

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ABSTRACT

This research aims to uncover the set of conditions that modular products lead to modular supply relationships. According to the mirroring hypothesis, the features of modular product architecture act as the coordination mechanism. Thus, firms can establish modular relationships with their suppliers, leading to the reduced coordination costs. However, the mirroring hypothesis has received partial support from the following studies. The criticisms directed to the mirroring hypothesis stem from its overlooking other operational factors playing a part in supplier relationships. The persistency of contradiction between the findings of studies calls for an analysis at a larger scope. For this reason, this research develops the mathematical model with multi-objective approach, considering many relevant contingent factors simultaneously. The numerical example applied shows a set of conditions for which the mirroring hypothesis holds, verifying the appropriateness of getting contingency approach to discuss the validity of the mirroring hypothesis. This study unveils the theoretical and practical relevance of the results as well.

Keywords: modularity, supplier relations, supply chain, supplier integration, multi-criteria decision making.

1. INTRODUCTION

Firms are limiting their scope of production to the components just related to their core competencies, which increases the portion of the components they outsource. Hence, the way firms establish their supplier relationships has more effect on their costs, new product development processes, and product performance. At this point, the aim of firms is to find the optimal supplier integration level on the decision continuum**,** the extreme points of which are arm's-length relationship and vertical integration (Lambert *et al.*, 1996). For the best decision, firms should be aware of the trade-offs between the points along this continuum.

The recent body of research has attempted to reveal the factors on which the ideal supplier integration level should depend after understanding that the increase in the level of supplier integration does not necessarily give better outcomes (Das *et al.*, 2006). For example, the levels of supply complexity (Gimenez *et al.*, 2012) and social capital (Villena *et al,* 2011) have been shown as the factors that should be considered to determine the integration level with suppliers. Similarly, modularity theory (Baldwin, 2008) focuses on the ideal supplier integration level. Accordingly, firms should integrate with their suppliers to the extent that their tasks are interdependent on the tasks of their suppliers. The technical interdependencies across the components, resulting from the product architecture design, largely determine the degree of task interdependencies with suppliers.

Product modularity (PM) is the term used to indicate the degree of technical interdependencies between the modules of a product (Schilling, 2000). Sanchez and Mahoney (1996) assert that the level of PM affects the design of organizations, i.e. the level of organizational modularity (OM). Respectively, the reduced technical interdependencies in modular products decrease the coordinative needs across firms, enabling them to form modular organizations (Cabigiosu and Camuffo, 2012). Colfer and Baldwin (2010) entitle this positive link as "the mirroring hypothesis" based on the empirical evidence that the levels of PM and OM mirror each other in the 69 % of the 102 cases they review.

The cases reviewed by Colfer and Baldwin (2010) include different analyses levels of organization, which are "within firm", "across firm", and "open, community-based projects". This research is interested in "across firm" analysis level, i.e. supply chain. There are supporting findings to the conjecture of the mirroring hypothesis at supply chain level as well: "modular products tend to be produced by modular (highly dispersed geographically and culturally, with few close organizational ties, and modest electronic connectivity) supply chains" (Fine *et al.,* 2005, p. 392).

However, the mirroring hypothesis has received partial support from the other body of studies. It has been subject to the criticisms because of its overlooking other operational factors that play a part in the type of relationship established with suppliers. Modular product may induce firms to form modular relationships with their suppliers in order to reduce the excessive coordination costs. Though, the relationship between PM and OM is not straight forward as hypothesised, according to the group of papers assuming a critical position. Despite a modular product, these papers put forward the factors that urge firms to couple with their suppliers (low OM), which are mainly related to the implementation of efficient logistics activities (Jacobs *et al.* 2007; Howard and Squire, 2007), the development of innovative product (Sabel and Zeitlin, 2004; Lau and Yam, 2005), and the accomplishment of efficient production (Frigant and Talbot, 2005; Tiwana, 2008).

The persistent contradiction across the findings of studies on the PM-OM relationship over a long time requires an analysis at a larger scope. Since the idiosyncratic features of the research contexts have effects on the findings, the empirical research based on single case study and/or industry are not sufficient to make general judgements on the mirroring hypothesis. Whereas the research conducted in the context where coordination costs are significant may give credit to the mirroring hypothesis, another one carried out in the context where logistics costs are significant may oppose to the mirroring hypothesis. For example, the multiple case study of Pero *et al.* (2015), examining the construction and shipbuilding industries, get different findings on the relationship between PM and supply chain integration (OM) due to the various contingencies identified. Therefore, the results of previous research affected by the particular contextual factors can only explain the PM-OM relationship partially. The authors of this study agree with the point of view that specifying under which conditions the mirroring hypothesis holds is more important than debating about whether it holds or not (Furlan *et al.*, 2014). This acknowledgement calls for more analytical studies taking into account many contingent factors simultaneously, being able to explain the full-extent of the relationship between PM and OM.

The aim of this research is to uncover the set of conditions that modular products (high PM) lead to modular supply relationships (high OM). The model developed based on multi-objective mixed integer program (MOMIP) considers four objectives, each of which indicates different optimal supplier integration level (OM level). They are namely: i) minimizing coordination costs, ii) minimizing inventory-carrying costs, iii) maximizing innovative outcomes, and iv) maximizing production efficiency. To draw the whole picture of the PM-OM relationship pattern, this research derives the efficiency frontier of these four objectives by identifying the nondominated points that show the set of conditions under which the mirroring hypothesis holds.

The large perspective of this research provides the results having important theoretical and practical implications. The results support the contingent approach arguing that the context specific factors determine whether the mirroring hypothesis holds or not. The findings of this research show that the mirroring hypothesis holds only if the coordination costs either is the top objective of the firm or it is the primary objective but equally with inventory-carrying costs. Another major contribution of this paper is that firms should adopt the one of three following supplier relationship patterns depending on the priorities of their objectives, which are i) the decoupling from suppliers to the extent that the technical interdependencies of product (PM level) allow, ii) the considerable cooperation with suppliers, making the most improvement to the objectives of reducing the inventory-carrying costs and of increasing the production efficiency, and iii) the full integration with suppliers to promote innovative outcomes.

The outline of the paper is as follows: Section 2 covers the relevant arguments and findings of the previous studies that underpin the research model. Section 3 explains the methodology followed. Then, Section 4 describes the mathematical formulation of the research model in detail. Section 5 develops an instance to apply the mathematical model, and presents the results obtained. Finally, Section 6 concludes the paper by discussing the theoretical and managerial implications of the results.

2. LITERATURE REVIEW

This section first gives the definitions of modularity in products and supply chains. Subsequently, it reveals the implications of the PM level on each of the four objectives considered in this research: i) coordination costs, ii) inventory-carrying costs, iii) innovative outcomes, and iv) production efficiency. Eventually, the last subsection covers the arguments of studies asserting that the latter three objectives require firms to integrate with their suppliers (low OM) despite modular product.

2.1. Modularity in products and supply chains

Modularity is the property of system design (MacDuffie, 2013). The system is the collection of subassemblies that work jointly for the pursuit of system goals. By this definition, both products and supply chains are systems (Schilling, 2000). While products are made of different components to carry out the functions of products for satisfying the consumer needs, supply chains consist of different firms that aim to deliver goods and services efficiently at the right time, place, and form to the end customers (Wang *et al.*, 2004). The level of interdependencies among the subassemblies of system, needed to accomplish its goals, determine the modularity level of systems. Whereas the ones characterized by low level of interdependencies are called modular, the others characterized by high level of interdependencies are called integral (non-modular) systems. Each of these types provides different advantages. While few interdependencies in modular product ease the reconfiguration and recombination, high interdependencies in integral products enable to maximize the collective synergy.

The product modularity level, shows the decoupling degree between the modules of a product (Schilling, 2000). High PM refers to that there are few spatial, structural, and material interdependencies across modules (Sosa *et al.*, 2003) because each module is responsible for one separate product function in modular product architecture (Ulrich, 1995). The standardized interfaces of modular products embed the remaining interdependencies across modules in the codified form (Sanchez and Mahoney, 1996). In contrast, integral product architecture (low PM) refers to the tightly coupled modules. Modules are jointly responsible for implementing each product function. As a consequence, the design change in one module entails the significant changes in other modules (Ulrich, 1995).

The organizational modularity indicates the decoupling degree between organizational units. Supply chain modularity is the analysis level of OM, showing the decoupling degree of different firms within the same supply chain. This decoupling (OM level) is the inverse measure of the geographic, organizational, cultural, and electronic proximity between firms within the same supply chain (Fine *et al.*, 2005). The organizational proximity, the measure with which this research operationalizes the OM level, is a function of the information sharing level with suppliers for the product development and logistics processes (Furlan *et al.*, 2014).

2.2 Implications of the product modularity level

Firms do not only have the dyadic relationship with each of their suppliers but they are also responsible for synchronizing the activities across suppliers, which may incur huge coordination costs. High PM level makes the savings in coordination costs by enabling firms to form modular relationships with their suppliers. Since each module carries out a separate product function in modular product architecture, firms do not need to keep in contact with their suppliers frequently for the concern that the modules outsourced to suppliers create a problem for the implementation of the relevant product functions. Moreover, modular products have the standardized interfaces in which all interdependencies between modules are specified ex-ante. This standardization ensures the compatibility and quality of the modules outsourced, decreasing the need for monitoring the activities of the suppliers closely (Hoetker *et al.*, 2007). In addition, once firms and their suppliers plan to make a design change in the modules they produce, the rules codified into the standardized interfaces draw the boundaries of the possible design change without affecting other modules (Sanchez and Mahoney, 1996). This feature of modular product eliminates the excessive amount of inter-firm interactions needed to manage the complicated effects of the design change in one module on the others. As a result, firms benefit from modular products to reduce coordination costs, which act as the auto-coordination mechanism.

The postponement is an important advantage that modular product architecture provides. The postponement, referring to the delaying activities, has positive effects on the efficiency of logistics activities, especially on inventory costs (Yang *et al.*, 2004). The customization of product to the customer specific needs enables firms to expand their market share, however, increases their operational costs too (Salvador *et al.*, 2002). The decomposable nature of modular products allows firms to postpone the final product assembly. That is to say, firms do not need to keep many product variants at the costly final product level based on their demand estimate (Liao *et al.*, 2013). They can source modules after customers make an order (Kristianto and Helo, 2015), Then, by mixing and matching the modules, they can easily address the customized needs of their customers with fewer inventory.

The other positive effects of product modularity (PM) on the inventory-carrying costs stem from the decreased number of stock keeping units and the lower supply disruption risk. First, modular products allow firms to satisfy the product variety with fewer stock-keeping units compared to integral products (Ulrich, 1995). Hence, firms are able to produce savings in inventory costs by the means of reduced modules' safety stock (Zhou and Grubbström, 2004). Second, the visible rules in modular products provide more sourcing alternatives to firms in case of any material supply disruption (Kleindorfer and Saad, 2005). Thereby, the higher number of sourcing alternatives, as firms possess modular product, eliminates the preoccupation against the supply disruption risk that may have caused firms to keep excessive levels of safety stock.

Current competitive market conditions compel firms to develop innovative products within short time intervals. Modular products are favourable regarding this concern because they enable parallel work, therefore, firms can quickly introduce novelties over the small changes in existing modules (Pil and Cohen, 2006; Pero *et al.*, 2015). Besides, the ease of recombining modules in modular products is another factor that facilitates to deliver innovative product solutions to customer needs. On the other hand, high PM boosts the radical product innovation as well, in which the technology that links the core components of product changes significantly (Henderson and Clark, 1990). The decomposed nature of modular product extends the knowledge search by leveraging the specialization related to different modules (Ethiraj, 2007). The integration and reconfiguration of these knowledge domains facilitate radical innovations (Bouncken *et al.*, 2015). The empirical study on Chinese firms in high technology industries by Hao *et al.* (2015) confirms that high PM gives rise to radical innovations.

The production efficiency improves in correspondence with the increases in the level of output per input (Avkiran, 2001). In contrast to the inventory-carrying costs and innovative outcomes, it is difficult to state precisely the way that the PM level affects production efficiency because of the existing two different viewpoints explained below.

One view asserts that integral products are superior to modular ones regarding the production efficiency. Accordingly, integral product architecture gives better overall product performance because it makes more feasible to exploit the synergy between components (Schilling, 2000; Ethiraj and Levinthal, 2004). Additionally, the integral products provide cost advantage too. The non-existence of standardized rules in integral products allow firms to minimize the size and mass of components (Ulrich, 1995).

The other view argues that modular product architecture yields more production efficiency. First, it provides local performance advantage because firms only focus on increasing the performance of their own module without considering other modules (Ulrich, 1995). Second, it has a positive impact on output control (Tiwana, 2008). Since modular product architecture refers to one-to-one mapping between modules and functions, it is easier for a firm to identify the supplier responsible for product failures and quality problems. Therefore, the quality problems due to the opportunism risk decrease with modular product (Hoetker, 2006). Modular product architecture also provides the cost advantage because the unit cost of standardized components is lower through the economies of scale effect (Jacobs *et al.*, 2007).

This research gives credit to these two viewpoints because the production of both modular and integral products may become more efficient subject to the contextual and contingent factors. Therefore, the research model of this study conjectures neither positive nor negative effect of the PM level on production efficiency.

2.3 Why may modular product not lead to modular supply relationships?

This section gives place to the criticisms to the proposition that modular product design is sufficient for firms to decouple from their suppliers (high OM). These criticisms do not reject that modular products have the properties that decrease the inter-firm managerial effort, hence coordination costs. Instead, they argue that firms have to integrate with their suppliers (low OM) despite modular product because of the three following concerns: inventory-carrying costs, innovation, and production efficiency.

The previous subsection describes the ways modular products can decrease the inventory-carrying costs. However, benefiting from modular product for this purpose also conditions the high levels of coordination and collaboration (low OM) with suppliers. For instance, the Just-in-Time is the production philosophy that aims to cancel out any held inventory. The examples in which this philosophy is executed for the modular production show that firms encourage their suppliers to locate within their production sites to reinforce the collaboration (low OM). Similarly, the objections to the mirroring hypothesis assert that low OM is necessary condition for minimizing inventory-carrying costs regardless the PM level. Modular products allow firms to postpone the assembly by sourcing modules from their suppliers after customers make an order (Liao *et al.*, 2013). Nevertheless, if firms do not share the demand information continuously with their suppliers (low OM), they cannot supply the modules on time in case of a significant change in demand (Lee *et al.*, 2000). Thereby, insufficient coordination with suppliers compel firms to keep excessive inventory for keeping their customer service level high. Lau *et al.* (2010) supports this argument based on their case study, illustrating that the case firm having modular product need to be in on-going communication with their suppliers to ensure on-time deliveries.

The inter-firm coordination and collaboration (low OM) are the important drivers of high innovative performance (Ahuja, 2000; Faems *et al.*, 2005; Soosay *et al.*, 2008). Many criticisms directed to the mirroring hypothesis point out that low OM is necessary during both the pre-design and post-design phases of innovative modular products (Lau and Yam, 2005). The product development teams attempt to codify all possible interdependencies across modules ex-ante to standardize the interfaces of modular products. Though, for innovative modular products, it is more difficult to codify these interdependencies in advance due to the novelty of links between modules. As a result, innovative modular products entail the collaborative work with suppliers (low OM) considering that unexpected interdependencies across modules are more likely to arise in time (Ernst, 2005; Pero *et al.*, 2010; Salvador and Villena, 2013). Thus, the firm has to act as system integrator in supply chain (Brusoni *et al.*, 2001) to manage the resulting unforeseen interdependencies (Puranam and Jacobides, 2006). Such integration mechanism is also important for the product research and development activities because the specialization of firms in distinct modules may bring cognitive limits, inhibiting the innovations. Instead, the supplier integration (low OM) allows firms to harmonize their product architectural knowledge with the component-specific knowledge, resulting in successful innovations (Brusoni, 2005).

The supplier integration (low OM) advances both product performance and cost control (Lo and Yeung, 2004). In this regard, the objective of maximizing the production efficiency casts doubts on whether the modular product design is sufficient to establish modular relationship with suppliers (high OM).

It could be argued that high PM renders each module responsible for one separate product function; thereby, the arm's-length supplier relationship (high OM) would not be an obstacle for maximizing the product performance. However, Zirpoli and Becker (2011) draw an attention to the fact the product can be decomposed into the components, however, it is not possible to decompose the performance of whole product that these components jointly provide. For example, the speed is the performance parameter of the car which depends on both engine and tyres. Even if the physical and functional separation of these two components are clear, their compatibility is crucial for attaining the expected product performance. Respectively, Ethiraj (2007) stresses the performance bottleneck risk for modular products. Some components might have shown much better performance if the suppliers of other components adopted and upgraded their components in parallel. Therefore, since functional interdependency and performance interdependency refer to different issues, one-to-one mapping between modules and functions in modular product architecture may not be a remedy for performance integration without the joint work with suppliers (low OM).

The decoupling from suppliers (high OM) also affects the cost performance negatively despite modular product. As firms do the outsourcing through the arm's-length relationship, their component-specific knowledge erodes in time (Takeishi, 2002). Such lack of knowledge makes more difficult for firms to assess their suppliers' cost-effectiveness. As a result, the opportunism risk may arise, referring to that suppliers do not give their best effort for cost reduction.

Figure 1 illustrates the research model based on the arguments highlighted in this section. The signs adjacent to the dashed lines show the ways that the PM level affects the OM level, the inventory-carrying costs, and the innovative outcomes. The signs adjacent to the straight lines indicate the ways that the OM level affects the four objectives considered in the model. .

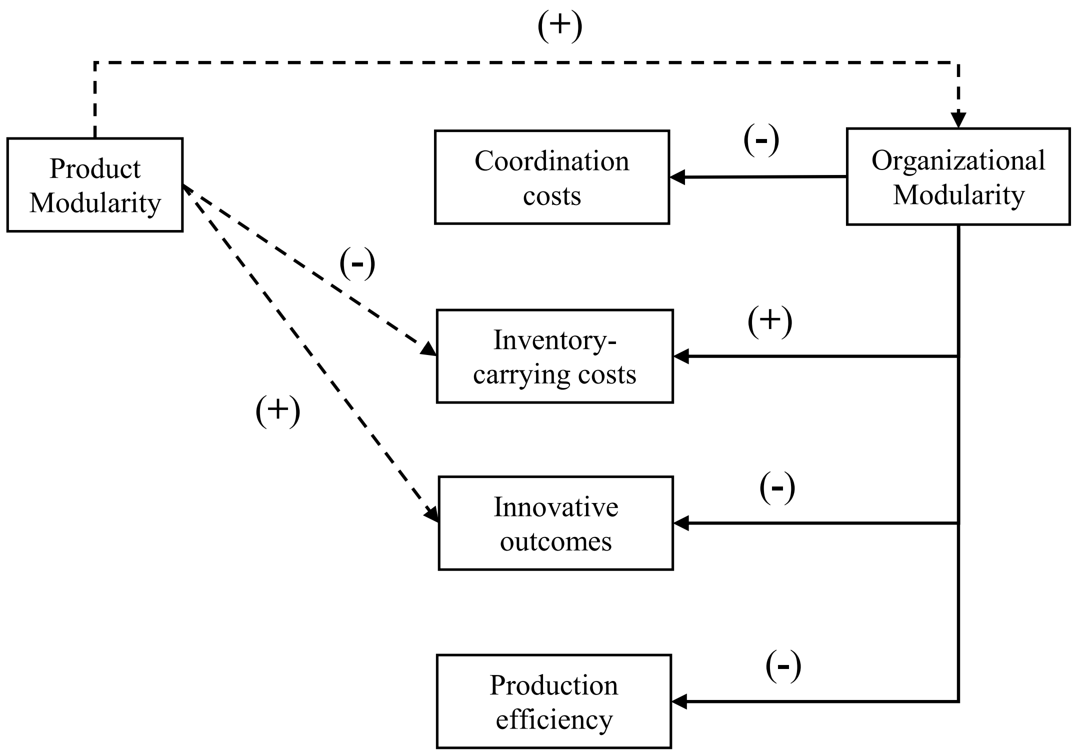


Figure 1 – Research model

3. METHODOLOGY

The main aim of this research is to show the set of conditions that modular products (high PM) lead to modular supply relationships (high OM). For this purpose, the mathematical model developed based on multi-objective mixed integer program (MOMIP) finds the optimal OM level depending on the priorities of objectives considered. The optimal level of OM found by the model shows whether the level of OM is around the level of PM (parameter of the model), i.e. shows whether the mirroring hypothesis holds or not. While the model operationalizes the OM level as the inverse measure of the information sharing level with suppliers for the product development and logistics processes (Furlan *et al.*, 2014), it operationalizes the PM level as the inverse measure of the technical interdependency degrees between modules of the product (Schilling, 2000).

The model includes the following four objectives, each of which indicates different optimal supplier integration level (OM level) for the given PM level: i) minimizing coordination costs,

ii) minimizing inventory-carrying costs, iii) maximizing innovative outcomes, and iv) maximizing production efficiency. Since the importance (weights) of these four objectives differs from context to context, this research aims to show the degree to which the mirroring hypothesis can be generalized. Hence, the algorithm of Özpeynirci and Köksalan (2010) is applied to find the all extreme supported nondominated points by changing the weights of the objective functions in a systematic way. This algorithm is a generalization of Aneja and Nair's (1979) algorithm designed for biobjective problems. It provides the set of nondominated points forming the efficiency frontier of the objectives, on which none of point is less preferable. Hence, they give the set of conditions under which the mirroring hypothesis holds. In Appendix A, there is a detailed description of the terms related to the multiple criteria decision making.

The mathematical model incorporates the supplier selection problem because of the following methodological motivation. Considering that each of four objectives in the model favours distinct supplier capabilities, firms select their suppliers having the capabilities more relevant to their high-priority objectives (Chai and Ngai, 2015). This implies that the values of firms' objectives are the functions of the capabilities of suppliers selected. Thus, the supplier selection setting allows the model to switch the suppliers selected, as the weights of four objectives change. This setting allows to explore of the extents of the possible relationships between PM and OM by expanding the search space. The alternative setting, to answer the questions of this study, could be fixing the suppliers and then investigating the different relationship types with them. However, such setting would not provide as great search space as the setting of several supplier alternatives with different characteristics enables.

4. THE MODEL

4.1 Notation

The notation used to depict the model's sets, parameters and decision variables is as follows:

Sets

m, h: modules of product; $m, h = 1,\ldots, M$

s: suppliers; $s = 1,\ldots, S$

Parameters

PM: product modularity level, $PM \in [PM_{min}, PM_{max}]$ where PM_{min} and PM_{max} are the minimum and maximum values in a range that PM may take respectively.

$Ommax_m$: the maximum OM level which does not cause any product failure for the module m

$$E_{ms} = \begin{cases} 1, & if\ supplier\ s\ is\ eligible\ to\ produce\ module\ m, \\ 0, & otherwise. \end{cases}$$

$Inform_s$: the quality of the information shared with supplier s

$Homl_s$: the highest allowable OM level with supplier s for the minimum inventory-carrying cost

Inv_s: the additional inventory-carrying cost if supplier s is selected

k_1: the reducing effect of PM on inventory-carrying costs $k_1 \in [0,1]$

Ic_s: the innovative outcome derived from the selected supplier $s \in S$

k_2: the boosting effect of PM on innovative outcomes $k_2 \in [0,1]$

Pe_s: the production efficiency of the selected supplier $s \in S$

$Homp_s$: the highest allowable OM level with supplier s for the maximum production efficiency

ϵ: a small positive number

B: a large number

The instance specific ϵ and B values are provided in subsection 4.2.

Binary Variables

$$X_{ms} = \begin{cases} 1, & if\ module\ m\ is\ assigned\ to\ supplier\ s, \\ 0, & otherwise. \end{cases}$$

$$Y_s = \begin{cases} 1, & if\ \ supplier\ s\ is\ selected, \\ 0, & otherwise. \end{cases}$$

Positive Variables

$R_{s:}$ the *OM* level (the inverse measure of information sharing level) with supplier s, $R_s \in (0,1)$

$G_{s:}$ the *OM* level indicator used to compute the inventory-carrying costs of suppliers

$$G_s = \begin{cases} R_s, & if\ R_s\ \geq Homl_s, \\ Homl_s, & otherwise. \end{cases}$$

$Q_{s:}$ the *OM* level indicator used to compute the production efficiency of suppliers

$$Q_s = \begin{cases} R_s, & if\ R_s\ \geq Homp_s, \\ Homp_s, & otherwise. \end{cases}$$

All three positive continuous variables – R_s, G_s, and Q_s – indicate the optimal *OM* level but in different scopes. While R_s illustrates the optimal *OM* level for the objective function vector, G_s and Q_s link the optimal *OM* level to the specific objective functions; G_s for inventory-carrying costs, and Q_s for production efficiency. This is because the decrease in the *OM* level has no marginal contribution to those objectives beyond some critical point ($Homl_s$ for inventory-carrying costs; $Homp_s$ for production efficiency). Therefore, R_s, G_s, and Q_s are of equal values above these critical points. However, the optimal levels indicated by G_s and Q_s fix respectively to $Homl_s$ and $Homp_s$ when R_s points out the optimal *OM* level lower than these critical points.

4.2 The mathematical model

The mathematical model is as below:

$$Max\ Z = (Z_A, -Z_B, Z_C, Z_D) \quad (1)$$

$$Z_A \leq R_S + (\varepsilon \times Inform_S) \qquad s \in S \quad (2)$$

$$Z_B = \left[(1 - k_1) \times \left(\frac{PM - PM_{min}}{PM_{max} - PM_{min}}\right)\right] \times \left[\sum_{s \in S}[Inv_s \times (G_s - Homl_s \times Y_s)] - \sum_{s \in S}[Inv_s \times (1 - Y_s)]\right] \quad (3)$$

$$Z_C = \left[(1 + k_2) \times \left(\frac{PM - PM_{min}}{PM_{max} - PM_{min}}\right)\right] \times \sum_{s \in S} Ic_s \times (1 - R_s) \quad (4)$$

$$Z_D = \sum_{s \in S}[(Pe_s \times Y_s - Q_s + Homp_s] - \sum_{s \in S}(1 - Y_s) \times (Homp_s - 1) + \sum_{s \in S} \varepsilon \times Homp_s \times Y_s \quad (5)$$

The objective function vector (1) maximizes the overall utility, regarding four objectives Z_A, Z_B, Z_C and Z_D.

Objective Z_A (i.e. the minimization of coordination costs) maximizes the minimum R_s among the suppliers selected $s \in S$ in the equation (2). Thereby, Z_A could have also been named "the maximization of *OM*" because high *OM* refers to modular relationship with suppliers, leading to lower coordination costs. This is the reason why objective Z_A has a positive sign in the objective function vector in the equation (1), even if it is called "the minimization of coordination costs". Additionally, the multiplier value ϵ in the equation set (2) ensures that when the model is indifferent to select the supplier among the eligible ones with the same R_s value, it breaks the tie considering the parameter $Inform_s$ indicating the quality of information shared with the supplier.

Objective Z_B minimizes the inventory-carrying costs. The second term of the equation (3) aims to bring the selected supplier's G_s (*OM* level) down to the level ($Homl_s$) that denotes the minimum reachable inventory-carrying costs with that supplier, where it is assumed that the respective supplier always makes the delivery on-time. The first term of the equation (3) provides the decrease in inventory-carrying costs as the *PM* value goes up.

Objective Z_C maximizes the innovative outcomes in the equation (4) when R_s (*OM* levels) of the selected suppliers fall down. The higher *PM* value has a positive impact on the objective Z_C similar to that on Z_B.

Objective Z_D maximizes the production efficiency in the equation (5) to the extent that Q_s (*OM* levels) of suppliers come close to the $Homp_s$ that represents the *OM* level, the below of which an additional supplier integration provides no further improvement to the production efficiency. Besides, when more than one supplier provides the same production efficiency, the multiplier value ϵ imposes the model to select the supplier with which the production efficiency is maximized with less information sharing, i.e. lower coordination costs.

The constraints of the model are as below:

$$\sum_{s \in S} Y_s = M \qquad (6)$$

$$\sum_{s \in S} E_{ms} \times X_{ms} = 1 \qquad m \in M \qquad (7)$$

$$\sum_{m \in M} X_{ms} = Y_s \qquad s \in S \qquad (8)$$

The constraint (6), and the constraint sets (7) and (8) regulate rules for supplier selection. First, the constraint (6) assures that the number of selected suppliers is equal to the number of modules forming a product. The constraint set (7) assigns one supplier $s \in S$ for each module

$m \in M$ among the eligible suppliers. Eventually, the constraint set (8) links the decision variables X_{ms} and Y_s, therefore, it warrants that a supplier $s \in S$ is an active supplier if the model selects it for a module $m \in M$. Besides, this constraint set (8) guarantees that a supplier $s \in S$ cannot provide more than one module $m \in M$.

$$\epsilon \leq R_s \leq 1 \qquad s \in S \qquad (9)$$

$$1 - Y_s \leq R_s \qquad s \in S \qquad (10)$$

$$R_s \leq PM + B \times (1 - Y_s) \qquad s \in S \qquad (11)$$

$$R_s \leq (1 - Ommax_m) + B \times (1 - X_{m,s}) \qquad s \in S, m \in M \qquad (12)$$

The constraint sets from (9) to (12) specify the range of R_s, (*OM* level) with supplier $s \in S$. The constraint sets (9) and (10) secure no relationship with non-selected supplier $s \in S$ by fixing their R_s values to 1. For the selected supplier $s \in S$, the constraint set (9) provides that the lower bound of R_s is not zero, but a small positive value ($0 < \varepsilon < 0.001$). The constraints sets (11) and (12) determine the upper bound of R_s for the selected suppliers in accordance with the technical requirements of the product. This upper bound for *the OM* level eliminates the product failure risk due to the lack of information sharing. In other words, it guarantees that the *OM* level does not exceed the *PM* level. The constraint set (12) relaxes this upper bound for non-selected suppliers with the help of sufficiently large number *B*, therefore, the R_s values of the non-selected suppliers are equal to 1. Note that, the setting $B \geq 1$ is sufficient for the model.

5. AN EXPERIMENTAL STUDY

This section conducts an experimental study on a numerical example. It first presents the experimental setting, and then reports the computational results.

5.1 The experimental setting

The numerical example of this study has been designed regarding the "modular consortium" production system in which "the plant is divided in modules that are operated by contracted companies" (Salerno et al., 1998, p.56). Accordingly, Original Equipment Manufacturer (OEM) does not directly involve into any manufacturing process (Frigant and Lung, 2002). Its role is only to coordinate the tasks of their suppliers and then assemble the modules outsourced to these suppliers.

The numerical example assumes a product consisting of four modules. Note that the number of modules has been determined arbitrarily. It is trivial to modify the example with a product composed of any number of modules. The formulation of this product's *PM* level aligns with the definition of Schilling (2000), according to which the decoupled modules refer to the high *PM* level. In other words, the *PM* level increases as there are fewer technical interdependencies $\alpha_{m,h}$ between modules $m,h \in M$. In order to assure that the extreme technical interdependencies do not manipulate the final *PM* level, the formula also regards the highest technical dependency of each module $m \in M$ to other modules, $maxi_m = \max_{h \in M}\{\alpha_{m,h}\}$. The formulation of the *PM* level is as below:

$$PM = 1 - \left[\frac{\sum_{h,m \in M} \ a_{m,h}}{|M| \times (|M|-1)} + \frac{\sum \underset{h}{maxi}\, \boldsymbol{\alpha}_{mh}}{[M]}\right] / 2 \quad \text{where} \quad \boldsymbol{\alpha}_{mh} \sim \text{Uniform}\ (0.001, 0.5)\ .$$

The OEM needs to exchange information with their suppliers to manage the technical interdependencies between modules. Accordingly, the *OM* level inversely indicates the information sharing level between the OEM and its suppliers to provide the level of coordination required. As noted in the model (Section 4), the *OM* level with a supplier cannot exceed the highest technical interdependency of the respective outsourced module because of the concern that the lack of information sharing may cause a product failure.

It is necessary to keep the *PM* level sufficiently high in the experiments considering that the aim of this research is to investigate whether modular products lead to modular supply relationships. Besides, high *PM* level enables observing the full extent of downward deviation of the *OM* level from the *PM* level. Thus, the uniform distribution U (0.001, 0.5) assigned to the technical independencies across the product modules provide that the *PM* level is sufficiently high (ranges between 0.509 and 0.853) to observe this deviation.

The nondominated points are those which are equally good from a non-subjective perspective. That is to say, there exists no point superior to the nondominated points regarding the values of all objectives they represent. The Appendix A contains the formal description and classification of nondominated points.

This experimental study uses the algorithm of Özpeynirci (2008) to find all extreme supported nondominated points. The algorithm systematically changes the weights of the objective functions and finds all extreme supported nondominated points. More information on the working of the algorithm to detect the nondominated points is available in Appendix C.

To capture the effect of *PM* on *OM*, this study implements the algorithm for different 12 *PM* levels. To put it differently, the algorithm solves the problem for 12 different cases. The comparison of the nondominated points across these 12 PM levels show the changes in the OM level as a consequences of the changes in the PM level. Note that the implementation of the algorithm with different 12 PM levels is sufficient for the purpose of this research. Increasing the number of PM levels would have further increased the computational effort without giving additional significant insights.

In the numerical example, the values of the four objectives are the functions of the suppliers' capabilities, which OEM selects, with respect to criteria shown in Table 2. Note that this example does not calculate the capability scores of suppliers by itself, but sources them directly (see Table 3) from the study of Narasimhan *et al.* (2001). Even if there are 23 suppliers in the example of Narasimhan *et al.* (2001), it is sufficient for this research to consider just efficient suppliers. It is because the involvement of inefficient suppliers would not make any contribution to the aim of expanding the search space through the supplier selection problem for a more elaborative analysis. For this reason, the suppliers which Narasimhan *et al.* (2001) identify as inefficient through data envelopment analysis, were first eliminated. Because of the same reason, it is unnecessary to keep suppliers that are dominated by any other supplier. Thus, this research develops a mathematical model (mixed integer programming) (see Appendix B) that maximizes the number of eligible suppliers subject to the following three constraints: i) if one supplier is dominated by another one, they cannot be eligible to produce the same module, ii) there is at least one eligible supplier for each module, and iii) one supplier cannot supply more than one module. As a result, the mathematical model (in Appendix B) identifies the eight nondominated suppliers with numbers 6, 10, 11, 12, 23, 29, 31, and 35 marked by Narasimhan *et al.* (2001). Table 1 lists the eligibility list of these 8 suppliers that the model assigns for each module. In other words, Table 1 shows the supplier alternatives among which OEM can make selection for each module. Note that a supplier may be eligible to produce more than one module in this experimental setting.

Table 1 – Eligibility list of suppliers for each module

Supplier #	**6**	**10**	**11**	**12**	**23**	**29**	**31**	**35**
Module 1	-	✓	✓	✓	✓	✓	-	-
Module 2	✓	-	✓	✓	✓	-	-	-
Module 3	✓	-	-	-	-	✓	✓	-
Module 4	✓	-	-	-	-	✓	✓	✓

OEM selects one supplier for each module among the eligible subset of eight suppliers based on their capabilities (see Table 2), which maximizes its objective function vector consisting of (i) coordination costs, (ii) inventory-carrying costs, (iii) innovative outcomes and, (iv) production efficiency. The value of each objective is the function of the selected suppliers' capabilities in different criteria. For instance, a supplier's on-time delivery capability affects inventory-carrying costs. If a supplier is always punctual on delivery, OEM can keep lower inventory levels, reducing its inventory-carrying costs. Nevertheless, the same supplier's lack of capability in design and development may have negative effect on another objective, innovative outcomes. Taking into account the trade-offs among the four objectives as exemplified above, OEM selects the suppliers whose capabilities maximize the composite objective function.

While Table 2 describes the criteria for supplier selection, Table 3 shows the capability scores of each supplier on these criteria.

Table 2 – Description of the criteria for supplier selection

Criteria	Description
Man	Management capability
Otd	On-time delivery performance
Ddc	Design and development capability
Pmc	Process and manufacturing capability
Crc	Cost reduction capability
Qmp	Quality management practices indicator
Sa	Self auditing indicator

Table 3 – Capability scores of the suppliers

Supplier #	Man	Otd	Ddc	Pmc	Crc	Qmp	Sa
6	0.9607	0.9661	0.9661	0.952	1.1402	1.1272	1.0438
10	1.0808	1.0466	1.0466	0.9376	0.9422	0.9877	1.0438
11	0.9607	1.256	1.256	1.0385	1.0768	0.8051	0.8351
12	1.0208	1.0627	1.0627	1.1251	1.0096	1.1809	1.0438
23	1.0808	1.1593	1.1593	1.1251	1.2115	1.0662	1.0438
29	0.9007	1.1593	1.1593	1.1251	0.9422	1.0735	1.0438
31	1.0808	0.6762	0.6762	1.1251	1.1442	1.0735	1.0438
35	1.0172	0.8695	0.8695	1.0385	1.0768	1.0735	1.0438

Source: Narasimhan *et al.* (2001)

Below, Table 4 lists some parameters of the mathematical model in the left column. The right column of Table 4 shows the operationalization of these parameters through relative supplier capabilities.

Table 4 – The operationalization of parameters through supplier capabilities

$Inform_s$:	The better-managed suppliers (Man_s) increases the quality of the information shared with supplier *s*.
$Homl_s$:	The better-managed suppliers (Man_s) provide more efficient communication, enabling to attain the minimum feasible inventory-carrying cost with less information sharing (higher $Homl_s$).
Inv_s:	On-time delivery capability of supplier (Otd_s) reduces the level of safety stock needed to hedge the stock-out risk, which lowers the inventory-carrying costs.
Ic_s:	The supplier having more design and development capability (Ddc_s) provides a more innovative outcome.
Pe_s:	The supplier capabilities – process and manufacturing (Pmc_s), and cost reduction (Crc_s) – increase the production efficiency (performance/cost, i.e. Pmc_s / Crc_s).
$Homp_s$:	Quality management practices (Qmp_s), and self-audit (Sa_s) indicate that suppliers have auto-control mechanism. Therefore, the production efficiency can go up to the maximum feasible level (higher $Homp_s$) with less information sharing.

Note that the assumptions made below are based on the arguments in Section 2.2, which indicate the effect of the PM level on the objectives of the mathematical model.

The scalars k_1 and k_2 in the model (Section 4) denote the positive effect of the PM level on inventory carrying costs and innovative outcomes respectively. The numerical example assumes a 25% improvement in both of these objectives when the *PM* level increases from 0.5 to 1. For the lower increases, the contribution of the increased *PM* level decreases proportionally.

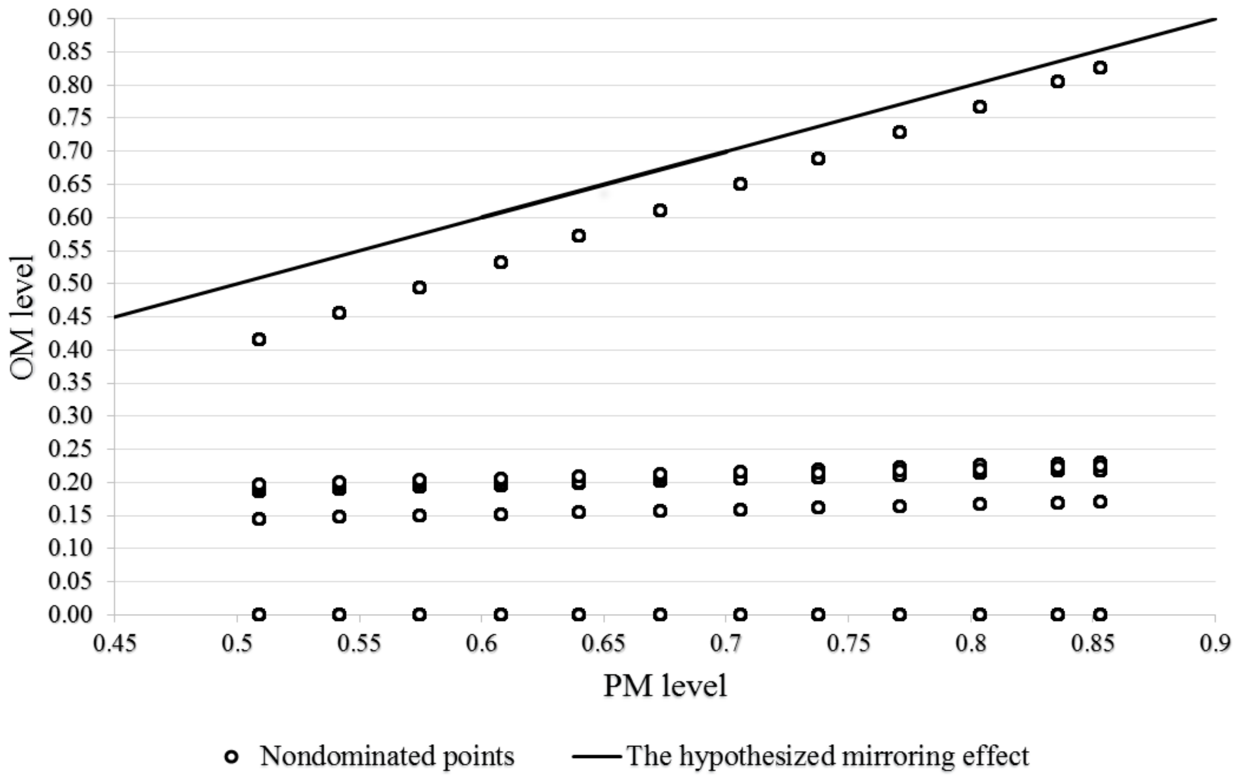
Similarly, the modular product increases the auto-control mechanism of suppliers in line with the argument that one-to-one mapping between modules and the functions of product decreases the opportunism risk, as a consequence, the suppliers give their best. Accordingly, this experimental study assumes that the auto control mechanism of suppliers ($Homp_s$) improves by 25 % as the *PM* level increases from 0.5 to 1. For the lower increases, the contribution of the increased *PM* level decreases proportionally. In order to align the $Homp_s$ values with those of *OM* (R_s), i.e. to normalize them, each $Homp_s$ is divided to the highest $Homp_s$ in the supplier data set, and multiplied with the constant 0.2.

$$Homp_s = \left(0.2 * \frac{Homp_s}{Homp\_max}\right) * \left((1 + 0.25) * \left(\frac{PM - 0.5}{1 - 0.5}\right)\right)$$

5.2 Computational results

The algorithm of Özpeynirci (2008) identified 621 extreme supported nondominated points. In other words, there exists no point more preferable than the each of these 621 points. Figure 2 graphs these nondominated points with respect to their corresponding PM and OM values. The straight line, on the top of Figure 2, represents the one-to-one mapping between the PM and OM values, i.e. the hypothesized mirroring effect. In overall, the positions of nondominatied points in the graph indicate three different group of points. The first group at the upper part of the graph move in parallel to the line representing the conjecture of the mirroring hypothesis. On the contrary, the second and the third group of points, lining up respectively at the middle of the graph and just over the x-axis, are almost independent from the PM level. Another remarkable result is that there is not any nondominated point in the area between these three group of points lined up.

Figure 2 – The corresponding PM and OM levels of the nondominated points



The results show that the PM level is positively associated with the OM level when the weight of coordination costs exceeds 41 %. In most of these cases, the reduction of coordination costs is the top concern of the firm. Only in few cases for which the mirroring hypothesis holds, the inventory-carrying costs is equally important with the coordination costs between the weight percentage ranges of 45% - 47 %. Another remarkable result is that the nondominated points give more support to the hypothesized mirroring effect as the PM level is getting higher. This is due to the fact that modular product design is also favourable for the other two objectives of the model, which are inventory-carrying costs and innovative outcomes. The higher PM level decreases the deterioration degrees of these two objectives caused by the high OM level.

The nondominated points positioning at the middle of graph and just over the x-axis show that PM has no deterministic positive effect on OM. In other words, modular product is not sufficient for firms to establish modular relationship with their suppliers in these cases. The results indicate that the integration with suppliers (low OM) seems necessary as other operational concerns outweighs the burden caused by the coordination efforts. The nondominated points positioned at the middle of Figure 2 illustrate that the OEM integrates with its suppliers to the extent that the OM level is between 0.144 and 0.228. Note that these levels approximate the inventory-carrying costs to its minimum level and the production efficiency to its maximum level with respect to the experimental design of this research. The positions of these points change between this OM level range mainly depending on the weight distribution of the inventory-carrying costs, innovative outcomes and the production efficiency. Finally, the higher PM level increases the OM levels of these points very slightly, since it relatively compensates the negative effect of high OM on the objectives of inventory-carrying costs and innovative outcomes.

The nondominated points just over x-axis refer to the full integration with suppliers. They represent the situation where the objective of making innovation is indispensable by exploiting the high design and development capability of suppliers through the collaborative work. Nevertheless, the innovation should not be necessarily the primary concern for seeing the full supplier integration as the optimal relationship type. Some of the points identified over the x-axis also make the full supplier integration optimal, where the sum of weights of inventory-carrying costs and production efficiency exceed 80 %, and the coordination cost is out of concern.

6. CONCLUSION

The main contribution of this research is its comprehensive modelling, considering many contingent factors simultaneously, which enables to understand the full extent of the relationship between PM and OM. The existence of contradictory findings on the mirroring hypothesis over long time has resulted from the lack of this type of mathematical studies capable of exploring the nuanced relationship between PM and OM (Gunasekaran, 2015). Taking into account many contingencies related to the different objectives of firms allow to understand the set of conditions that the modularity level of products affects the supplier relationships significantly. Hence, the authors believe that the results of this research serve well for this purpose.

Depending on the degree of importance attached to the different objectives, the results give a credit both to the studies supporting the mirroring hypothesis and to the ones refuting it. Therefore, it is not possible to mention the deterministic effect of PM on the type of supplier relationship established. The mirroring effect can only be seen when the coordination cost is the primary concern of firms. In these cases, firms choose to decouple from their suppliers (high OM) by leveraging the modular product architecture. In other cases, despite the modular product architecture, there seems to be an urgent need for firms to integrate with their suppliers to reduce their inventory-carrying costs, make innovation, and improve the production efficiency. This finding refers to that the relationship type established with suppliers may also become irrelevant from the PM level, on contrary to the conjecture of the mirroring hypothesis.

Another original contribution of this research comes from the finding that suggests three types of supplier relationships in overall, giving optimal outcomes. Firms should follow one of these three subject to the particular contextual factors. The first one is in line with the mirroring hypothesis, suggesting firms to decouple from their suppliers (high OM) to the extent that the technical interdependencies of product (PM level) allow because the features of modular product architecture decreases the amount of managerial effort needed to provide coordination. The second one suggests the integration with suppliers, but to the some specific level where other operational objectives related to logistics and production are accomplished, since there is no marginal benefit of integrating more for these objectives. Finally, the third one suggests the full supplier integration for promoting innovations through the joint and collaborative work with suppliers.

The results of this study have important theoretical implications. Modularity theory attempts to explain the supply chain design through the product design strategy, i.e. PM level (Brusoni and Prencipe, 2001). However, there are other thought of schools as well, attempting to explain the effect of products on supply chain design. For example, Fisher (1997) describes the right supply chain for the product in hand, whether it is innovative or functional. This confirms that the modularity theory co-operates with other competing theories to delineate the configuration of supply chains (D'Adderio and Pollock, 2014). At this point, the theoretical contribution of this research is its multi-objective approach. The involvement of many contingencies, related to different objectives, reflect the propositions of different theories. Thus, the results help to understand the degree to which the mirroring hypothesis can be generalized. Besides, they show that there is no one absolute true type of supplier relationship, instead, they suggest the different levels of optimal supplier integration depending on the contextual factors.

This research has important managerial implications for the ideal supplier relationship pattern that firms should establish. Results illustrate that the supplier relationship strategies should be sharp. That is to say, firms should either manage to establish its modular supply network or should achieve sufficient supplier integration. The intermediate ones do not give the most preferable results according to the findings of this study. The examples of success stories based on supplier relationships also verify this finding. While Toyota's trust based close supplier relationships enabled it to reduce its operational costs far beyond its competitors (Dyer and Singh, 1998), the IBM's modular supply network led to the business ecosystem for which all participants of the industry made contribution to IBM's growth (Baldwin and Clark, 2003).

The mathematical model of this research can also support managerial decisions by directing the research and product development activities based on the capabilities of suppliers available to work with. As exemplified by Ülkü and Schmidt (2011), when there is no goal alignment with suppliers like the case of General Motors, the development of modular product is more rational because it can mask the operational deficiencies caused by lack of collaboration. In contrast, if it is possible to work with collaborative suppliers as in the case of Toyota, the development of integral product is better to get higher product performance. Rather than just the supplier relationship quality, the model of this research allows to make this type of analyses with many other supplier capabilities like those related to design, production, and logistics capabilities. Therefore, it assists firms to determine the optimal level of PM at product design phase subject to the capabilities of suppliers in various criteria.

This study incorporates four objectives in its mathematical model to find the answer of its research questions. Future research can enhance the model by adding more objectives which include the additional relevant contingencies likely to moderate the relationship between PM and OM. Besides, for the cases in which it is not possible to change the type of relationships with suppliers in the short-term, future studies can transform the model in a way that it finds the optimal PM level for the given OM level. Furthermore, modelling the problem in a non-linear and dynamic ways might capture the different aspects of the PM-OM relationship that the linear model of this research could not. Last, this research sets the values of objectives as a function of the capability scores of the suppliers selected. Future studies may devise other measures that might increase the robustness of results.

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Appendix A - Multiple Criteria Decision Making Background

A *multi-objective mixed integer programming problem* with *p* objective functions is written as:

$$\text{"}max\text{"}\ Cx = \left(f_1(x), f_2(x), \dots, f_p(x)\right)^T\ s.t.\ x \in X$$

where $X = \{Ax \leq b, x \geq 0, x = (x', x''), x' \in \mathbb{R}^{n'} and\ x'' \in \mathbb{Z}^{n''}\}$. There are n' real valued and n'' integer valued decision variables and $n = n' + n''$. A is a $m \times n$ matrix, $A \in \mathbb{R}^{m \times n}$ and $b \in \mathbb{R}^m$. There are *p* objective functions, all to be maximized, and *C* is a $p \times n$ matrix. Row q of C corresponds to the q^{th} objective function, $f_q(x)$. Quotation marks are used to indicate that the maximization of a vector is not a well-defined mathematical operation.

The set X is the feasible *decision space* and, for each solution $x \in X$, there is a point y in the *objective space* Y such that $y = (y_1, y_2, \dots, y_p)^T \in \mathbb{R}^p$ and $Y = \{y: y = Cx, x \in X\}$. From this point on, the transpose sign is omitted for the sake of simplicity of notation, since all vectors in the objective space are column vectors of dimension *p*. It is assumed that Y is bounded and there exists no point $y \in Y$ maximizing all objective functions simultaneously. Note that there may be multiple feasible solutions in the decision space corresponding to the same point in the objective space. For the purpose of this research, it is sufficient to find one of such solutions.

Consider points $y, y' \in Y$. Point y' *dominates* point y if and only if $y'_q \geq y_q$ for all q and $y'_q > y_q$ for at least one q. If $y'_q > y_q$ for all q then y' *strictly dominates* point y. If there exists no $y' \in Y$ that dominates *y*, then y is *nondominated*. A point *y* is *weakly nondominated* if and only if there exists no point $y' \in Y$ such that $y'_q > y_q$ for all q. Note that all nondominated points are also weakly nondominated points. Moreover, some special dominated points are also weakly nondominated. The set Y_{ND} denotes the set of nondominated points.

In vector notation, $y' \geqq y$ means $y'_q \geq y_q$ for all q, $y' > y$ means that $y'_q > y_q$ for all q, and $y' = y$ means $y'_q = y_q$ for all q. Hence y' dominates y if and only if $y' \geqq y$ and $y' \neq y$, and y' strictly dominates y if and only if $y' > y$.

This research considers three types of nondominated points: extreme supported, nonextreme supported, and unsupported. Consider a point $y \in Y_{ND}$, and let y^c represent a convex combination of the remaining nondominated points. Point y is extreme supported if, and only if there exists no y^c such that $y^c \geqq y$, nonextreme supported if, and only if, there exists no y^c such that $y^c > y$ but there exists y^c such that if $y^c = y$, and unsupported if, and only if, there exists y^c such that $y^c > y$.

The definitions provided in this section apply to a problem with maximization objectives. Note that it is trivial to convert a minimization objective into a maximization one.

Appendix B – The Assignment of Module Production Eligibilities to Suppliers

Notation:

The notation used to depict the model's sets, parameters and decision variables is as follows:

Sets:

m: modules of product; $m = 1,\ldots, M$

s, r: suppliers; $s,r = 1,\ldots, S$

Parameters:

$$D_{sr} = \begin{cases} 1, & if\ supllier\ s\ dominates\ the\ supplier\ r\ for\ module\ m, \\ 0, & otherwise. \end{cases}$$

Decision Variable:

$$E_{ms} = \begin{cases} 1, & if\ supplier\ s\ is\ eligible\ to\ produce\ module\ m, \\ 0, & otherwise. \end{cases}$$

Mathematical Model:

$$\sum_{s} E_{ms} \geq 1 \qquad \text{(B.1)}$$

B.1 maximizes the number of suppliers to which the module production eligibilities are assigned.

Subject to:

$$E_{ms} + E_{mr} \leq 1 \qquad \forall\ m, r, s\ such\ that\ D_{sr} = 1 \qquad \text{(B.2)}$$

B.2 provides that if one supplier is dominated by another one, they cannot be eligible to produce the same module.

$$\sum_{s} E_{ms} \geq 1 \qquad \forall\ m \qquad \text{(B.3)}$$

B.3 ensures that there is at least one eligible supplier for each module.

$$\sum_{m} E_{ms} \leq 1 \qquad \forall\ s \qquad \text{(B.4)}$$

B.4 provides that one supplier cannot supply more than one module.

Appendix C – The Working of Algorithm to Identify Nondominated Points

The algorithm of Özpeynirci (2008), called as *ExA*, identifies the nondominated frontier for also multi-objective problems having any number of objectives. Thus, it is a generalization of Aneja and Nair's (1979) algorithm designed for biobjective problems. Figure C.1 lists the steps of *ExA* to identify nondominated points.

Figure C.1 – The corresponding PM and OM levels of the nondominated points

Initialize	1. Set $Y_E = \emptyset, k = 1, V = \emptyset, F = \emptyset, L = \{(m^1, m^2, \dots, m^p)\}$
Search	2. Select an element $L = \{(r^1, r^2, \dots, r^p)\}$ and set $V = V \cup \{R\}$ 3. Calculate λ such that $\lambda r^1 = \lambda r^2 = \cdots = \lambda r^p$ 4. If $\lambda \in \mathbb{R}^p_>$ 4.1 Solve problem MOMIP (λ) and let the optimal point be $r^* = \{(r^1, r^2, \dots, r^p)\}$ 4.2 if $r^* \notin R$ then set $F = F \cup \{R\}$ 4.3 if $r^* \notin R$ then 4.3.1 $L = L \cup \left\{\{r^1, \dots r^{p-1}, r^*\}, \{r^1, \dots r^*, r^p\}, \dots, \{r^*, \dots r^{p-1}, r^p\}\right\}$ and $L = L - (L \cap V)$ 4.3.2 If $r^* \notin Y_E^1$ then $y^k = r^*, Y_E^1 = Y_E^1 \cup \{y^k\}$ and $k = k + 1$ 5. If $\lambda \notin \mathbb{R}^p_>$ then go to step 6/
Control the loop	6. $L = L - \{R\}$ 7. If $L = \emptyset$ then report Y_E^1 and stop, otherwise go to step 2.

Source: Özpeynirci (2008)

The algorithm searches for the extreme nondominated points Y_E forming the nondominated frontier. The algorithm may also find the facets F as a part of nondominated frontier considering that the problem of this research has four objectives (more than two). Define $Y^l{}_E$

as a set of nondominated points having already been identified. In addition, *k* shows the cardinality of the set Y^{l}_{E}. Note that *k* is set to one at the beginning. The algorithm defines a stage set $R = \{r^1, r^2, r^{3,} r^4\}$. The number of elements in each stage r is 4 for the case of this research because the model has 4 objectives. The algorithm tracks the set of these stages in three following three lists. These are: i) *L* containing the stages that will be searched, ii) *V* showing the list of stages already visited, and iii) *F* including the stages defining facets.

The initialization of algorithm starts with the dummy stage $M = \{m^1, m^2, m^{3,} m^4\}$in *L*, which provides that the initial search area is sufficiently large in order not to miss any nondominated point. The next step calculates the normal vector, λ, passing through the stage in place. Next, the third step searches for an optimal r^* by solving the problem with multi-objective mixed integer programming with this λ. If the solution is r^*, but has already been in *R*, then this *R* is included into the set of *F*, referring to that it is the facet defining stage.

Alternatively, if the stage r^* identified is different from the stages in *R,* the new 4 stages are generated by replacing each member with r^*. Then, while r^* is transferred from *L* to the set of the Y^{l}_{E} as the k^{th} member*,* the new 4 stages generated are put into the set of *L*. Note that new 4 stages generated will be visited unless they are already in *L*.

The algorithm stops when the set *L* remains empty, It shows that the stages at Y^{l}_{E} are those that form the nondominated frontier. Otherwise, if *L* still includes stages, the algorithm returns back to the second step and picking new stage from *L* to search for more nondominated points.

CONTRARY EVIDENCE: PRODUCT MODULARITY AND SUPPLIER INTEGRATION

Metehan Sorkun

ABSTRACT

This research investigates whether there is any relationship between the modularity levels of products and supplier relations. Moreover, it explores the implications of this relationship on inventory performance. The controversial proposition, the mirroring hypothesis, states that the modularity levels of products and organizations are positively linked. Hence, modular product leads firms to disintegrate from their suppliers and vice-versa. However, many studies direct their criticisms to this controversial proposition due to the different factors. Even if not being uncovered yet, the goal of high inventory performance is likely to be another factor because it requires the pair "modular product – supplier integration", indicating a negative relationship. This research collects data on the product architectures, supplier relationships, and inventory performances of Turkish manufacturing firms through online survey. The results, obtained through using structural equational model, provide important theoretical and managerial insights. They unveil for the first time that there is a negative correlation between the modularity levels of products and supplier relations. Although many research have analysed the effects of modular products on supplier relations before, this study additionally uncovers: i) the effects of integral products on supplier relations, and ii) the counter-effects of the supplier integration level on the product modularity level.

Keywords: product modularity, organizational modularity, inventory management, buyer-supplier relationship, vertical integration, supply chain, mirroring hypothesis.

1. INTRODUCTION

Systems come into existence to carry out the specified functions through the cooperation of its components. One of the properties of a system design is modularity (MacDuffie, 2013), showing the degree to which a system is partitioned into loosely coupled components. Therefore, both products and organizations conform to the system definition (Schilling, 2000) because while products are composed of various interdependent subassemblies to perform their functions, supply chains (an organization at inter-firm level) consist of different but interdependent firms to implement various operations. The reason for drawing such analogy is to stress that the architectural designs of both products and organizations are modular in some degree.

Product modularity (PM) is the term used to describe a product's design property. Products are called modular to the extent that they are separable and the interactions between its modules are well specified through standardized interfaces (Sanchez and Mahoney, 1996; Schilling, 2000). Each module is responsible for separate product function in modular products. In contrast, the design of integral products (low PM) features tightly coupled modules that carry out product functions jointly (Ulrich, 1995).

Organizational modularity (OM) is an attribute of the organizational design. The functions of organizations are performed by its constituents that are either organizational units within the firm or distinct firms within the supply chain. The latter one, supply chain, is the OM analysis level of this research. Firms are geographically, informatively, and governmentally dependent on their suppliers in some degree to carry out various tasks and processes (Fine *et al.*, 2005). In this respect, while the loose coupling of firms with their suppliers indicate high OM, the tight coupling of them refers to low OM.

The mirroring hypothesis proposes that the modularity levels of products and organizations mirror each other (Colfer and Baldwin, 2010). There are mainly two views on the causality direction between PM and OM. One view argues that all interdependencies between modules are codified into the standardized interfaces of modular products. Hence, this codification reduces the need for managerial authority, leading to modular organizations (Sanchez and Mahoney, 1996). On the contrary, the second view asserts that OM is the exogenous factor that causes the mirroring. Firms in modular organizations specialize in different separate knowledge domains because of their relatively fewer interactions. Thus, modular organizations that lack the mechanism for integrating these dispersed knowledge cannot afford to design integral products, thus, they design modular products (McCormack et. al, 2012).

The mirroring hypothesis has not received full support from the following studies. There are many criticisms in literature on the proposed positive link between PM and OM. These criticisms are thematically related to various factors ranging from uneven technological change rate of components (Brusoni and Prencipe, 2001), product performance (Zirpoli and Becker, 2011) to the efficiency of logistics activities (Lau and Yam, 2005; Frigant and Talbot, 2005).

This research specifically draws an attention to the role of inventory performance while considering the PM-OM relationship. High inventory performance indicates that firm is able to manage its inventory-related processes in a cost-effective way while ensuring the expected customer service level. In other words, inventory performance increases as firms can deliver their products to customers at the right place, time, and form with keeping minimum level of inventory. It is important to note that this the assessment of inventory performance should consider the expectations of customers. For example, it would not be appropriate to claim that the inventory performance of two firms, which both produce the same product and hold the same level of inventory, are equal if one of these firm's customer request the product within shorter lead time.

The inventory performance can reach its peak with the pair "high PM - low OM (i.e. integration with suppliers)". First, modular products provide an improvement in inventory performance owing to its features such as the high carry-over component rate, the existence of common modules, and the postponed assembly. Second, non-modular organizations (integral supply chains) ensure higher inventory performance with its features such as the geographical proximity, the frequent information sharing and the collaboration among its members. Hence, high inventory performance entails the pair "high PM – low OM", which contradicts with the mirroring hypothesis. Given that the levels of PM and OM mirror each other, it is not possible for firms to attain a global maxima for inventory performance. On the contrary, if the mirroring cannot be validated, it is possible to infer that high inventory performance is the prior objective of firms, which may annihilate the positive PM-OM link.

There are also other point of views in literature even asserting that the levels of PM and OM are negatively linked. One of these argues that modular product design leads to the coupling of firms because of the relationship-specific investments having been made during the modularization process (Howard and Squire, 2007). Another point of view remarks the appropriability concerns (Gerwin, 2004; Lau, 2011) that induce firms to decouple from their suppliers (high OM) despite an integral product architecture.

The controversial arguments on the mirroring hypothesis and the contrast between the modularity and supply chain literatures call for more empirical research. In addition, Pashaei and Olhager (2015) stress that many research are available that focus on the effects of modular products on supplier relations. However, there is a lack of studies revealing i) the effects of integral products on supplier relations, and ii) the counter-effects of the supplier integration level on the PM level. This empirical research makes important contributions regarding these two points. The results unveil for the first time a negative correlation between the modularity levels of PM and OM, in contrast to the conjecture of the mirroring hypothesis. Besides, firms show superior inventory performance when they involve their suppliers into the planning of activities, make relationship-specific investments to their suppliers, and use advanced information technologies to ensure constant coordination with them. These findings give credit to the concerns stemming from the resource dependency, appropriability, and effective inventory management.

The structure of the paper is as follows. The development of hypotheses takes place in Section 2 with the relevant theoretical background. Section 3 gives information on research design. Next, Section 4 describes the data analysis process starting from data purification to construct validation. Then, while Section 5 reports the results, Section 6 discusses their theoretical and managerial implications.

2. THEORETICAL GROUNDING AND HYPOTHESES DEVELOPMENT

2.1 Product modularity and organizational modularity

The mirroring hypothesis embeds a more than one-way cause-effect relationship. It implies a positive correlation between the levels of PM and OM. That is to say, while modular (integral) products lead a way to the modular (integral) organizations, the formation of modular (integral) organizations inherently develop modular (integral) products. The rationales behind these two causational relationships are conveyed below in turn.

The aim of product modularization is to minimize interdependencies between modules by gathering interdependent components into the same module (Gershenson *et al.*, 1999). Thus, each module in a modular product architecture performs only one product function (Ulrich, 1995). Less functional interdependencies between modules reduce the coordination needs across firms because any design change in one module does not require a change in other modules. The remaining interdependencies across modules are codified into standardized interfaces that embed the necessary information for coordination (Sanchez and Mahoney, 1996).

The characteristics of the modular product architecture encourage firms to establish the arm-length relationships (high OM). Initially, the standardized interfaces reduces the need for the excessive inter-firm processes to provide coordination (Pero et al., 2010). Besides, firms gain flexibility (Khan et al., 2012) because the visibility of standards in modular products makes modules non asset-specific, increasing the available number of suppliers for the outsourced modules. This situation decreases the hold-up risk to the specific supplier. Therefore, the modular product architecture leads to an organizational flexibility through which firms can switch their suppliers easily, and can exploit the multiple sourcing options to change their production scales in response to demand fluctuations. In addition, as firms have to quickly address the changing market needs, the modular product architecture allows them to be easily part of different organizational forms temporarily (high OM), such as contract manufacturing, alternative work arrangements, and alliance formation (Schilling and Steensma, 2001).

In case there is an integral product (low PM), the maximization of the working harmony between components is critical because each product function is jointly performed by many components. This high interdependency between components results in the loss of firms' absolute independence on the design of their components, since there would be significant consequences of their design change on other components of the product, and on relevant product functions. For this reason, the high levels of coordination and collaboration with suppliers are necessary for the development of successful integral products. Therefore, firms attempt to achieve cooperative, geographic and goal integrity with their suppliers (low OM).

Empirical evidence of the way PM affects OM positively is available in literature. For instance, the analysis of Schilling and Steensma (2001) on the U.S. manufacturing industries show that the availability of industrial standards (high PM) help firms to gain flexibility through the formation of modular organizations, eventually meeting the heterogeneous demand in market. Cabigiosu and Camuffo (2012) find that there is less information sharing between the buyer and its suppliers (high OM) for the modular components of the air-conditioner. Another recent support comes from the empirical research (Hao *et al.,* 2015) on Chinese hi-tech firms. The authors argue that the standardized interfaces of modular product provide common knowledge across firms, hence tacit coordination. According to them, this tacit coordination replaces the explicit coordination (high OM) across firms for interaction and integration.

On the contrary, the study of Hoetker *et al.* (2007) on U.S. carburettor and clutch manufacturers reveals that the buyer-supplier relationships are longer in case of non-modular components, which implies higher inter-firm dependency (low OM). Similarly, Fixson and Park (2008) document the transformation of supply chains in the bicycle industry from modular to integral form after it was seen that newly introduced integral product architecture provided superior performance.

Hypothesis 1a: Product modularity affects organizational modularity positively.

Another body of research supporting the mirroring hypothesis similarly asserts that the levels of PM and OM move in parallel, but the indicated exogenous variable is the OM level. Their arguments have its roots in the study of Conway (1968) stating that the designs of products reflect the communication channels of organizations. In other words, the product design (PM level) mirrors the design of organization (OM) that develops it. The underlying argument of this view is that the design of organizations cannot change in the short-tem (MacCormack *et al.*, 2012). Therefore, it is more rational to assume that the structures of organizations (OM level) determine the solution space for the product development (PM level). For example, it is difficult to expect from modular supply chains to develop integral product, due to the fact that the design of integral products requires the broad inclusive knowledge, sufficient to exploit the performance and spatial synergies among components. Instead, the geographical dispersion and the limited information sharing between firms in modular supply chains make the development of modular products more likely.

Henderson and Clark (1990) attribute the failure of established firms in the semiconductor photolithographic alignment equipment industry to their pre-existing organization structure. These firms' information channels and filters, built over time, directed them to address the specific subset of the problem solution space in which they could not recognize new component interactions. This case shows that the current organizational structure of firms limits the product design range they can realise. To test the validity of this argument, MacCormack *et al.* (2012) compare the product designs of two different organizational forms, namely the commercial software firm and the open source project community. In contrast to the former, the open source project community has a modular organizational form that consists of geographically dispersed development teams having no goal alignment. The results reveal that while the product developed by open source communities is modular, the software developed by commercial firms is integral. Likewise, the review of Colfer and Baldwin (2010) on empirical studies find that the designs of developed products mirror the corresponding organizational architectures in 69 % of the cases analysed.

Hypothesis 1b: Organizational modularity affects product modularity positively.

2.2 Product modularity and inventory performance

The customer service level depends on the ability of firms' making products available when and where requested in the form tailored to customer needs. Thus, in order to ensure high customer service level, firms need to keep sufficiently sized inventories in different locations to provide time and place utility. This creates a trade-off between customer service level and inventory carrying costs.

The way to keep inventory carrying costs low without sacrificing from customer service is to achieve mass customization through the postponement of assembly. Duray *et al.* (2000) call mass customization as “paradox-breaking manufacturing reality” because it enables to address the high variety of needs in market in a cost-effective manner. Such advantageous but at the same time difficult-to-implement practice requires both standardization and customization. Modular products here play important role because their design architecture provides both economies of scale and scope. Since the product is partitioned into well-defined standardized modules, modularity makes possible to reconfigure and recombine the modules quickly in response to different customer specifications. Hence, modular products pave a way to the postponement strategy, referring that firms can delay the assembly of their product modules even until the receipt of customer order (Skipworth and Harrison, 2006). Owing to this postponement, firms do not have to keep their inventory at final product level.

Feitzinger and Lee (1997) show that modular products have the merit of both improving the customer service level and reducing the inventory level because they allow to postpone the product differentiation to the point of supply chain closer to customers. Their study exemplifies the case of Hewlett-Packard in which the company customizes its printers for European and Japanese markets. Their modular product design enabled Hewlett-Packard to customize its printers at local distribution centres instead of main factory, which led to 25% cost reduction, including the inventory costs. Similarly, their modular printer design for MAC and DOS users reduced the required inventory level of Hewlett-Packard by 50%.

Modular product design enables the multiple use of components in different product variants (Salvador *et al.*, 2002). This high carry-over component rate reduces the number of stock keeping units (SKUs) that firms need to hold regarding the product variety level they need to provide (Ulrich, 1995). That is not to say that higher product variety in modular products does not increase the costs but has lower negative effect compared to integral products. For any specific product variety level, since one module can be resued in many product variants, firms have less SKU in total regarding all product variants in case they have modular product architecture than non-modular one. Thus, the lower inventory-carrying cost incurs owing to modular product design considering that firms need to keep a safety stock for each SKU to hedge stock-out risk. High carry-over component rate has also positive effect on the fixed part of the inventory ordering costs, incurring regardless of lot size, but as a consequence of transaction process, once the order is placed to suppliers. In this regard, the lower number of SKUs in modular products implies that a firm deals with the lower number of suppliers, which reduces its inventory ordering costs.

Modular product design enables a risk pooling for demand uncertainty by bringing the individual demand varieties together (Oeser, 2015). One of the suggested instruments for reducing demand uncertainty is inventory centralization. The application of this instrument for integral products is difficult, as firms need to separate their inventory policies for each product variant due to the absence of common components across product variants. In contrast, common components in modular products allow firms to formulate a consolidated inventory strategy for different product variants. For example, when there is a significant increase in the demand of one product variant, the stock of common component kept for all product variants can be used to replenish it (Weng, 1999). This centralization considers all demand patterns of product variants at macro level, maintaining an optimal safety stock level regarding inventory costs and stock-out risks (Van Hoek and Weken, 1998).

Hypothesis 2: The product modularity level affects the inventory performance of firms positively.

2.3 Organizational modularity and inventory performance

Modular supply chain refers to the organizational structure in which firms are quasi-decoupled. A wide range of different measures are available in literature for such decoupling. However, the three following dimensions broadly contain most of the measures, which are the information sharing level (Cabigiosu and Camuffo, 2012; Furlan *et al.*, 2014), the degree of authority delegation (Helfat and Karim, 2014), and geographical proximity (Fine *et al.*, 2005).

The frequency and intensity of the information shared between a firm and its suppliers for operational activities is the inverse measure of the OM level. The information flow is an important coordination mechanism that can substitute the role of inventory held to buffer demand fluctuations (Lau *et al.*, 2004). Conformingly, the simulation study of Costantino *et al.* (2014) shows the positive impact of information sharing to decrease the information distortion on the market demand level along the supply chain. More information sharing (low OM) via electronic connectivity and the formation of inter-firm teams provides more accurate demand forecasting, which leaves no room to keep excessive inventory against the stock-out risk. Therefore, firms are able to keep their customer service at high level with lower safety stock (Moyaux *et al.*, 2007).

Another determinant of the OM level is the degree of autonomy that each firm has in the supply chain. Modular organizations characterized with short-term relationships make firms to have more independency in giving their own decisions. However, this causes a lack of cohesion between firms, having a negative effect on inventory performance. First, the lack of central planning constrains the full efficiency in inventory management (Lee *et al.*, 2004) because firms try to optimize their own inventory-related processes, trapping them into sub-optima. Conversely, centralized inventory planning can accomplish the attainment of global-optima, which brings further efficiency. The second disadvantage related to high autonomy in modular organizations is its effect on the quality of information shared. The previous paragraph emphasized the importance of the frequent and intense information sharing, but these may not be effective when the shared information lacks relevance (Kembro and Selviaridis, 2015). At this point, the long-term and cooperative inter-firm relationships (low OM) provide the goal alignment, which improves the quality of information shared. Hence, inventory performance is expected to go up when firms work with their suppliers for a long time (Prajogo and Olhager, 2012).

Geographically dispersed firms refer to modular supply chains. The long distance between the facilities of buyer and suppliers causes low inventory performance (Bennett and Klug, 2012). More geographical distance does not only result in higher transportation costs; but also affects the inventory costs negatively (Larsson, 2002). In addition, the long distance has indirect negative effects on the information sharing frequency, intensity, and quality. First, it limits the communication links of a firm with its suppliers. Second, more distance escalates the leading time for receiving components after the placement of an order. The prolonged leading times increase uncertainty, which makes harder to reduce safety stock (De Treville *et al.*, 2004). On the other hand, the Just-In-Time (JIT) is the production philosophy according to which any held inventory is redundant and waste. However, the successful JIT practices show that suppliers locate within the production site of manufacturer to eliminate any geographical constraint that decreases the productivity of inventory-related processes.

Hypothesis 3: The organizational modularity level affects the inventory performance of firms negatively.

Figure 1 shows the hypothesised causal relationships among product modularity, organizational modularity, and inventory performance.

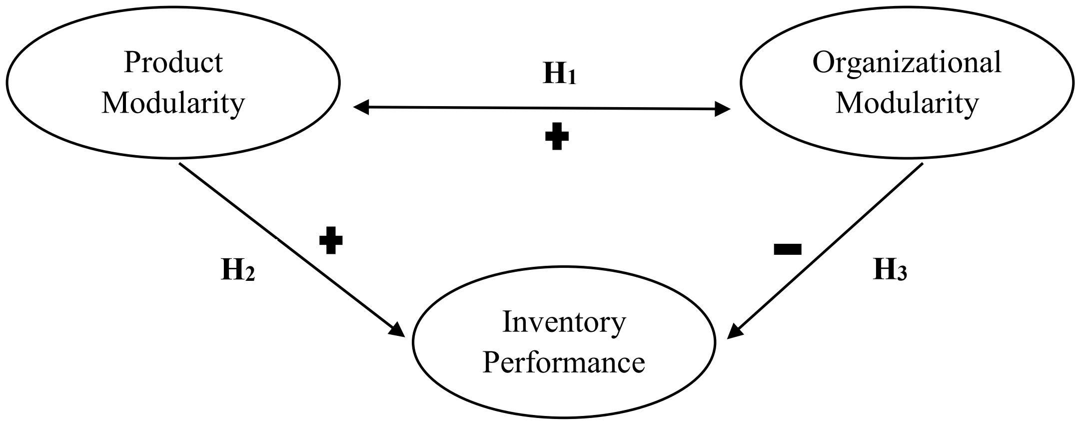


Figure 1 – The hypothesised research model

3. RESEARCH DESIGN

3.1 Survey

An online survey instrument was utilized to collect data to test the research hypotheses. While some of survey questions were adapted from previous papers, the rest of them was developed based on an extensive literature view. To avoid any measurement error, the survey was pre-tested on various scholars and practitioners and was translated to the respondents' native language, Turkish. For each question of the survey, a seven-point Likert scale was used with the end points "strongly agree" and "strongly disagree". Finally, the survey included 5 questions to measure the PM level, 6 questions to measure the OM level, and 4 questions to measure inventory performance. The survey questions asked are available in Appendix.

The online survey software, SurveyMonkey, was used to design the survey. The survey link was e-mailed to the 2235 Turkish manufacturing firms with the cover letter containing all relevant information such as the purpose of research and the description of the technical terms in the survey. This cover letter was also requesting that the survey shall be filled out by employees having knowledge on the firm's product development, supplier relationships, and inventory-related processes. The responses show that positions of the respondents in firms are mostly CEO, production manager, product development manager, sales manager, and process managers.

The reminder e-mails were sent after 15 and 30 days of the first e-mailing date to those who did not complete the survey. In the end, 148 complete and consistent responses were obtained, indicating the response rate of 6.6 percent. To check non-response bias, the sample was divided into two on the basis whether firms returned their replies after the remainder e-mail. While 44 firms in our sample sent their responses back after the remainder e-mail, the remaining 104 firms returned the survey after the first e-mail. Mann-Whitney U test showed no significant difference between these two groups regarding the distribution of their replies for each question, eliminating the concern of non-response bias. On the other hand, taking into account that a single person in each firm completed the survey form, Harman's single factor test (Harman, 1967) was conducted to check a common method bias. The factor analysis of all survey items ruled out such bias because i) four factors were found to have eigen values above 1 and, ii) the factor with the highest variance (23 %) was reasonable considering that the total explained variance was 58 percent (Paulraj and Chen, 2007).

3.2 Sample

For the data collection, this research addressed the Turkish manufacturing firms whose products are under the two-digit SIC (standard industrial classification) codes from 25 to 32. The reason for choosing these eight industry groups is that the designs of products in these industries are sufficiently physically complex, allowing the assessment of their modularity level. Otherwise, it would not be possible to understand the effects of PM level on other research constructs truly if the design architecture of product either was primitive or had a non-physical essence.

The chart in Figure 2 shows the frequency distribution of the firms sampled within eight industrial groups. The names of these industry groups with their codes are as below:

(25) Manufacture of fabricated metal products, except machinery and equipment;
(26) Manufacture of computer, electronic and optical products;
(27) Manufacture of electrical equipment;
(28) Manufacture of machinery and equipment n.e.c.;
(29) Manufacture of motor vehicles, trailers and semi-trailers;
(30) Manufacture of other transport equipment;
(31) Manufacture of furniture;
(32) Other manufacturing.

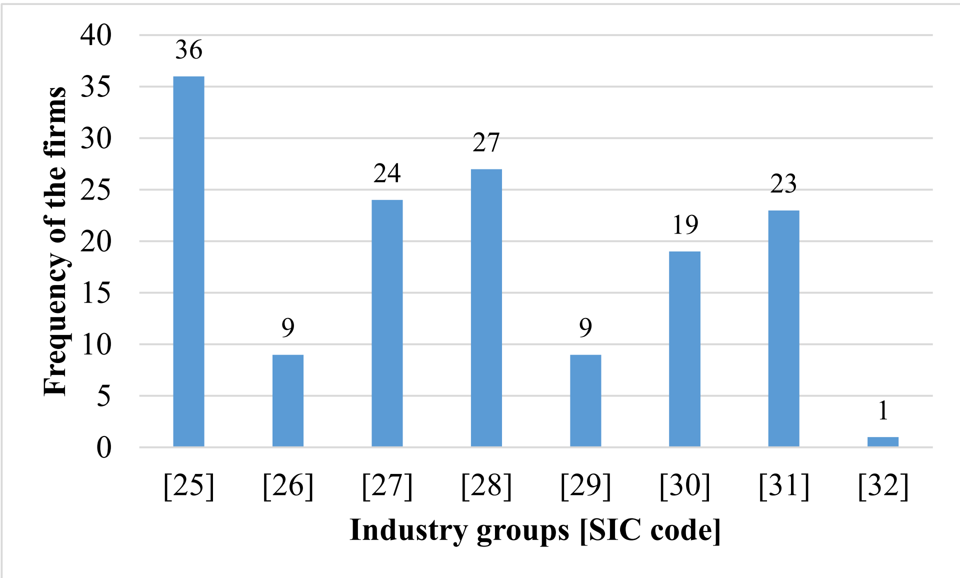


Figure 2 – The frequency distribution of the firms sampled within 8 industrial groups

TOBB (The Union of Chambers and Commodity Exchanges) is the formal supreme board of all professions in Turkey, to which all firms are registered. E-mail addresses of all manufacturing firms classified in the eight industry groups were obtained via the industrial information database of TOBB. Considering that the survey was sent to all firms in population through the database of TOBB (over 2000 firms), the 6.6 % survey response rate is sufficient because it is somewhat equal to the sample representation rate of the addressed population.

Moreover, this response rate is also sufficient with respect to the liberal conditions (sampling error is 10 % and confidence interval 80 %) which require 1 % response rate at minimum for the populations over 2000 (Nulty, 2008).

The criterion specified by the Turkish law for determining the enterprise size is the number of working employees. Based on this classification, firms in which the number of employees lower than 10 are (i) micro; between 10 and 49 are (ii) small-sized, between 50 and 249 are (iii) medium-sized; and higher than 249 are (iv) large-sized. The pie chart in Figure 3 shows the percentage distribution of firms among size categories.

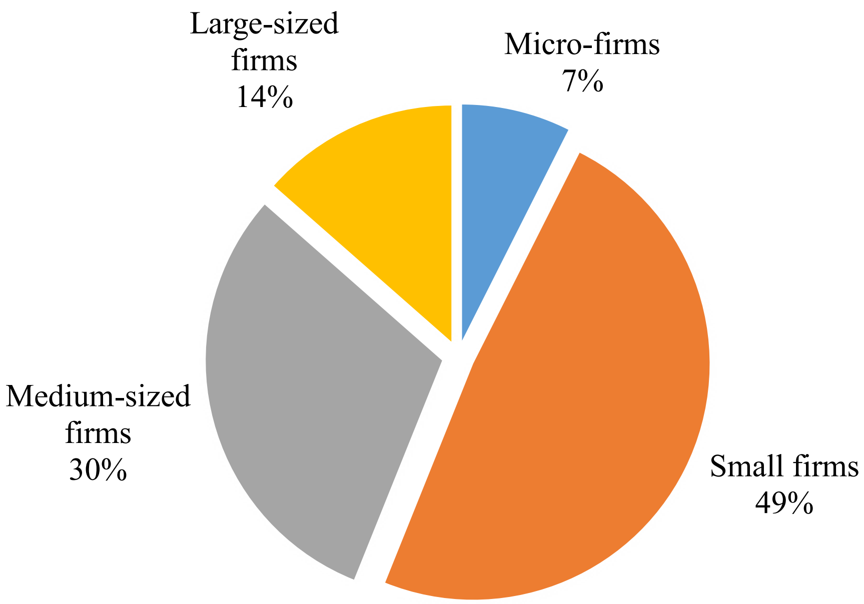


Figure 3 – The percentage distribution of the firms among size categories

3.3 Construct operationalization and scale development

Table 1 shows the scale items used to measure three constructs, which are product modularity, organizational modularity, and inventory performance. The signs adjacent to the scale items indicate how the survey responses were coded with respect to each scale item. In contrast to

PM and inventory performance, the scale items for OM were reversely coded. That is to say, the respondents' disagreement to the statements scaling the OM level in the survey were scored high. On the other hand, while some of the scale items were directly adopted from previous research, the rest of them was developed based on the arguments of other studies. Table 1 lists all these studies at the right column.

Table 1 – The scale items in survey

Construct	**Item**	**Scale Item** *(Type of relationship with construct)*	**Source**
Product Modularity	X_1	Standardized components (+)	Antonio *et al.* (2009)
	X_2	Component carry-over rate (+)	Antonio *et al.* (2009)
	X_3	The definition of product platforms as a basis of future product variety and options (+)	Salvador and Villena (2013)
	X_4	The easiness of adding options to the standard product (+)	Bush *et al.* (2010)
	X_5	One-to-one mapping between product functions and components (+)	Ulrich (1995)
Organizational Modularity	Y_1	The formation of joint problem solving teams with suppliers (-)	Monczka *et al.* (1998)
	Y_2	The involvement of suppliers into the activities of the manufacturing firms (-)	Lau (2011)
	Y_3	The availability of the advanced information technologies that provides electronic connectivity with suppliers (-)	Fine *et al.* (2005)
	Y_4	The interdependency of the suppliers to make design changes in their components (-)	Malone (1999)
	Y_5	The relationship specific investments made with suppliers (-)	Cousins (2002)
	Y_6	*Dropped* - The geographical proximity between the locations of the manufacturing firm and their suppliers (-)	Fine *et al.* (2005)
Inventory Performance	Z_1	The inventory cost performance considering over last five years (+)	Stevenson and Sum (2009)
	Z_2	The inventory level held considering over last five years (+)	Stevenson and Sum (2009)
	Z_3	*Dropped* - The customer service level considering over last five years (+)	Stevenson and Sum (2009)
	Z_4	The inventory turnover rate considering over last five years (+)	Rabinovich *et al.* (2003)

For PM, this research utilizes the previously used scales such as standardization (X_1), combinability (X_2), commonality (X_3), and the ease of adding options (X_4). The item (X_1) measures the product's standardization, showing the degree to which the interfaces between modules are fully pre-specified. The carry-over rate specified in questionnaire indicates the components' reusability in different product variants, hence shows the degree to which product architecture enables combination (X_2). The item (X_3) questions the availability of product platforms (i.e. commonality) on which firms can develop different product variants. Next, the item (X_4) indicates the degree to which the product can be customized via adding options in response to customer requests. Finally, the item (X_5) was developed according to the PM definition of Ulrich (1995) that product design is modular as each component is responsible for only one product function.

The scales developed to measure the OM level cover three following dimensions: information sharing, autonomy, and geographical proximity. First, two scale items, the formation of inter-firm problem-solving teams (Y_1) and the joint activities (Y_2) measure the information sharing level with suppliers. Similarly, the scale item (Y_3) measures the information sharing level, albeit in an electronic environment. Next, the scale items (Y_4) and (Y_5) were developed to measure the autonomy degree of firms. The need to get authorization before making any design change in components (Y_4) and the relationship-specific investments having been made before (Y_5) are indicators that limit the autonomy of firms (low OM). Finally, the item (Y_6) measures the geographical proximity of firms with their suppliers (low OM).

Inventory performance was operationalized with four scale items: inventory costs (Z_1), inventory level (Z_2), customer service level (Z_3), and inventory turnover rate (Z_4). First, inventory costs (Z_1) cover the costs of carrying, ordering and stock-out. Inventory level (Z_2) shows the level of inventory that firms hold. Next, the customer service level (Z_3), measures the inventory performance based on if products are available where and when needed by customers. Last, the inventory turnover rate (Z_4) measures the degree of good coordination between sales and inventories (Rabinovich *et al.*, 2003). Note that five-year time period was specified in the questions to account the effects of the levels of PM and OM on inventory performance more clearly. The purpose of specifying such time period was to lessen the risk that other external factors rather than PM and OM might affect inventory performance significantly in the particular short time period during which the survey was made.

The descriptive statistics and correlation matrix are depicted respectively in Tables 2 and 3.

Table 2 – Descriptive statistics

	X_1	X_2	X_3	X_4	X_5	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Z_1	Z_2	Z_3	Z_4
Mean	4.57	4.43	4.56	5.05	4.17	3.21	3.72	3.93	2.55	3.11	3.64	4.37	4.59	5.8	5.11
Std. Dev.	1.85	1.90	1.83	1.62	1.74	1.63	1.65	1.76	1.43	1.52	1.72	1.63	1.65	0.88	1.24
N	148	148	148	148	148	148	148	148	148	148	148	148	148	148	148

Score range: min = 1; max = 7

Table 3 – Correlation matrix

	X_1	X_2	X_3	X_4	X_5	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Z_1	Z_2	Z_3	Z_4
X_1	1.000														
X_2	.200*	1.000													
X_3	.350**	.369**	1.000												
X_4	.266**	.230**	.274**	1.000											
X_5	.236**	.126	.284**	.277**	1.000										
Y_1	-.015	.006	-.099	-.107	.021	1.000									
Y_2	-.154	-.073	-.197*	-.039	-.010	.377**	1.000								
Y_3	.001	-.039	-.143	-.049	-.149	.328**	.385**	1.000							
Y_4	-.140	.063	-.154	-.220**	-.180*	.373**	.225**	.189*	1.000						
Y_5	-.024	-.091	-.144	-.113	-.135	.394**	.273**	.303**	.354**	1.000					
Y_6	-.038	-.007	-.050	-.065	-.014	.078	.111	.169*	.018	-.003	1.000				
Z_1	.097	.058	.108	.048	-.020	-.166*	-.297**	-.111	-.121	-.091	-.242**	1.000			
Z_2	.072	.156	.081	-.034	.003	-.103	-.278**	-.088	-.083	-.132	-.220**	.700**	1.000		
Z_3	.061	.103	.073	.026	.088	-.209*	-.174*	-.304**	-.211*	-.178*	-.178*	.147	.142	1.000	
Z_4	.140	.143	.148	-.043	.013	-.140	-.181*	-.226**	-.071	-.172*	-0.124	.389**	.362**	.451**	1.000

Notes: X_1, X_2, X_3, X_4, X_5 –> PM; Y_1, Y_2, Y_3, Y_4, Y_5, Y_6 –> OM; Z_1, Z_2 Z_3 Z_4 –> inventory performance.
*Correlation is significant at the 0.01 level ($p < 0.05$); ** correlation is significant at the 0.01 level ($p < 0.01$).

The scale item – geographical proximity (Y_6) - was dropped from the model because the correlation matrix shows that Y_6 has very low correlation with other items measuring the OM level. It is probable that the conceptual subjectivity of distance, especially considering today's globalized world, might cause a measurement error by confusing the respondents. Similarly, customer service level (Z_3) was dropped from the model due to its low loading, which will be discussed in Section 4.

3.4 Method

This research uses a structural equation model (SEM) to test hypotheses. SEM attempts to explain as much variance as possible in the constructed model based on the covariance matrix of the sampled data (Kline, 2011). SEM includes two parts: measurement and structural models. While the former operationalizes latent variables (constructs) that cannot be measured per se, the latter enables the testing of many relationships simultaneously in one model.

The features of SEM serve well for the aim of this research. First, the constructs in the model – PM, OM, and inventory performance – are not directly observable, therefore the relevant indicators are necessary to measure them. Second, and more importantly, SEM is a convenient technique to test theories and hypotheses. This research tests the mirroring hypothesis on which there are contradictory views and findings. Hence, SEM both enables to test the PM-OM relationship and shows its impact on inventory performance in a convenient way.

4. DATA ANALYSIS

This study used two types of software, SPSS and AMOS, for the data analysis and parameter estimations. The maximum likelihood (ML) estimation was used to predict 29 distinct parameters of the model. The multivariate normal distribution is one of the assumptions in ML estimation technique. Since some of the indicator variables showed non-normality, two tests were made – *the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy, and the Bartlett* *test of sphericity* – to check if the normality and outliers in the sampled data might cause problems for the estimates. The KMO score of 0.70, and the Bartlett test of sphericity of 384.467 ($p<0.0001$) ensure that the sampled data is sufficient for the factor analysis (Rovai *et al.*, 2013). Also, the ML estimation requires sufficiently large sample size for consistent estimates. The sample size of this research (148) is five times greater than the number of estimated parameters (29) in the model, showing that the sample size is sufficiently large (Bentler and Chou, 1987). In addition, the distributions of the responses with respect to industry and firm size are very similar to the distributions of them in population. This is another evidence that the sample selected reflects the research background.

An issue with the data screening is the possible high multicollinearity between the indicator variables. The variance inflation factor (VIFs) is a measure developed to detect if multicollinearity creates a problem for the prediction of the parameters by increasing their standardized errors (O'Brien, 2007). The series of linear regressions among the indicator variables by changing iteratively the independent variable showed that all VIF scores were below the threshold value 4 (O'Brien, 2007). Therefore, high multicollinearity is not the concern for the sampled data of this study.

The technique analysing the measurement model, the confirmatory factor analysis (CFA), allows to measure latent variables (constructs) through the pre-specified observed (indicator) variables. In CFA, while the indicator variables are endogenous, the constructs are exogenous (Kline, 2011). This research applied CFA analysis to measure three constructs - PM, OM and inventory performance - through the indicator variables (scale items) specified in Table 1.

The standardized results of the measurement model show that the loadings of all indicators expect from the indicator Z_3 (customer service level) are significant and their standardized loadings are above 0.4, hence exceed the cut-off value 0.3 (Hair *et al.*, 1998). The indicator Z_3

was dropped from the model due to its very low loading and non-significant p-value. Table 4 shows the unstandardized estimates of the indicators with their standard errors, and with their standardized loadings on the respective construct.

Table 4 – The results of confirmatory factor analysis

Prod. Mod.	Estimate (SE)	Std. Loading	Org. Mod.	Estimate (SE)	Std. Loading	Invent. Perform.	Std. Loading	Estimate (SE)
X_1	1.00	0.506	Y_1	1.050 (0.225)	0.652	Z_1	0.868	1.00
X_2	0.938 (.264)	0.461	Y_2	1.157 (0.251)	0.587	Z_2	0.804	0.937 (0.134)
X_3	1.359 (0.331)	0.696	Y_3	1.00	0.522	Z_3*	0.239	0.962 (0.117)
X_4	0.811 (0.218)	0.469	Y_4	0.781 (0.199)	0.502	Z_4	0.457	0.402 (0.081)
X_5	0.791 (0.226)	0.424	Y_5	0.951 (0.217)	0.575	----	----	----

SE: Standard Errors
*The p-value for Z_3 is not significant. The rest of all other estimates are significant at $p < 0.001$ level.

To validate the specified measurement model, the following analyses were made: i) the scale reliability, ii) unidimensionality, iii) convergent validity, iv) divergent validity, and iv) construct validity.

The scale reliability indicates the internal consistency of the scale items. High reliability scale score ensures the retrieval of same replies if the survey is distributed to the respondents repeatedly. The internal consistency of the scale items, Cronbach's alpha scores, for both OM ($\alpha = 0.701$) and inventory performance ($\alpha = 0.745$) exceed the conventional threshold 0.70 (Nunnally, 1978). In addition, Cronbach's alpha for PM ($\alpha = 0.638$) is greater than 0.6, which indicates the adequate scale reliability (Lin et al, 2006, Kline, 2011).

The establishment of unidimensionality is a requisite for a measurement model. Accordingly, each indicator variable should load significantly only on the pre-specified construct in the measurement model and the error terms of the indicators should not covary. The rotation component matrix (Table 5) resulting from the factor analysis illustrates that each indicator loads significantly on the constructs that they are linked to. Additionally, there is no considerable covariance between the error terms. While the total explained variance is around 58 percent, the eigen values of all three underlying constructs are above the cut-off value 1.

Table 5 – Rotated component matrix

Components	Y_1	Y_3	Y_5	Y_2	Y_4	Z_1	Z_2	Z_4	X_4	X_1	X_5	X_3	X_2
1 (OM)	0.74	0.72	0.68	0.62	0.49			-0.23				-0.18	
2 (Inv. Perf.)				-0.31		0.89	0.88	0.57		0.17			
3 (PM)			-0.15		-0.46				0.72	0.63	0.63	0.54	0.28
4	0.18	-0.25		-0.13	0.47			0.30		0.20		0.51	0.73

Extraction Method: Principal Component Analysis; Rotation Method: Varimax with Kaiser Normalization.

This research applied the procedure introduced by Anderson and Gerbing (1988) to check convergent and divergent validity. First, all indicators' estimated path coefficients are larger than the double of their standard errors (Table 6), ensuring the convergent validity. Second, in order to check divergent validity, the pairwise construct analysis was made for all possible construct pairs in the model, i.e. "PM-OM", "PM-Inventory performance", and "OM-Inventory performance". For each pair, the chi-square difference tests were made by comparing the model in which the covariance between two constructs was constrained to 1 with the other model in which the covariance was unconstrained. The statistically significant results of the chi-square difference tests (+/- 3.841 with degree of freedom = 1 for $p < 0.01$) between the compared two models provide an evidence of divergent validity (Table 6).

Table 6 – The test for discriminant validity

Analysed Factor Pairs	Chi-Square of Constrained Model	Chi-Square of Unconstrained Model	Δ Chi-square	Δ Df	p
PM-OM	92,425	39,762	52,663	1	< 0.01
PM-Inv. Perf.	32,301	18,672	13,629	1	< 0.01
OM-Inv. Perf.	78,163	23,227	54,936	1	< 0.01

Finally, the model fit indexes illustrate that the model provides a good fit to the data. Table 7 reports the values of the following model fit indexes: the relative chi-square (χ^2 / df), the goodness of fit index (GFI), comparative fit index (CFI), parsimony ratio (PRATIO), root mean square error approximation (RMSEA), standardized root mean square residual (SRMR), and the Hoelter 0.5 index that accounts the largest sample size for accepting the correctness of the model. Table 7 also includes the thresholds for these fit indexes suggested by the previous studies.

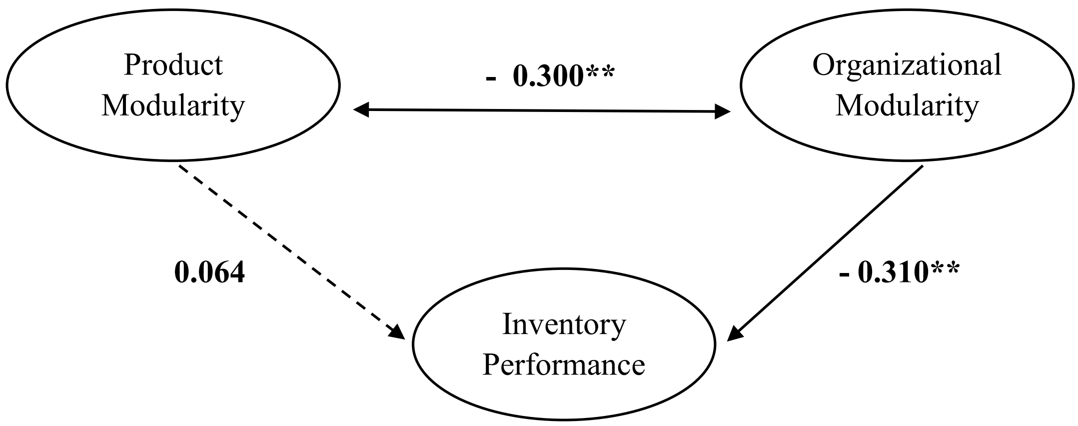
Table 7 – The overall model fit

Fit Index	Values	Cited Benchmark
χ^2 / df	1.11*	< 2, *(Byrne, 1998)*
GFI	0.93	> 0.90, *(Baumgartner and Hombur, 1996)*
CIF	0.98	> 0.95, *(Hu and Bentler, 1999)*
PRATIO	0.80	> 0.60, *(Hollist and Miller, 2005)*
RMSEA	0.03	< 0.06, *(Hu and Bentler, 1999)*
SRMR	0.06	< 0.08, *(Hu and Bentler, 1999)*
HOELTER 0.5 INDEX	N= 148	174, *Maximum.N for accepting the model*

* $\chi^2 = 68.871$; df = 62; Probability level = 0.256

5. HYPOTHESES TESTING

This section reports the results of three hypotheses developed in Section 2. Below, Figure 4 illustrates the standardized estimates of the path coefficients. Whereas the straight lines refer to that the estimates are significant at $p < 0.05$ level, the dashed line shows that the respective estimate is not significant.



** denotes the significance at $p < 0.05$ level. The dotted line represents the non-significant path

Figure 4 – The standardized results of the model's path coefficients

The first hypothesis conjectured that modular (integral) products lead to modular (integral) supplier relationships, and vice-versa. In other words, the positive correlation between the levels of PM and OM was investigated. Interestingly, opposite to the conjecture of the mirroring hypothesis, a significant negative correlation was found (path coefficient = - 0.256, standard error = 0.120, *t*-value = - 2.139, p = 0.032). The possible reasons and implications of this interesting result will be discussed in the next section.

The second hypothesis stated that the PM level affects the inventory performance positively. Even if the sign of the path coefficient is positive as hypothesised, the estimate is not significant (path coefficient = 0.097, standard error = 0.176, *t*-value = 0.551, p = 0.582).

The third hypothesis postulated that inventory performance increases as firms integrate with their suppliers (low OM). The negative sign of the respective significant path coefficient verifies that the OM level affects the inventory performance negatively (path coefficient = -0.476, standard error = 0.193, *t*-value = - 2.474, p = 0.013).

PM and OM account 11.2% of the variance in inventory performance together. When any of two constructs (PM or OM) is excluded from the model, the percentage of the variance in the inventory performance individually explained by PM and OM are respectively 2.5% and 10.7%.

6. DISCUSSION, CONCLUSION AND LIMITATIONS

This research is the first to empirically show that the modularity levels of products and organizations (the supplier relations of firms) are negatively correlated. There are many studies in literature disagreeing with the mirroring hypothesis. The few of these even draw on cases in which the relationship between PM and OM is negative. However, they either show the cases where modular organizations tend to develop integral product (Howard and Squire, 2007) or reveal the ones in which non-modular organizations possess modular products (Lau, 2011). The results of this research provide the first empirical evidence by unveiling both types of cases based on the same dataset. Besides, they make two important contributions overlooked by previous research: i) the effects of integral products on the supplier relations, and ii) the counter-effects of the supplier integration level on the PM level (Pashaei and Olhager, 2015).

The reason why firms having modular products are integrated with their suppliers point out a modularization process. Designing a modular product, the modularization process, is not an easy task. It requires the anticipation of all possible emerging interdependencies between modules. Only non-modular organizations (low OM) are able to design modular products (high PM) because the specification of standardized interfaces in the product design phase requires great combination of architectural and component specific knowledge that can only be achieved through the high levels of coordination and collaboration among supply chain partners (Hsuan, 1999). During modularization process, firms make a series of asset and relationship-specific investments with their suppliers. As a result, it becomes difficult for firms to decouple from their suppliers even after the product becomes modular (Howard and Squire, 2007).

The case of Lego is a very good example supporting the finding that non-modular organization is a requisite for designing modular products. The products of Lego can be defined as purely modular. In addition, its organization structure is based on crowdsourcing platform, named as Cuusoo, in which the voluntary designers from all around world participate (Schlagwein and Bjorn-Andersen, 2014). However, the high interaction and integration level among these designers to develop new product is the evidence that geographical distance is the irrelevant measure of OM due to the available advanced information technologies. On the online platform of Lego, all designers, enthusiastic to Lego, post and discuss their ideas via the moderation of Lego employees, then the ideas exceeding 10000 votes gain an eligibility of being considered by the company. Moreover, many designers have started up their own ventures by keeping their collaborative relationships with Lego (Hienerth *et al.*, 2014). All this integrated organizational system (low OM) boosts the organizational learning that makes possible to fully specify interfaces, leading to the development of modular products.

The negative correlation also implies that firms having integral products form modular relationships with their suppliers. The absence of interface constraints in integral products make easier to maximize product performance through the exploitation of synergies across components (Schilling, 2000). Therefore, the attainment of superior product performance via a successfully developed integral product can provide a competitive advantage to firms. As a consequence, firms are unwilling to establish close ties with their suppliers, e.g. involving them into the product design phase, because these suppliers are likely to be their competitor in future or they can be the supplier of their competitors too. For this reason, firms just establish market relationship with their suppliers against any knowledge risk to maintain their competitive advantage.

The second counter-intuitive finding is that modular products do not necessarily improve inventory performance. This finding points out the fact that the modular product architecture has positive effects on the inventory performance only if firms need to make efficient mass customization to deal with high level of product variety requested by market (Danese and Romano, 2004). Though, in case of homogenous demand in market, the PM level may not have any effect on the inventory performance.

The result of the third hypothesis verifies that supplier integration (low OM) improves inventory performance. The products in the examined industry groups of this research are usually comprised of physically large and complex components that can skyrocket inventory costs. This contingent factor, the high importance of reducing inventory costs, may explain why firms having modular products sometimes tend to integrate with their suppliers (Sorkun and Özpeynirci, 2015).

Modularity theory (Baldwin, 2008) explains the vertical contradiction of industries depending on the firms' task interdependencies that are largely shaped by a product architecture. However, the empirical verifiability of modularity theory hinges on the competing theories that also attempt to delineate the formation of organizations through other factors (D'Adderio and Pollock, 2014). Therefore, the finding, the negative correlation between PM and OM, gives credit to other theories in the context of Turkey, which are the resource dependence theory and the resource based view. In spite of modular product, firms' not being able to decouple from their suppliers may relate to their increasing dependency on their suppliers with which they have modularized a product together. On the other hand, integral products may discourage firms to establish close ties with their suppliers for keeping their high performing product architectures non-imitable.

The results provide managerial insights as well. First, the integration with suppliers is essential for firms to increase their inventory performance. However, modularizing a product may not pay unless firms have to highly customize their products in response to the requirements of customers. On the other hand, an important advantage attributed to modular product design is its enabling high flexibility (e.g. the ease of switching suppliers). Nevertheless, the results suggest that modularization process erodes this advantage, making firms to remain coupled with their current suppliers. Thereby, managers may choose to undergo the modularization process with larger supplier pool to maintain their flexibility.

This research has a number of limitations, which could guide future work. First, the findings can only be generalized to the contexts having similar characteristics to Turkey. As a developing country, the proportion of high-tech industries in Turkey is lower than in advanced economies; therefore different results can be derived in the countries where the weights of high-tech industries are higher. Future work could also test the hypotheses of this study by addressing industries individually. In addition, the sample of this research is mostly comprised of small and medium sized firms. The results may vary for large firms. Another limitation is the assumption that the firm has the similar relationship pattern (OM level) with its all suppliers, which may change in practice depending on the outsourced component.

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Appendix – The Survey

Basic Information:

1. Which of the following best describes the principal industry of your organization?

- Manufacture of fabricated metal products, except machinery and equipment
- Manufacture of computer, electronic and optical products
- Manufacture of electrical equipment
- Manufacture of machinery and equipment n.e.c.
- Manufacture of motor vehicles, trailers and semitrailers
- Manufacture of other transport equipment
- Manufacture of furniture
- Other

2. Which of the following best describes your position in an organization?

- Production Manager
- Production Supervisor
- Process Engineer
- Sales Manager
- Purchasing Manager
- Logistics Manager
- Information Technology Manager
- Product Development Manager
- Other

3. Which of the following range covers number of employees working in your organization?

- Less than 10 employees
- 10-49 employees
- 50-249 employees
- 250 employees and above

Product Modularity ***(Strongly Disagree = 1; Strongly Agree = 7)*****:**

X_1 – Our product components are standardized.

X_2 – Our product components can be reused in various products.

X_3 – We have defined product platforms as a basis of future product variety and options.

X_4 – Options can be added to standard product easily.

X_5 – A change in one component's design requires a design change in other components.

<u>Organizational Modularity</u> ***(Strongly Disagree = 7; Strongly Agree = 1)*****:**

Y_1 – To integrate the dispersed specialized knowledge, we form problem solving teams with suppliers.

Y_2 – We involve our suppliers into activities such as product design, process engineering and inventory management.

Y_3 – We have information technologies enabling us to visualize activities of our suppliers closely.

Y_4 – We usually contact with our suppliers only when we need to order components.

Y_5 – We are making asset specific investments to develop capabilities of our suppliers and to improve processes we conduct with them.

Y_6 – Locations of our suppliers are geographically close to us.

<u>Inventory Performance</u> ***(Strongly Disagree = 1; Strongly Agree = 7)*****:**

Z_1 – Our inventory costs have reduced in last five years.

Z_2 – We have decreased the level of inventory in last 5 years.

Z_3 – We have improved our customer service level in last 5 years.

Z_4 – Our "inventory turnover" rate has improved in last five years.

Estratto per riassunto della tesi di dottorato

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Dottorato: **Economia Aziendale - Management**

Ciclo: **27**

Titolo della tesi: **Three Essays on the Relationship between Product Modularity and Organizational Modularity**

Abstract:

This dissertation, composed of three chapters, examines the relationship between product modularity and organizational modularity. The proposition, called as "the mirroring hypothesis", establishes the positive direct relationship between the levels of modularity in products and organizations. However, there are different viewpoints and findings in literature on this proposition, requiring a deeper analysis. The three chapters of this dissertation aim to find the answer of the existence of such contradiction. The first chapter groups the papers according to their viewpoints. After it statistically analyses the research constructs of papers grouped, the citation network analysis explores the contingent factors, which are likely to cause the contradictory findings in literature. The second chapter delivers a multi-objective approach based on the fact that papers having different viewpoints stress different firm objectives. For this purpose, it develops the mathematical model, considering many relevant contingent factors simultaneously. This research, in the end, shows the set of conditions that modular products lead to modular supply relationships. The third chapter is the empirical study based on the data collected by Turkish manufacturing firms on their product architectures, supplier relationships, and inventory performance. This study tests the positive relationship between product modularity and the type of relationship established with suppliers (organizational modularity). Additionally, it examines the intervening effect of the inventory performance into this relationship. In conclusion, the results of all three chapters show that the relationship between product modularity and organizational modularity is more nuanced than its being hypothesized.

Estratto:

La tesi, composta dai tre capitoli, esamina la relazione fra la modularità dei prodotti e la modularità delle organizzazione. La proposta, si chiama "the mirroring hypothesis", trova un legame diretta e positiva fra i livelli di modularità dei prodotti e le organizzazioni. Comunque, ci sono i diversi punti di vista e le scoperti in letteratura su questa proposta, che occorre un'analisi più profonda. I tre capitoli di questa tesi mirano a trovare la risposta delle cause per questa contradizione. Il primo capitolo classifica degli studi seconda ai loro punto di vista. Dopo statisticamente analizza la costruzione della ricerca degli studi classificati, l'analizza della citazione network esplora i fattori contingenti che potrebbero causare le diverse risulte in letteratura. Il secondo capitolo ha l'approccio di multi-obbiettivo su base che gli studi avendo le diverse punte di viste sottolineano le obbiettive diverse. Dunque, questo saggio sviluppa il modello di matematica che considera molti fattori contingenti simultaneamente. Questa ricerca, al fine, mostra la collezione delle condizioni, in cui un prodotto modulare determina una relazione modulare con i fornitori. Il terzo capitolo è un articolo empirico che fa la ricerca sulle informazioni raccolte dalle produttore turche. Così, controlla la relazione fra la modularità dei prodotti e il tipo di relazione fondato con i fornitori (modularità delle organizzazione). Inoltre, investiga l'intercorrente effetto dell'inventario presentazione dei produttori. In conclusione, le risulte dei tutti tre capitoli mostrano che la relazione fra la modularità dei prodotti e la modularità delle organizzazione è più complesso che aver ipotizzata.

Firma: