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The effect of product complexity and modularity on new product development and supply chain management integration

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Abstract
The purpose of this paper is to explore whether product complexity and product modularity influence the integration of objectives and procedures in new product development and supply chain management. Results are based on statistical analyses of data collected from an international sample of manufacturing firms through the last edition of the International Manufacturing Strategy Survey (IMSS 5). The main findings are that with an increase of the complexity of products, activities to integrate product development and supply chains are more likely to happen. In subsequent research, the findings will be generalized and extended using longitudinal data and in-depth case studies, before an elaborated theory on the integration of new product development and supply chain management can be formulated and tested. Practical implications concern the necessity to integrate the two functional areas, in case of high product complexity.

Keywords: product complexity, new product development, supply chain management

Introduction
While in both fields, new product development and supply chain management, a plethora of scientific and practice-oriented studies have been published (with specialized journals in either of the fields), they are hardly considered together. This negligence hinders to exploit the benefits that lie in an integrated view on product development and supply chain management. For instance, the development of a new product might become at risk, when the supply with specific materials and components is not secured in an efficient way. Thus, integrating the two functional areas is certainly beneficial, for some products it could even simply be necessary. This would be the case, when the complexity of the new product is so high that a firm is dependent on the integration with its suppliers, in order to allow for a cost-efficient supply of highly sophisticated parts, without which the whole process of developing the new product is at risk.

One reaction to an increase in product complexity is the modularization of products. In particular with highly modularized products, an integrated approach to new product
development and supply chain management seems crucial. For instance, available modules and their suppliers need to be identified and their quality must be evaluated, in order to guarantee high quality products and efficient supply and production processes.

Our research objective in the long run is to explain the relationship between the complexity of products and the level of integration of new product development (NPD) and supply chain management (SCM), with the ultimate goal to provide guidelines for manufacturing companies about the appropriate level of integration between the two functional areas. As a first step to achieve this objective, the purpose of this paper is to provide a description of the relationship between product complexity, product modularization and integration, based on a large sample of manufacturing companies. With the help of an accurate description, we are confident to be able to formulate further research questions towards our long-term goal.

This paper is structured as follows: In the next section, the relevant literature on the integration of NPD and SCM is reviewed, together with material about the influence of product complexity on the management of manufacturing firms. The third section starts with a presentation of the research questions we address in this paper; furthermore, this section contains information about the data set used, the operationalization of variables and the statistical analyses that have been used. The section thereafter describes the results of these analyses. In the last section, we discuss our findings and formulate implications for research and practice.

**Literature Review**
In the last years, the attention on the issues related to the interdependencies between NPD and SCM is growing, in both research and practice (Pero et al., 2010). Several different streams of research have contributed to this body of knowledge, taking different aspects into consideration. In this brief literature review, the main strands of an integrated perspective on NPD and SCM are explored and research gaps are identified.

*Product features and supply chain design*

The first research stream focuses on the relation between the features of the products, i.e. the output of the NPD process, and the features of the supply chain that will deliver those products. Several contributions have analyzed the impact of product modularity: for instance, Fine (1995) points out that a modular product often leads to a modular supply chain. Other authors show how modularity affects the role of first tier suppliers (Ro et al., 2007; Doran, 2004) that, most of all in the automotive industry, produce systems by controlling complex networks of second tier suppliers.

Pero et al. (2010) propose a framework to study the impact of three product features on supply chains, namely modularity, variety and innovativeness. Their findings show that the product innovativeness positively affects supply chain complexity, as both configuration and collaboration are concerned.

The impact of product features—in particular of product modularity—on the intensity of the interactions between supply chain partners has been identified as relevant by other authors as well (Sanchez and Mahoney, 1996). Some of these contributions emphasize that modular products and supply chains usually positively affect inter-company collaboration on product development activities (Lau and Yam, 2005).
NPD and operations – within firms’ boundaries
Another set of contributions adopts a more dynamic and process perspective, by looking at the interactions between NPD process and operational processes, underlining the importance of integrating operations and product development activities (Christopher et al., 2004). Many articles in this stream are related to concurrent engineering and to other interventions on the timing of the NPD process with the aim of considering earlier in this process constraints and opportunities coming from operations (e.g. Balasubramian, 2001).

A different approach is related to the definition of design rules that should be followed in designing new products. Most traditional rules are related to design for assembly and manufacturing. More recently, some authors have been focusing also on design for supply rules (e.g. Burkett, 2006), trying to include in the NPD process the opportunities and the constraints related to the suppliers by integrating the internal purchasing unit.

Finally, more recent studies (Khan and Creazza, 2009) have looked in a more comprehensive way at the integration of other business units of a firm in the NPD process, in order to build a “design centric business”.

NPD and operations – across firms’ boundaries
More recently, the interaction between operational and NPD processes have been considered at a design level. Some contributions propose an extension of the design rule concept outside firms’ boundaries, i.e. design for supply chain, meaning the consideration of supply chain operations in product development (Dowlatshahi, 1999; Gubi et al., 2003; Klevas, 2005; Singhal and Singhal, 2002).

A second set of contributions stresses the importance that pre-informing supply chain partners before the launch of new products can help in preventing product availability problems. Some of them discuss the importance of early involvement of suppliers to manage supply risk (Zsidisin and Smith, 2005).

These two sets of contributions have the objective to improve the operational performance of the new products and the efficiency of the NPD process. In other words, they are aimed at anticipating production problems, avoiding availability problems, shortening time-to-market and reducing NPD costs. Van Hoek and Chapman (2006) have shown that this view is limited and that, even though the improvement explained so far are relevant, firms can get even more benefits when they exploit their supply chain relations to innovate. Indeed, the focus should be not only on the efficiency side, but it should include the effectiveness of the NPD process, i.e. the improvement of the performance of new products through a better management of supply chain relationships.

Conclusions from Literature Review
Studies focusing on the relation between product characteristics and SCM have shown that some features, e.g. modularity, have a strong impact on the nature of supply chains. However, some gaps can be identified. First, these studies are usually restricted to a limited set of product features, neglecting for instance product complexity issues. Second, they show the impact of product features on the structural characteristics of supply chains and on the extent to which companies collaborate on product development processes. However, the impact of product features on the level of internal integration between NPD and operations and on the level of inter-firm coordination on operational processes is not considered.
At the same time, most studies that analyze the interaction between product development and operations seldom investigate the link between the internal and the external dimension. The few exceptions (e.g., Hillebrand and Biemens, 2004) point out the link between internal and external integration, but they look at inter-firm collaboration on product development activities, without considering operational coordination issues.

**Research design**

**Research questions**

This paper aims at filling the gaps identified in the existing literature, by analyzing the impact of product features on the integration between NPD and operations within companies and on SC integration between buyer and supplier.

![Research framework](image)

Specific research questions are the following (see also Figure 1):

**RQ1:** Which is the impact of product modularity and product complexity on the integration between NPD and operations?

The first research question therefore aims at investigating the impact of product characteristics on the internal integration between product development and subsequent operations (mainly manufacturing).

**RQ2:** Which is the impact of product modularity and product complexity on SC integration?

The second research question broadens the scope of the analysis, investigating the impact of product characteristics on external integration among different players in the supply chain, focusing in particular on operational issues. Moreover, the impact of the two types of integration on operational performance will be investigated:

**RQ3:** Which is the impact of integration between operations and NPD and of supply chain integration on operational performance?

With this research design we aim at describing the current state of affairs, i.e. what is the current practice in manufacturing companies regarding the integration between (1) NPD and operations, (2) the firm and its suppliers, and (3) the impact of these integration activities on operational performance.

**Data**

The data for this paper were collected in 2009 as part of the fifth round of the International Manufacturing Strategy Survey (IMSS). For more information about the IMSS surveys, see Laugen et al. (2005) and Taylor et al. (2006). The IMSS
questionnaire contains items about the strategic objectives, programs, and capabilities of manufacturing firms, their business environment, and (operational and financial) performance measures. Firms in the ISIC 28-35 industries were targeted, i.e. producers of machinery, tools, electrical, electronic and optical devices, measurement devices, and transportation equipment. Most questionnaire items were measured inquiring about the respondents’ perceptions using five-point Likert scales. The questionnaires were sent to the directors of operations of the firms per post, fax or e-mail, after establishing a phone contact. Data in 19 countries was gathered; the size of the data set is 677 for IMSS-5.

Procedure and analyses
The variables related to the features of the products have been operationalized as follows. In case of multi-item constructs, principal components factor analysis with varimax rotation has been performed and Cronbach’s alpha has been computed to check reliability.

Product modularity is a single item, since in the IMSS questionnaire a question specifically asks for this product characteristic; product complexity is a factor grouping together 3 different items, namely the extent to which company’s products are finished products rather than components, the extent to which products are made up of a high number of different components, and the extent to which the production process is complex.

The variables related to integration have been operationalized as the firms’ improvement programs adopted by companies over the last three years, i.e. the extent to which they have invested in the improvement of integration practices:

- The integration between NPD and operations is a factor grouping together three different items, namely design integration, organizational integration and technological integration;
- SC integration is a factor grouping together three items, namely supply strategy redesign, supplier development and coordination with suppliers.

The details of these factorizations are given in Table 1.

Table 1: Factor analysis; code of IMSS question in brackets (1/2): Constructs

<table>
<thead>
<tr>
<th>Constructs</th>
<th>Items</th>
<th>Cronbach’s Alpha</th>
<th>Mean</th>
<th>Std deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modularity</td>
<td>Degree of product modularity (B2a)</td>
<td>n.a.</td>
<td>3.37</td>
<td>1.22</td>
</tr>
<tr>
<td>Complexity</td>
<td>Extent of finished products (B2b)</td>
<td>.726</td>
<td>3.77</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>Number of different components (B2c)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Complexity of production process (B2d)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Op-NPD integration</td>
<td>Design integration (PD3a)</td>
<td>.768</td>
<td>2.86</td>
<td>.92</td>
</tr>
<tr>
<td></td>
<td>Organizational integration (PD3b)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Technological integration (PD3c)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC integration</td>
<td>Sourcing strategy (SC9a)</td>
<td>.766</td>
<td>2.97</td>
<td>.94</td>
</tr>
<tr>
<td></td>
<td>Supplier development (SC9b)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coordination with suppliers (SC9c)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Performance was operationalized as the firms’ operational performance improvement over the last three years. From the many sub-items in this question, statistical factors were extracted, as shown in Table 2.
Table 2: Factor analysis; code of IMSS item in brackets (2/2): Performance

<table>
<thead>
<tr>
<th>Quality</th>
<th>Items</th>
<th>Factor loadings</th>
<th>Cronbach’s Alpha</th>
<th>Mean</th>
<th>Std Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Manufacturing Conformance (B10a)</td>
<td>.865</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Product Quality And Reliability (B10b)</td>
<td>.798</td>
<td>.823</td>
<td>3.25</td>
<td>.88</td>
</tr>
<tr>
<td>Innovativeness</td>
<td>Time To Market (B10f)</td>
<td>.824</td>
<td>.672</td>
<td>3.06</td>
<td>.87</td>
</tr>
<tr>
<td></td>
<td>Product Innovativeness (B10g)</td>
<td>.743</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexibility</td>
<td>Volume Flexibility (B10d)</td>
<td>.860</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mix Flexibility (B10e)</td>
<td>.821</td>
<td>.805</td>
<td>3.34</td>
<td>.91</td>
</tr>
<tr>
<td>Deliveries</td>
<td>Delivery Speed (B10i)</td>
<td>.814</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Delivery Reliability (B10j)</td>
<td>.761</td>
<td>.806</td>
<td>3.27</td>
<td>.90</td>
</tr>
<tr>
<td>Cost</td>
<td>Unit Manufacturing Cost (B10k)</td>
<td>.840</td>
<td>.735</td>
<td>2.83</td>
<td>.82</td>
</tr>
<tr>
<td></td>
<td>Procurement Costs (B10l)</td>
<td>.832</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As shown in the next section, the impact of product features on integration and the impact of integration on performance have been analyzed through multivariate linear regression analyses.

Results

Product features and integration

Tables 3 and 4 show the results of the multivariate regression analyses on the relation between product features and integration (research questions RQ1 and RQ2).

Table 3: Multivariate regression analysis (R square .078)

<table>
<thead>
<tr>
<th>Dependent variable: Integration between NPD and Operations</th>
<th>Independent variables</th>
<th>Std coefficients</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Product Complexity</td>
<td>.202</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Product Modularity</td>
<td>.128</td>
<td>.002</td>
</tr>
</tbody>
</table>

With respect to RQ1 (see Table 3), both product complexity and modularity show a significant positive impact on the internal integration between NPD and operations. First, the more complex the product, the more companies pursued an integration between NPD and operations over the last three years. This demonstrates that, when more complex products are at the stake, the integration between these two processes is crucial, and companies are pushed towards a better integration level.

Second, the more products have a modular architecture, the more companies were busy with NPD/operations integration. In some sense, this result shows the other side of the coin: product modularity is one of the main levers that can be used to reduce the complexity that companies have to manage during operational processes. As a consequence, companies that have been working on product architecture are the ones that are more likely to have been working on the integration between NPD and operations as well.
Table 4: Multivariate regression analysis (R square .028)

<table>
<thead>
<tr>
<th>Dependent variable: Supply Chain Integration</th>
<th>Independent variables</th>
<th>Std coefficients</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependents</td>
<td>Product Complexity</td>
<td>.115</td>
<td>.008</td>
</tr>
<tr>
<td></td>
<td>Product Modularity</td>
<td>.083</td>
<td>.055</td>
</tr>
</tbody>
</table>

With respect to RQ2 (see Table 4), both product complexity and modularity have a positive impact on SC integration, but only the impact of product complexity is significant (the effect of product modularity on SC integration is only weakly significant, p<=0.1). This means that companies have directed their improvement programs on SC integration with suppliers when more complex products are at the stake. Production and logistics processes are more difficult to be managed across firms’ boundaries the more complex products are, so companies that manage complex products have been pushed towards a higher integration with suppliers. Product modularity has probably a double effect on this: on the one side, modular products usually imply fewer suppliers and higher SC integration opportunities; on the other side, modularity reduces product complexity and the pressure on SC integration.

Integration and performance

With respect to research question RQ3, the impact of the two kinds of integration on performance has been evaluated. Results of the multivariate linear regression analysis are shown in Table 5.

Table 5: Multivariate regression analysis

<table>
<thead>
<tr>
<th>Dependent variables</th>
<th>Independent variables</th>
<th>Quality</th>
<th>Innovation</th>
<th>Flexibility</th>
<th>Delivery</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OP-NPD integration</td>
<td>.208</td>
<td>.231</td>
<td>.133</td>
<td>.130</td>
<td>.146</td>
</tr>
<tr>
<td></td>
<td>SC Integration</td>
<td>.072</td>
<td>.141</td>
<td>.156</td>
<td>.149</td>
<td>.159</td>
</tr>
<tr>
<td></td>
<td>R square</td>
<td>.065</td>
<td>.109</td>
<td>.065</td>
<td>.061</td>
<td>.072</td>
</tr>
<tr>
<td>Sig. of R square change</td>
<td>OP-NPD x SC Integr</td>
<td>.337</td>
<td>.209</td>
<td>.067</td>
<td>.333</td>
<td>.220</td>
</tr>
<tr>
<td></td>
<td>R square</td>
<td>.076</td>
<td>.113</td>
<td>.066</td>
<td>.071</td>
<td>.077</td>
</tr>
<tr>
<td>R square</td>
<td>.011</td>
<td>.106</td>
<td>.619</td>
<td>.012</td>
<td>.096</td>
<td></td>
</tr>
</tbody>
</table>

The integration between NPD and operations has a significant positive impact on all the performance categories, while SC integration has a positive impact on all the performance except product quality. A significant joint effect has been observed with respect to quality and delivery performance.

These results confirm findings that are quite common in the literature about SC integration and about product development processes. Anyway, some interesting insights can be observed.
The significant impact of both internal and external integration on almost all performance dimensions suggests that today manufacturing firms need both practices to improve their competitiveness. Since we have already observed that product complexity drives integration, we can conclude that integration, both internal and external, is the key to achieve better operational performance for complex products.

The missing link between external integration and quality is quite surprising, given the importance of suppliers in achieving quality performance today. However quality can be achieved also without supply chain integration, e.g. by selecting the right suppliers upfront.

The joint impact of internal and external integration on quality and delivery performance suggests that these two dimensions are not only both relevant, but they also reinforce each other, thus providing an additional contribution to the existing literature, which has considered them separately so far.

In particular, the joint impact on quality suggests that, while supply chain integration alone does not provide a significant impact, when adopted jointly with internal integration it can increase the benefits achieved. This can happen for complex products whose quality depends jointly on the collaboration between NPD and production, as well as on the collaboration with suppliers. Probably a third integration dimension, not considered in this study, could be also relevant: collaboration between customer and supplier on NPD, i.e. co-design.

The joint impact of both integration dimensions on delivery performance instead shows that not only both dimensions are significant when considered separately, but their joint adoption provides even better results. Indeed, when NPD and production collaborate internally in designing products that are not only easy to manufacture, but whose components are also easy to supply, and subsequently suppliers are integrated in the production process, the best results in terms of delivery can be achieved.

**Discussion and implications**

This paper shows the existing relationship between product complexity on the one hand and NPD/operations integration as well as SC integration on the other hand. Since product complexity seems to positively affect both forms of integration, we assume that in practice all three functional areas of manufacturing firms are integrated: new product development, operations, and supply chain management. In a sense, practice seems to be guiding research because the scientific interest in an integration of NPD and SCM has just started.

Product modularization seems to be a coping strategy that firms use to deal with increasing product complexity. While it has a clear relationship to NPD/operations integration, the link to SC integration is doubtful. Anyhow, we assume modularization to be an effect of product complexity and integration activities, not a cause of these concepts. Thus, a managerial implication of this study could be to emphasize that integration activities might be the prerequisite of product modularization: modularization does not occur to a substantial degree without integration activities.

Analyses of the relation between integration activities and operational performance indicate a positive effect of integration on the performance of firms, regarding four out of five performance factors. Right now, we do not have a clear explanation for the missing link to quality performance and the joint effect influencing quality and delivery. Further statistical analyses can shed light on this issue.

The discussion about the relationship between product complexity/product modularity and NPD/operations integration exemplifies another limitation of this study
which is caused by the cross-sectional nature of IMSS. Our argument is that firms have to integrate more when complexity is high but—as a reaction—they try to modularize their products as much as possible. However, whether this chain of events is correct, we cannot say with certainty. Longitudinal analyses might be useful for this end; using the former four rounds of IMSS can be instrumental regarding this endeavour. Furthermore, a clear conceptual synthesis of causalities between the relevant variables could be helpful in this regard, for instance using system dynamics modelling techniques (Großler et al, 2008). For a first attempt in this direction see Figure 2 that depicts the causal relationships between variables in form of a causal-loop diagram (Senge, 1990).

In summary, our analyses seem to confirm that product complexity is a driver of NPD and SCM integration. For product modularization the case is more difficult: it mainly seems to be a coping strategy of complexity and driven by as well as a driver of integration activities.

References


