Paper to be presented at the DRUID Summer Conference 2007

on

APPROPRIABILITY, PROXIMITY, ROUTINES AND INNOVATION

Copenhagen, CBS, Denmark, June 18 - 20, 2007

THE NATURE OF PRODUCTION AND ORGANISATION. AN N/K MODEL OF MODULARITY, (DIS)INTEGRATION AND PERFORMANCE

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Abstract:
This paper investigates the link between product modularity and (dis)integration. A theoretic model benchmarks relative performance of (dis)integration for different degrees of modularity. As in existing work, (nearly) modular production processes befit disintegration while non-modular ones require integration. However, modularity and disintegration only lead to greater product differentiation if there is competition. Empirical evidence is then used to investigate, whether the link between product modularity and disintegration is encompassing or whether a role for some large, integrated firms (systems integrators) remains. This aspect is found to depend on the type of industry studied.

JEL - codes: L14, L60, R10

The nature of production and organisation
An N/K model of modularity, (dis)integration and performance

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Abstract

The present paper investigates the effects of product modularity for the optimum form of industrial organization (markets versus firms). A theoretic model benchmarks the performance of (dis)integrated settings for different degrees of modularity in the production process. Performance is measured by welfare-related indicators including average and top product quality as well as product differentiation. In line with conventional wisdom, (nearly) modular production processes befit disintegration while non-modular ones call for integration. However, (near) modularity and disintegration only lead to greater product differentiation if competition is at work. Empirical evidence is then used to investigate, whether the link between product modularity and disintegration is an encompassing one or whether a role for some large, integrated firms (systems integrators) remains. This aspect is found to depend on the type of modular product industry studied.

1 Introduction

Since the pioneering work of Coase (1937), the determinants of the boundaries of the firm have been a central issue in economics. While different motivations for (dis-)integration are discussed in the literature (see Langlois (1992b, 1988) or Mahoney (1992) among many others), one of the key determinants of the choice of firms or markets lies with the nature of products and production, since "although organizations ostensibly design products, it can also be argued that *products design organizations*, because the coordination tasks implicit in specific product designs largely determine the feasible organization designs" (Sanchez and Mahoney, 1996, p.64). If such a link between production and organisation exists, new product designs also affect the boundaries of the firm.

One new product design that has achieved growing attention in the literature is modularity. Originating from engineering science, modularity is a principle that splits a product (production process) into smaller subproducts that are connected via standardised interfaces. It aims for nearly or even fully independent sub-products (Simon, 2002) by reducing or eliminating interdependence between them (Langlois, 2002). Once the architecture and interfaces of a (nearly) modular product are established, subproducts can be developed and modified independently, which is argued to lead to greater product differentiation (mix and match) as well as faster innovation dynamics (Baldwin and Clark, 1997; Langlois and Robertson, 1992; Sanchez and Mahoney, 1996; Sturgeon, 2002).[1] The benefits of such modular product architectures are then

[1] In addition, modular products can be more robust against interruptions affecting individual subproducts than very interconnected ones (Langlois, 2002; Simon, 2002).

argued to underlie the success of high profile industries like aircraft, automobile, computers and semiconducters.

While a number of contributions discuss the benefits and downsides of modular product architectures (Baldwin and Clark, 1997; Langlois, 2002; Robertson and Langlois, 1995), their emergence (Langlois, 2002, 1992a) as well as their current and expected future prominence (Langlois and Robertson, 1989; Langlois, 2003, 2004, 2006), the link between modularity and industry organisation is less well understood. Some argue that the (near) decomposability of production achieved by modular product architectures favours disintegration and the use of the market mechanism (Baldwin and Clark, 1997; Sanchez and Mahoney, 1996).[2] In this view, growing modularity in products and production leads to greater disintegration. Others (Brusoni and Prencipe, 2001; Langlois, 2002; Sturgeon, 2002) maintain that modular architectures need some integrated firms that act as 'systems integrators' alongside predominantly smaller sub-product manufacturers. In this second view, increasing modularity can imply greater decentralisation for most, while requiring integration on behalf of a few firms.

The present paper investigates the link between the degree of modularity in production processes and industry organisation from two different angles. In the first part (Sections 2 and 3), a theoretical model is developed to investigate the relative efficiency of large firms (integrated setup) versus markets (disintegrated setup) in manufacturing products with different degrees of modularity. In contrast to most of the literature, we measure efficiency through product quality and variety instead of focussing on (transaction) cost aspects. In line with previous work, the paper finds that product quality is highest in the market (disintegrated) setting if production processes are fully or nearly modular. Less modular production processes in turn benefit from integration. With respect to differentiation, findings are more nuanced. Differentiation in terms of product quality is always higher in the market setup as common wisdom would suggest. However, this is not owed to a greater variety of (sub)product configurations. Instead, integrated firms deliver more differentiated product configurations that nonetheless have a similar quality. This finding is reversed, once competition is introduced (Section 4).

In a second step (Section 5), the paper then investigates empirically whether disintegration is a general phenomenon in modular product industries. To do so, cross-sectional evidence on firm size distributions for modular and non-modular product industries is presented. The paper finds that modular industries tend to be more disintegrated as is evidenced by lower average firm sizes and standard deviations. However, disintegration need not be encompassing as is highlighted by different breadths of firm size distributions. More precisely, a group of modular product industries (Cutlery, Footwear and Furniture) shows overall disintegration while another one (Aerospace, Automobile, Computers and Semiconductors) retains a role for large and small firms. These findings suggest that the link between product modularity and industry organisation is more nuanced than sometimes acknowledged.

[2]This is very much in line with related findings in organisation studies where fully and to some extent near-decomposable production processes are most efficiently organised by firms with fairly independent departments (Frenken *et al.*, 1999; Marengo *et al.*, 2000; Simon, 2002).

2 The model

To assess the link between product modularity and (dis)integration, the present paper takes production as its basic unit of analysis. We model production as a process with N activities. Each activity (x_n) can be conducted in a specific way which is represented by its state. For simplicity, it is assumed that activities can only take the states 0 or 1. The entire set of production activities corresponds to the final product. It can be represented as a string $Y = x_1x_2\ldots x_n$ (Fig. 1).[3]

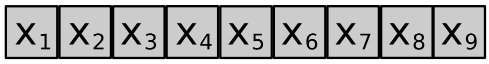
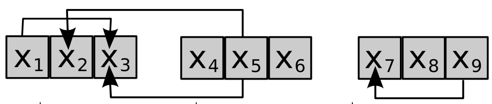


Figure 1: A product represented by string of $N = 9$ production activities

Modularity then implies that this production process is split into more or less independent sub-sets of activities (modules) that give rise to different sub-products. For example, in automobiles, activities in one module produce the engine while others provide chassis, brakes, tires and so on. We represent modularisation by splitting the production process Y into into I equally sized modules $Y = X_1X_2\ldots X_I$ that each yield one sub-product (Fig 2).



	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
w_1	X	-	-	-	-	-	-	-	-
w_2	-	X	-	-	X	-	-	-	-
w_3	X	-	X	-	X	-	-	-	-
w_4	-	-	-	X	-	-	-	-	-
w_5	-	-	-	-	X	-	-	-	-
w_6	-	-	-	-	-	X	-	-	-
w_7	-	-	-	-	-	-	X	-	X
w_8	-	-	-	-	-	-	-	X	-
w_9	-	-	-	-	-	-	-	-	X

Figure 2: The product from Fig. 1 is split into $I = 3$ modules. Now we can differentiate between internal (x_1, x_3/ x_9, x_7) and external (x_5, x_2/ x_5, x_3) dependencies.

The problematic aspect in modularisation is the fact that production activities are usually interdependent, i.e. the way of doing one activity (research) impacts on the success of another (production). Thus, the decomposition of production generates interdependencies connecting activities within and between modules. The first are called internal, the latter external dependencies. Figure 2 illustrates this: Imagine we split process Y in three modules, $Y = X_1X_2X_3$. Dependencies $(1, 3)$ and $(9, 7)$ are internal (to X_1 and X_3). Dependencies $(5, 2)$ and $(5, 3)$, however, are now external (between X_1 and X_2). The share of external dependencies (α) proxies

[3]Henceforth we will use lowercase x for single variables. Uppercase letters denote strings representing sub-products (X) and final products (Y).

the degree of modularity by defining to what extent sub-products depend on each other.[4] More precisely, consider the process in Figure 2, which has two internal and two external interdependencies. In total, it exhibits 4 dependencies between its elements. The share of external dependencies would therefore be $\alpha = 0.5$ (50%), making this process lean towards the non-modular end of the spectrum.

Having outlined the nature of the production process, it is obvious that in every industry, there are several products being offered and thus several, parallel production processes. We thus assume that there are J final products offered in the industry, which results in $J \times I$ sub-products. Each sub-product is manufactured by one agent. As a result, $X_{i,j}$ denotes the string of activities that lead to the i^{th} sub-product and that are controlled by the j^{th} of all agents manufacturing that sub-product. Figure 3 depicts an industry where $I = J = 3$.

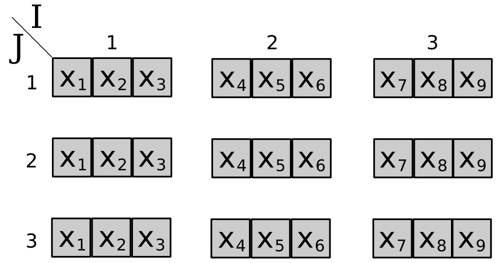


Figure 3: An industry with J agents producing each of the I sub-products. Columns are groups of sub-product manufacturers while lines correspond to producers of one final product.

The question of the relative advantage of firms and markets comes into play when looking at different ways of organizing such a decomposed production process at the industry level. One could imagine that each final product is made by one firm (*integrated setup*). In this case, sub-products are manufactured by firm departments. The combination of sub-products into final product is then fixed according to organisational boundaries (Fig. 4).

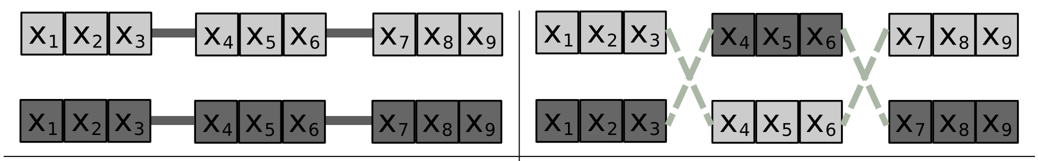


Figure 4: Organising production. In the integrated case, sub-product combinations are fixed. In the disintegrated case, different sub-product combinations are possible.

Alternatively, sub-products could be made by different manufacturers which would interact in a market to produce the final product (*disintegrated setup*). In this case, each manufacturer develops her sub-product independently and then attempts to combine it with complementary

[4] Please note that the degree of modularity is fixed in our model. We do not investigate what the best decomposition of the production process is or whether rationally bounded firms can "find" it (as in Marengo and Dosi (2005); Dosi *et al.* (2003); Marengo *et al.* (2000)). Instead, α is an independent variable in our model.

sub-products from other manufacturers. This means that we have the freedom to pick any combination of sub-products.

The model developed in Section 3 addresses the question of how the benefits to (dis)integration relate to the degree of product modularity (α). The answer will depend on [i] the relative advantage of fixed versus flexible combination of sub-products and [ii] the behavior of business units in the (dis)integrated setup.[5] The latter is described in the following section.

3 Model dynamics: Industry organization and efficiency

In order to compare the efficiency of firms and markets for differently modular production processes, we need an evaluation criterion. In the present model, we use product quality as the measure of efficiency, arguing that quality determines the utility that the product generates for the user. As a result, all quality values are relative and higher values are assumed to be preferred. Consequently, firms in the model try to maximise the quality of their (sub)product.

A framework that gives a recipe for calculating a quality value based on the configuration of (interdependent) activities is the N/K model Kauffman (1993).[6] This framework proceeds by representing a system (the production process) as a collection of N elements $x_n \in \{x_1, x_2 \ldots x_N\}$ that can take on two different states $a_n \in \{0, 1\}$. The N/K model then defines that the state of each activity contributes to the quality of the entire product, i.e. a_n has a quality contribution w_n which is determined as a random draw from a uniform distribution between 0 and 1.[7] The model then introduces interdependence between activities by arguing that the state of one activity influences the quality contribution of another. If interdependencies exist, we read $w_n(a_n, Y)$ as the quality contribution of a_n given that other variables have those states that lead to the final product configuration Y. If K denotes the number of activities that x_n depends on, then $w(a_n)$ has 2^{K+1} (randomly drawn) values: One for for each possible combination of a_n with the states of the K other activities that x_n depends on.

From the states and quality contributions of individual production activities, one can derive the quality of the current configuration of the production process Y, which we use to represent product quality. It equals the average of the quality contributions of all N production activities:

$$W(Y) = \frac{1}{N} \sum_{n=1}^{N} w_n(a_n, Y). \tag{1}$$

[5]One would expect that independent manufacturers face very different behavioral incentives than firm departments, even if they are developing the same sub-product.

[6]While there are multiple ways of constructing utility values, the N/K model offers a variety of benefits in the context investigated here. One of these is flexibility of implementation: various market or firm models are possible. Furthermore N/K provides an external performance criterion by determining quality values for all configurations of production. Finally, the model avoids an over-parameterization by determining quality values randomly. Thus, we do not have to argue for the assignment of a quality value for each specific production activity, i.e. there is no need to determine what value an activity like research has for the final product.

[7]The closer w_n is to 1, the higher the quality contribution of the corresponding state a_n.

In analogy to total product quality $W(X)$, we can also determine the quality of a sub-product X_i in the context of a given set of complementary sub-products. This quality is again equivalent to the average of quality contributions of those activities that yield the respective sub-product:

$$W(X_i, Y) = \frac{I}{N} \sum_{n=(i-1)*\frac{N}{I}+1}^{i*\frac{N}{I}} w_n(a_n, Y). \tag{2}$$

$W(X_i|Y)$ denotes the quality of the configuration of sub product X_i *if* it is combined with the other sub-products leading to the final product Y. Figure 5 illustrates this: To evaluate sub-product X_2, we set it in the context of a product Y, which means that the states for the activities in other sub-products (X_1 and X_3) are taken as given.

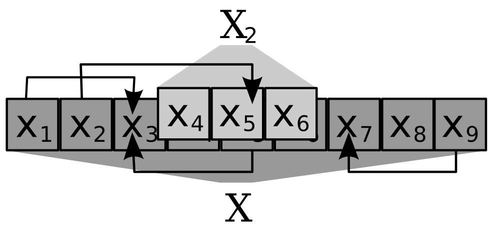


Figure 5: To assess the quality of sub-product X_2, we need a context $Y = (X_1, X_3)$ as there is an external dependency (x_2 to x_5) influencing the fitness of element x_5 in X_2.

For each configuration of production activities, the N/K model thus provides a quality value. These quality values are determined once and remain fixed, thereby forming a "landscape" of different configurations of production activities and their corresponding quality values. The N/K model thereby allows for a direct comparison of the relative effectiveness of the integrated and disintegrated setup simply by comparing the product quality that either mode of organization delivers. This relative performance will be driven by agent- ("search", "adoption") and industry-level ("assembly") dynamics in both setups, which are now introduced in more detail.

3.1 Search

To start the model, all agents (firm departments in the integrated and manufacturers in the disintegrated setup) are endowed with an initial configuration of activities for their sub-product. All agents then search for a better configuration of these activities, i.e. one that delivers better quality. This *search* is implemented as a one bit mutation of the agent's activities $X_{i,j}^{(t)}$.[8] This produces a configuration $\tilde{X}_{i,j}^{(t+1)}$ differing in the state of one activity from $X_{i,j}^{(t)}$. Moving from $X_{i,j}^{(t)} = 010$ to $\tilde{X}_{i,j}^{(t+1)} = 011$ would constitute an example. This search activity takes place in *each* simulation step and is conducted in parallel by *all* agents.[9]

[8] We are using the superscript to denote time, where t is the current simulation step and $t+1$ the next.

[9] The amount of search (i.e. the number of activity states changed) is a key performance determinant in the N/K framework (Auerswald *et al.*, 2000; Kauffman *et al.*, 2000; Kauffman and Macready, 1995; Kauffman, 1993).

Search activity is identical in both cases, suggesting that firm departments and independent manufacturers have similar capabilities in improving their sub-products. While this may be a heavy simplification in real life, the focus of the present analysis is on the relative advantage of different forms of organization. Endowing agents with different search capabilities would introduce an additional parameter in the analysis that is not of direct relevance to the question addressed here. In addition, it is difficult to justify an advantage of firm departments or independent manufacturers in sub-product development: The latter enjoy a specialization advantage insofar as they focus exclusively on a subset of the entire production process (Becattini, 2002; Marshall, 1920; Paniccia, 2002) whereas the former benefit from many scale and scope effects (e.g. regarding resource availability). As a result, we are aware of the importance of agent search ability but leave this concern for later analysis. The differences between the disintegrated and integrated case then arise in the adoption of new sub-product configurations (as agents face different behavioural incentives) as well as in the assembly of the final product. Both are elaborated in the following sections.

3.2 Disintegration

The disintegrated setup has the advantage that sub-products are assembled flexibly. A "good" manufacturer of one sub-product is therefore able to search for "good" manufacturers of complementary sub-products. However, agents pay for this freedom with greater uncertainty in adopting sub-product configurations. First, there is uncertainty about the partners with whom one will assemble a final product since there may be a different matching every time. Second, all agents conduct their search activity simultaneously implying that there is uncertainty about what the future configuration of other sub-products will be. As a result, manufacturers wanting to adopt a sub-product configuration have to make assumptions about the configurations of other sub-products, which may turn out to be incorrect (Axelrod and Cohen, 1999). Both aspects are reflected in the adoption and assembly dynamics of the disintegrated setup.

3.2.1 Adoption

Through search, all manufacturers in the disintegrated setting arrive at a tentative new sub-product configuration $\tilde{X}_{i,j}^{(t+1)}$. Adoption then determines, whether this configuration is chosen over the previous one ($X_{i,j}^{(t)}$). As agents in the disintegrated setup are autonomous, they make opportunistic decisions: They select the alternative which optimizes the quality of their sub-product without considering effects on the quality of complementary sub-products. One question remains: As there may be external dependencies in the production process, in which context do manufacturers assess the quality of these alternatives?[10] We assume that all firms try to contribute the best final product. As a result, they try to develop sub-products that would be

In addition, the number of production activities per agent matters. As both parameters are identical in the integrated and disintegrated setup, they do not interfere with our results on their relative performance.

[10]Each firm has to make assumptions about the final product it will contribute to (see also Section 2).

suited to the configuration of the top product (Y^*). Unfortunately, the firms do not know who will contribute to the top product in $t+1$ and what sub-products the other firms will offer. So, the present best product $Y^{*(t)}$ becomes the common benchmark, meaning that each firm evaluates its old and new sub-product configuration as if they were to be integrated in the previous top product $Y^{*(t)}$. In doing so, the firm obtains an expected quality for its tentative configuration $W(\tilde{X}_{i,j}^{(t+1)}, Y^{*(t)})$ as well as for the old one ($W(X_{i,j}^{(t)}, Y^{*(t)})$. It will select the new configuration, if it provides a higher expected quality:

$$X_{i,j}^{(t+1)} = \begin{cases} \tilde{X}_{i,j}^{(t+1)}, & \text{if } [W(\tilde{X}_{i,j}^{(t+1)}, Y^{*(t)}) > W(X_{i,j}^{(t)}, Y^{*(t)})] \\ X_{i,j}^{(t)}, & \text{otherwise.} \end{cases} \tag{3}$$

3.2.2 Assembly

Final product assembly is complicated by the flexibility in relationships between manufacturers. We assume that the disintegrated setup has a "*market mechanism*" that matches sub-product manufacturers. The logic behind the market mechanism is very straightforward: Agents take the expected quality of their adopted configuration ($W(X_{i,j}^{(t+1)}, Y^{*(t)})$) to signal others in the market. Manufacturers with high expected qualities would make very attractive assembly partners able to choose other high quality firms (and vice versa). As a result, we rank agents according to their expected quality. Those producers with the best, second-best, third, etc. quality values get matched to manufacture a final product (Fig. 6).

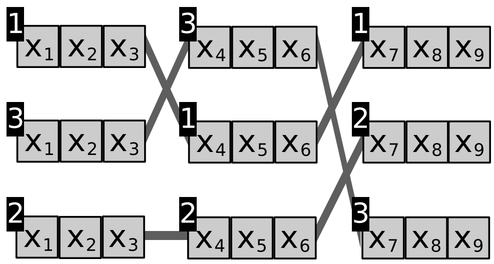


Figure 6: Product assembly in the disintegrated case: All firms are ranked (1-3) according to expected sub-product quality. Firms with the same rank contribute to one final product.

3.3 Integration

Agents in the integrated setup lack the freedom of flexible combination of sub-products that is found in the disintegrated case. This implies that a department manufacturing a "good" sub-product may be held back by departments with inferior performance in the same organization. On the other hand, the decisions made by agents in the integrated setup are not based on assumptions about the activities of others as a control instance enables coordination between departments. These aspects map out as follows.

3.3.1 Adoption

The modelling of the integrated setup (the "firm") takes its cues from Siggelkow and Rivkin (2005). It is a highly stylized model that abstracts from a variety of issues such as incentive problems in organisations. As was explained before (Section 3.1), each department generates a tentative alternative ($\tilde{X}_{i,j}^{(t+1)}$) to its current configuration ($X_{i,j}^{(t)}$). Both old configurations are presented to a coordinator, which could be the the organization's CEO. The coordinator then has the task to choose while being subject to limited cognitive power. Thus, not all possible combinations of old and new sub-product configurations are tried out. Instead, the coordinator generates one alternative configuration of the final product ($\tilde{Y}_j^{(t+1)}$) by randomly combining old and new department sub-products. In determining $\tilde{Y}_j^{(t+1)}$, she includes a new ($\tilde{X}_{i,j}^{(t+1)}$) or an old ($X_{i,j}^{(t)}$) sub-product with probability 0.5.[11] The alternative configuration ($\tilde{Y}_j^{(t+1)}$) is then tested against the status quo ($Y_j^{(t)}$) and the one with the higher quality is adopted:

$$Y_j^{(t+1)} = \begin{cases} \tilde{Y}_j^{(t+1)}, & \text{if}[W(\tilde{Y}_j^{(t+1)}) > W(Y_j^{(t)})] \\ Y_j^{(t)}, & \text{otherwise.} \end{cases} \tag{4}$$

3.3.2 Assembly

Based on the coordinator's decision, firm departments put together the sub-product configurations ($\tilde{X}_{i,j}^{(t+1)}$ or $X_{i,j}^{(t)}$) to form the final product (Y_j^{t+1}). This is illustrated in Figure 7.

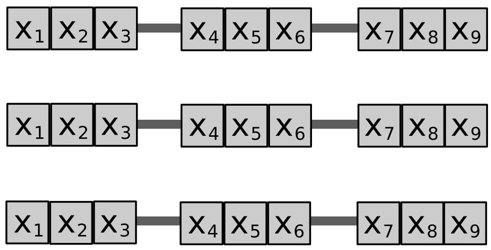


Figure 7: Product assembly in the integrated case: Firm departments (row) contribute to one final product.

For the disintegrated and the integrated setting, these dynamics of search, adoption and assembly lead to J final products with configurations $Y_j^{(t)}$ in each simulation step t. Based on these final product configurations, quality and differentiation are measured at the industry level to assess the relative performance of either mode of organising production.

[11] In this form, the implementation of the firm is a special case of the Siggelkow and Rivkin (2005) model. The integrated case in this paper is defined there as a hierarchy with parameters: COMP = ALT = 2.

4 Results: Modularity and (dis)integration

In this section, we discuss the setup and the results of simulating the model introduced in the previous section. We start with the setup by explaining the independent and dependent variables (4.1). Next we present the results (4.2) and finally we add competition to the model and investigate its effect (4.3).

4.1 Parameter settings

The model described in Section 3 was implemented[12] as follows. We use the degree of modularity (α)[13] and the type of industry organization (integrated or disintegrated) as independent variables. We simulate a production process with $N = 64$ activities. This leads to 2^{64} possible configurations of the process which represent variants of the final product. The production process is split into $I = 8$ modules (sub-products). Each sub-product is manufactured by $J = 10$ agents, bringing the total number of agents to 80. Regarding interdependence, we used $D = 32$ dependencies per sub-product. This means on average $K = 4$ dependencies per activity.[14] All results presented here are based on 500 independent simulation runs.

To know which form of industry organization is better for a certain degree of modularity, we measure product quality in each setup. We assume that the setup with higher quality will tend to be more prominent. To assess relative product quality, we measure *average product quality* ($\bar{W}$) and *top product quality* (W^*) in the (dis)integrated setup.

$$\bar{W} = \frac{1}{J}\sum_{j=1}^{J} W(Y_j). \tag{5}$$

$$W^* = \max_j(W(Y_j)) \tag{6}$$

The former measure gives insight into product quality at the level of the entire industry. The latter captures relative performance of both setups in “winner takes all” markets.[15]

Alongside product quality, we use product diversity as a second measure of efficiency when comparing the performance of the (dis)integrated setup. Product diversity can be interpreted in two fashions here. First, diversity can mean *diversity in quality.* We visualise this aspect by plotting the quality distributions. Second, one could interpret diversity as *diversity in product*

[12] The model was implemented in Java. To obtain the N/K fitness landscapes, a random number generator (Java Version 1.5.0) was used. Over 120 different setups were simulated 500 times to generate significant results.

[13] α denotes the share of external dependencies in the interrelations of the production process. See also Sec. 2.

[14] We changed the setup to include simulations with different numbers of agents ($J = 5$) or dependencies ($K = 2$ and $K = 8$), as well as with varying sizes of the production process ($N = 32$) and its modules ($I = 4$). The relative performance of the (dis)integrated setup (see Sections 4.2 and 4.3) was not sensitive to these changes.

[15] Such “winner takes all” markets are industries where the agent with the best product would eventually monopolize the market. In such a constellation, passing judgement on the relative performance of (dis)integration according to average product quality would be mislead.

configurations. To evaluate this, we measure the difference between products by calculating the aggregate Hamming distance of their production processes (assuming that differently configured production processes lead to products with different characteristics). To arrive at the aggregate Hamming distance, we start by calculating the mutual Hamming distance. For two production processes $A = a_1 \dots a_N$ and $B = b_1 \dots b_N$, it is defined as:[16]

$$H(A,B) = \sum_{x=1}^{N} \begin{cases} 1 & \text{if}[a_x \neq b_x] \\ 0 & \text{otherwise.} \end{cases} \tag{7}$$

To measure total diversity for the (dis)integrated setup, we then calculate the average of the mutual Hamming distances ($\bar{H}$) between all products. The higher $\bar{H}$, the higher the *diversity in configuration* for the respective setup.

$$\bar{H} = \frac{1}{J^2} \sum_{m=1}^{J} \sum_{n=1}^{J} H(Y_m, Y_n). \tag{8}$$

4.2 Industry organisation and efficiency

The relative performance of the (dis)integrated setup is found to be determined by the degree of modularity in the production process. When plotting average and top product quality against the share of external dependencies (α), we see that there is a break even point (Fig. 8). For non-modular production processes (high α) the integrated setting delivers best average and top product quality. More modular production processes (low α) find better average and top quality in the disintegrated case. Overall, this suggests that (nearly) modular production processes benefit from disintegration.

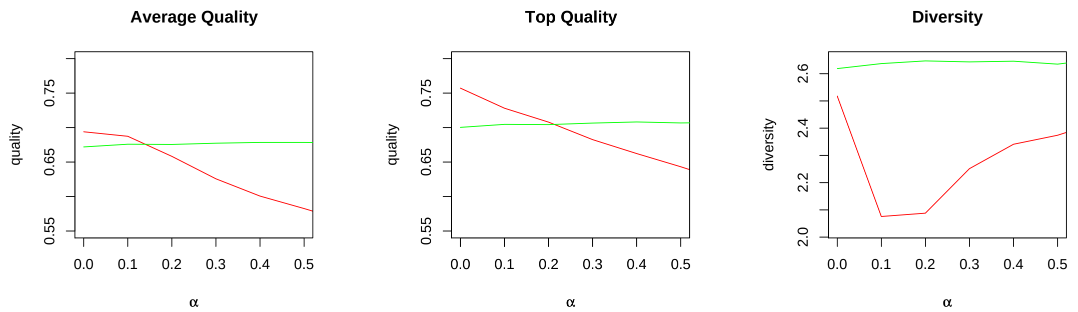
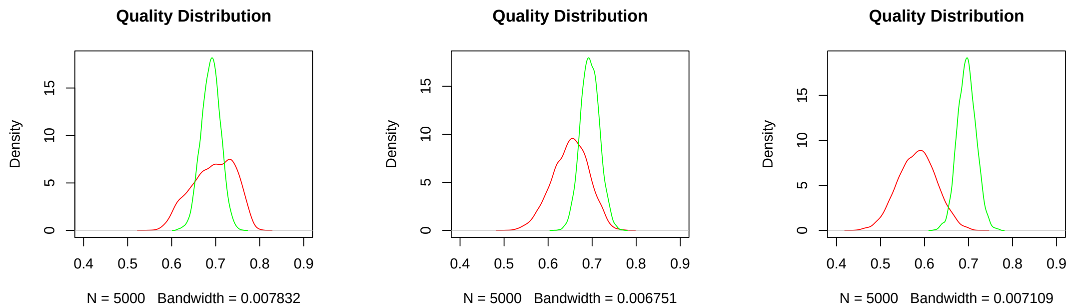


Figure 8: Average quality, top quality and product diversity in the integrated (green) and disintegrated case (red) for different values of α.
Results reported here are averages of 500 simulations measured at the final simulation step.

[16]The Hamming distance $H(A, B)$ of processes A and B gives the number of production activities with different states. For instance, if $A = 110$ and $B = 101$, then $H(A, B) = 2$ as the states of x_2 and x_3 differ.

Regarding diversity, findings are not that intuitive. A plot of the quality distribution in either setup (Fig. 9) reveals that the disintegrated case exhibits greater diversity in quality as it has a higher quality variance. Diversity in quality is lower in the integrated case as its quality distribution is more concentrated around the average.



$\alpha = 0.0$ $\alpha = 0.25$ $\alpha = 0.5$

Figure 9: Product quality distribution for different α in integrated (green) and disintegrated (red) industries.
The distribution is based on the quality of all products in the last simulation step (for 500 runs).

Findings are opposite for the diversity in configuration. As can be obtained from Fig. 8, the *integrated* case delivers greater degrees of diversity in product configuration than the disintegrated setup for all levels of α. This is opposed to conventional wisdom where modularity and disintegration are argued to be accompanied by greater variety. Instead, the disintegrated setup shows a sharp decrease in product diversity for low levels of α. This push towards more homogeneous product configurations is due to the market mechanism. As was outlined in Section 3.2.1, each manufacturer tries to improve her sub-product in the context of the best current configuration of the production process.[17] For low levels of α, the changes made by sub-product manufacturers have only limited effects on the success of other firms (those making complementary sub-products). This would result in low mutual disturbance between manufacturers, allowing agents to settle with one sub-product configuration relatively soon. As the evaluation of these configurations is done against the background of the same complementary sub-products, agents in each group of sub-product manufacturers would tend to come up with very similar configurations, thereby reducing heterogeneity in the configurations of final products. In situations with higher α this effect no longer holds as the greater mutual disturbance between agents acting independently produces more and more changes in sub-product configuration. This effect reduces the tendency of having homogeneous configurations in each group of sub-product manufacturers and thereby works to increase diversity of final products again.[18]

[17]This was seen as an attempt of all manufacturers to contribute to the best product in the market while acting under uncertainty and limited cognitive ability.

[18]In the independent setup (α=0.00), diversity is higher than in the low alpha case since agents are free to chose any configuration for their respective sub-product as the configurations of other sub-products is irrelevant for their quality. As a result, different configurations of agent sub-product may be optimal (due to internal interdependencies), thereby giving rise to greater product diversity.

From these findings, one would argue that conventional wisdom applies insofar as (nearly) modular production processes tend to favour disintegrated settings. Conventional wisdom is also confirmed for one aspect of differentiation. When looking at product quality, the disintegrated setting provides greater diversity (Fig. 9). However, this does not result from greater diversity in product configurations. Instead, it seems that quality diversity is caused by alignment problems of firms in the disintegrated setting (i.e. cases where the subproducts of matched manufacturers do not produce very well working final products). As these alignment problems increase with less modular production processes, so does the resulting quality variance.

Summing up, the present model confirms the discussion in the existing literature insofar as greater degrees of modularity allow for greater disintegration. However, we do not find support for the notion of greater variety in product characteristics if (nearly) modular products are manufactured in the disintegrated setting. While this finding is related to the assumptions about the market mechanism in the decentralised case, it does suggest that modularity and decentralisation need not always lead to a greater variance in product configurations. However, it has to be noted that the results outlined so far are set in a situation where poorly performing producers stay active in the industry. Section 4.3 therefore benchmarks the present findings against those of a model with a simple selection mechanism.

4.3 The role of competition

In order to account for competition, we include a selection mechanism in the model. Selection is implemented as least fit removal meaning that the agent with the lowest product quality is taken out. The removal takes place in equidistant time intervals (every 20 simulation steps). The removed business unit is replaced with a perfect copy of the top performing one. The rationale behind this is that the new space could be filled by a new competitor imitating the top performer or by the top performer expanding her production capacities.[19]

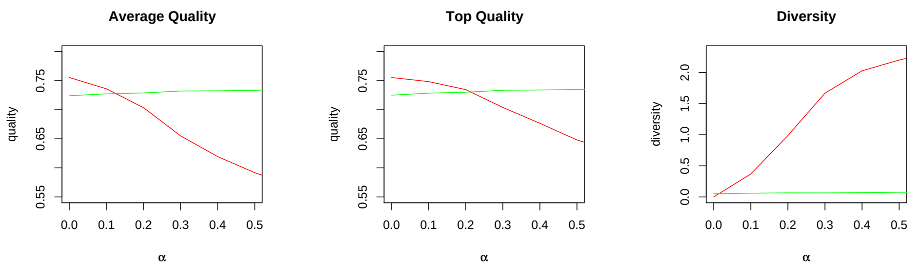
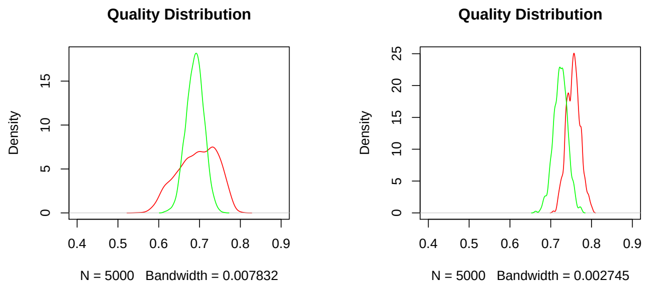


Figure 10: Competition and average quality, top quality and product diversity in integrated (green) and disintegrated industries (red) for different α.
Results reported here are averages over 500 runs (measured at the final simulation step).

[19] We are aware that the assumption of perfect imitation of top performers is a strong one (especially against the research of Rivkin (2000) or Nelson and Winter (1982)). Reducing the goodness of imitation reduced the effect of selection but did not alter the qualitative nature of the results presented here.

What emerges is that selection has little effect on the benefits to (dis)integration. Average and top quality values exhibit similar dynamics as in the model without competition, i.e. (nearly) modular production process befit disintegration and non-modular ones call for integration. What is notable, however, is the effect of selection on diversity. Selection reduces *quality diversity* in the disintegrated case and to some extent in the integrated one (Fig. 11). At the same time, average quality is increased for both settings. However, the effect of selection on product quality in the disintegrated case decreases with α, showing that it is conditional on the degree of modularity in production (results not reported here).



without competition   with competition

Figure 11: Competition increases quality and lowers its variance in a fully modular production process ($\alpha = 0.0$).
The distribution is based on the quality of all products in the last step (500 runs in total).

In both settings, the *diversity in configuration* is reduced by selection (Fig. 10). This effect is stronger in the integrated case, bringing results more closely in line with conventional wisdom: If there is competition, the disintegrated case delivers more differentiated product configurations than the integrated one. Moreover, these different configurations have similar (high) qualities if production processes are (nearly) modular. The benefits to modularity and disintegration that are emphasised in the literature thus depend on the extent of competition in the industry. If competition is strong, they materialise more strongly than in cases of little or no selection.

5 Modularity = Disintegration? The Evidence

The previous sections have outlined a model that addressed the link between product modularity and the optimal form of industry organisation (firms versus markets). It was found that disintegration delivers the suggested benefits (better product quality and greater differentiation) in situations where production processes are (nearly) modular and where competition leads to entry and exit of firms. The present section investigates this link from an empirical viewpoint. It seeks to answer two questions. Does modularity lead to greater disintegration? If this were the case, industries with modular products would have more, small firms than sectors with non-modular products. The second question then regards whether modular products lead to *overall* disintegration or to situations where most firms are small and disintegrated while a few large companies remain.

To answer these questions, the present paper proxies (dis)integration with company size. We therefore address the link between modularity and disintegration by comparing firm size distributions between industries argued to have (non) modular products. We postulate that industries with modular products should be more disintegrated. i.e. they would have lower average firm sizes as compared to sectors with non-modular products. In a second step, we investigate the firm size distributions of modular product industries more closely in order to assess whether modularity leads to overall disintegration or not. We find that sectors with modular products tend to be more disintegrated than those with non-modular ones. However, disintegration is not necessarily an encompassing feature. Some industries (cutlery, footwear and furniture) show overall disintegration as is suggested by comparatively small average firm sizes and low standard deviations. In other industries (aerospace, automobile, computers and semiconductors), average firm sizes are larger and their distribution is more broad (higher standard deviations), indicating that small and large firms co-exist. Overall, these findings suggest that the effect of modularity on the degree of (dis)integration is mediated by industry-specific factors which could be imagined to lie with aspects like minimum scale of production, R&D intensity or stage of the life cycle. A direct link between modularity and disintegration as postulated in some of the existing literature (Baldwin and Clark, 1997; Sanchez and Mahoney, 1996) is not supported by the evidence.

The following sections elaborate on these findings in more detail. Section 5.1 introduces the data source and discusses the intuition underlying our classification of sectors as industries with (non)modular products. The following section (5.2) presents the findings on modularity and (dis)integration. Section 6 concludes.

5.1 Data

As the degree of (dis)integration cannot be measured directly from available data, we have to find suitable proxies. While a variety of possible indicators spring to mind (e.g. firm numbers, degree of integration in their international operations), we focus on a variable that is readily obtained from available data sources and that has a direct link with (dis)integration: *firm size*. We argue that - all else held equal - more integrated sectors should find larger manufacturers as firms have to conduct a greater number of production activities in house. As the integrated setting delivers better results for non-modular production processes, we expect average firm sizes to be greater for non-modular product sectors than for industries with modular products. We proxy firm size by two variables that are often used in the literature on company growth and industrial dynamics (Mansfield, 1962; Sutton, 1997; Hart and Prais, 1956; Hymer and Pashigian, 1962): *total assets* as well as the *number of employees*.[20]

[20]The advantage of using both indicators is that it allows us to control for potential bias between industries. For instance, capital-intensive industries could have higher average values for total assets, regardless of their degree of integration. The opposite holds for labour-intensive sectors. By investigating both proxies for company size, we

A second requirement for the analysis is that we need to gather data on firm size distributions in sectors with modular and non-modular products. In selecting suitable sectors, we focussed on manufacturing industries where most of the discussion on modularity and (dis)integration has taken place. When classifying sectors as having (nearly) modular and non-modular production processes, some intuition was applied. Out of all manufacturing sectors, the following were judged as having (nearly) modular production processes (akin to Baldwin and Clark (1997); Sanchez and Mahoney (1996)): Aerospace (including parts), Automobile, Computer & Peripherals, Cutlery & Handtool, Footwear, Office Furniture and Semiconductors. The distribution of manufacturing activity in the European Aircraft industry (which is shared between different locations in the respective member states) would suggest that production is (nearly) modular. In a similar vein, Automobiles as well as Computer & Peripherals or Semiconductors have been subject to a strong trend towards interface standardisation in order to obtain modular product architectures. Finally, Footwear, Office Furniture and Cutlery/ Handtool are sectors found in clusters where production of the final good is conducted in a division of labour between local firms (Becattini, 2002; Bresnahan *et al.*, 2001; Marshall, 1920; Paniccia, 2002). To allow for this, their production processes have to be (nearly) modular.

Sectors judged as having non-modular production processes include the manufacturing of: Aluminia & Aluminium, Basic Chemicals, Iron/ Steel & Ferroalloy, Petroleum/ Coal, Pharmaceuticals as well as Rubber (Braunerhjelm *et al.*, 2000; Coombs and Metcalfe, 2002). Most of these products have non-modular production processes as activities in one stage (e.g. material composition in the foundry stage) have significant impact on how the product can be processed in later stages (like rolling). Moreover, timing of different production steps (e.g. in chemical production) and transportability of intermediate products (like molten steel or aluminium) act as additional sources of interdependence. In the case of Pharmaceuticals, the strong feedback between production and clinical trials over the course of the drug development process constitutes a source of complexity and non-modularity in the production process.[21]

5.2 Findings

We measured firm size distributions (in terms of total assets and employees) for the aforementioned sectors by taking 2006 data on all firms (worldwide) that had the corresponding industry (4-digit NAICS) as their main field of activity. The data was obtained from the ORBIS[22] database, which contains information on public and private companies around the world, including 135 countries and approximately 19 million companies. For all firms listed in an industry, we eliminated those observations where the respective information was not available and those companies that were classified as inactive. The resulting number of observations is given

are more certain that any size differential is related to the degree of (dis)integration in the sector.

[21] Pharmaceuticals could be a critical industry. While production tends to be non-modular in the later stages (drug approval), there is a division of labour in very early stages where small dedicated biotech firms specialise in drug discovery. As, non-modularity applies to most of the production process, the industry is classified accordingly.

[22] Orbis provides income and cash flow statements, balance sheet information and different profitability ratios as well as news, ownership and subsidiary information for these firms. See `http://www.bvdep.com/en/ORBIS.html`.

in Table 1. To allow for a better comparison between sectors (especially regarding the higher moments of the distribution), *logarithms* of total assets and employee numbers were used. The results of this enquiry are summarised below.

Table 1: Size distributions in modular and non-modular product industries

Total Assets[a]	Code[b]	Average	Std	Skew	Kurtosis	N[c]
Aerospace	3364	9.3050	3.3647	0.3090	2.6937	360
Automobile	336x[d]	9.4839	2.4560	-0.0036	3.8902	2,714
Computer	3341	7.6245	3.0440	0.2086	2.8627	1,382
Cutlery	3322	7.1381	1.9317	0.1041	3.5594	1,511
Footwear	3162	7.9546	1.9105	0.2156	3.9026	1,001
Furniture	3372	6.8092	2.2787	-0.4974	3.1729	2,231
Semiconductors	3344	9.6131	2.2906	-0.1845	3.3816	3,232
Aluminium	3313	9.2319	2.2933	-0.4661	4.0826	549
Chemical	3251	9.0182	2.8211	-0.2100	2.9929	1,570
Iron	3311	9.7787	2.5367	0.1583	3.2276	714
Petroleum	3241	10.2381	2.6837	0.5703	3.2645	482
Pharmaceutical	3254	9.3749	2.9734	-0.3792	3.2529	2,421
Rubber	3262	7.7366	2.6534	0.0383	3.1460	1,435

Employees[e]	Code	Average	Std	Skew	Kurtosis	N
Aerospace	3364	4.3946	2.8318	0.4299	2.5590	360
Automobile	336x	4.5767	2.0980	0.3239	3.6780	2,714
Computer	3341	3.4378	2.1431	0.9018	3.8916	1,382
Cutlery	3322	2.7958	1.5613	0.3805	3.5755	1,511
Footwear	3162	3.4163	1.7175	0.8917	5.8915	1,001
Furniture	3372	2.8813	1.3419	0.3358	3.6223	2,231
Semiconductors	3344	4.6811	2.1187	0.1448	2.9158	3,232
Aluminium	3313	4.1615	1.7225	0.3732	3.8293	549
Chemical	3251	4.0570	1.9123	0.3639	3.2571	1,570
Iron	3311	4.1890	2.1929	0.6010	3.5143	714
Petroleum	3241	4.0871	2.2312	0.6349	3.1943	482
Pharmaceutical	3254	4.3848	2.0376	0.3592	3.2284	2,421
Rubber	3262	3.6029	1.9496	0.7396	3.9569	1,435

[a]Logarithms of total assets (measured in thousands of USD).
[b]NAICS 2002 classification.
[c]Number of observations.
[d]Automobile contains NAICS 3361 (Motor Vehicle Manufacturing) and 3363 (Parts Manufacturing).
[e]Logarithms of employee numbers.

When measuring firm size with *total assets*, the findings support the notion of a link between product modularity and disintegration. Comparing average firm sizes between modular and non-modular product industries reveals that the latter tend to have larger firms on average.

Moreover, firm sizes are similar in these sectors as is evidenced by the low standard deviations. This would suggest that non-modular product industries tend to be more integrated insofar as they host many large firms.[23] In modular product industries, there seem to be two groups with respect to the extent of disintegration. Some sectors show overall disintegration (Cutlery, Footwear, Furniture), which is evidenced by low average firm sizes and low standard deviations. Other sectors (Aerospace, Automobile, Computers and Semiconductors) seem to be partially disintegrated while also retaining large companies. Figure 12 plots the histograms of logarithmic firm sizes for three industries. It shows that the second group of modular product industries (Computers) has a broader distribution of firm sizes hosting small and large firms, with a stronger role for small companies. The first group (Furniture) in contrast witnesses a relatively even and much more narrow distribution of firm sizes. In contrast, the distribution of firm size in the non-modular sector (Chemicals) is much more symmetric around a higher average. Summing up, the findings on total assets reveal that modular product industries are not uniformly disintegrated. While product modularity tends to favour disintegration relative to non-modular product sectors, some industries do retain a role for large firms while others do not. It therefore seems as if the link between modularity and (dis)integration was influenced by industry-specific features.

Figure 12: Histogram of firm size distributions (total assets) in modular (left and center) and non-modular (right) product industries
Results are logarithms of total assets (thousands of USD).

When measuring firm size in terms of *employee numbers*, findings are similar. With the exception of Chemicals and Iron, all non-modular product sectors have lower standard deviations suggesting that they again have very similar firm sizes. Comparing average firm sizes, the aforementioned grouping of modular product industries emerges once more: Companies in the 'disintegrated' group of modular product industries (Cuterly, Footwear, Furniture) are still smaller than firms in the non-modular product sectors as well as firms in the partially integrated modular product industries. The second group (Aerospace, Automobile, Computers, Semiconductors) in turn has similar average firm sizes as non-modular product sectors but exhibit a greater standard

[23]Results on skewness and kurtosis also indicate that these distributions are reasonably symmetric and not excessively tailed relative to a normal distribution. See also the top part of Table 1.

deviation, suggesting that there are more extreme realisations in terms of firm size than in the non-modular product industries (see bottom part of Table 1).

Figure 13: Histogram of firm size distributions (employees) in modular (left and center) and non-modular (right) product industries
Results are logarithms of employee numbers.

A closer look at the distribution of firm sizes for the previous sample industries reveals that the size distribution in the non-modular sector (Chemicals) is still relatively symmetric and exhibit a higher average than that of the non-modular industries. In these sectors, small firms are predominant regarding their absolute numbers. Once more, the size distribution in the partially disintegrated case (Computers) is far broader than in the generally disintegrated industry (Furniture). These findings suggest a link between product modularity and disintegration. The degree to which disintegration is an encompassing phenomenon however differs again between modular-product sectors.

6 Conclusion

The present paper set out to study the link between product modularity and the degree of (dis)integration in an industry from a theoretic and empirical perspective. It started out by developing a model able to assess, for which degrees of modularity in products and production, firms or markets were preferable. In line with existing work (Baldwin and Clark, 1997; Langlois, 2002; Sanchez and Mahoney, 1996), a minimum degree of modularity is required for a disintegrated organisation of production. Put differently, fully and nearly modular production processes allowed for disintegration. Non-modular ones required integration into firms to be efficiently conducted. Beyond this, the paper showed that the benefits to modularity and disintegration (namely greater product quality and in particular *variety*) are conditional on the existence of competition and selection. In absence of competition, integrated firms delivered more differentiated products (regarding their configuration), which is opposite to conventional wisdom. As a result, we can conclude that (nearly) modular products do favour disintegration but their second benefit (greater product differentiation) is conditional on competition.

The empirical part of the paper then set out to investigate if disintegration is a general phenomenon in modular product industries. Using firm sizes as a proxy for the degree of (dis)integration and comparing modular and non-modular product sectors shows a link between modularity and disintegration. However, the strength of this link differs between industries. In some cases, product modularity is accompanied by widespread disintegration (Cutlery, Footwear, Furniture). In other sectors (Aerospace, Automobile, Computers, Semiconductors), part of the industry is disintegrated while several large firms (which may correspond to the 'systems integrators' of Langlois (2002)) remain. In the present sample, the second type of industries has strong scale requirements and high R&D intensity in final product design and assembly. This would lend a natural role to some large end-producers able to provide the required resources and investment while many suppliers could be relatively small. More extensive empirical analysis would be required to determine whether this finding is related to the present sample or whether scale and research concerns (among many other industry-specific factors) do play a role in mediating the link between product modularity and (dis)integration. So far, the findings do suggest that this link may well be more nuanced than sometimes acknowledged.

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