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Vanishing hands? On the link between product and organization architecture

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The present article investigates whether modular product architectures deliver better and more differentiated products, given their production in disintegrated and integrated settings. A theoretic model benchmarks the performance of disintegration and integration for different degrees of product modularity by measuring both product quality and differentiation. In line with conventional wisdom, (nearly) modular products befit disintegration insofar as disintegration increases quality. However, disintegration only leads to greater product differentiation than integration if there is substantial entry and exit. These findings—albeit developed with stylised models of disintegration and integration—provide a possible explanation for empirical results showing a decrease in product variety when modular products were produced by independent manufacturers (disintegration). Moreover, the model results predict that industries with limited entry and exit as well as strong winner-take-all dynamics tend to incur a loss in variety if modular products are produced in a disintegrated setting.

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 (Williamson, 1991; Langlois, 1988, 1992b; Mahoney, 1992; Dosi *et al.*, 2007 among many others), an important factor in the choice of firms or markets lies with the nature of products. It is sometimes even argued that "although organizations ostensibly design products, it can also be argued that *products design organizations*, because the coordination tasks implicit in specific product designs

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largely determine the feasible organization designs" (Sanchez and Mahoney, 1996: 64).

This link of product and organization architecture has received renewed attention with the emergence of modularity. Originating with engineering science, modularity denotes a principle for splitting a product into sub-products that are connected via standardized interfaces. It aims at obtaining (nearly) independent sub-products (Langlois, 2002). Once the architecture and interfaces are established, sub-products can be developed and modified independently, which is argued to lead to greater product differentiation (mix and match, Prencipe *et al.*, 2003), more robust production processes (Langlois, 2002; Simon, 2002) and faster innovation (Langlois and Robertson, 1992; Sanchez and Mahoney, 1996; Baldwin and Clark, 1997; Sturgeon, 2002).

While a number of contributions discuss the benefits and downsides of modular product architectures (Robertson and Langlois, 1995; Baldwin and Clark, 1997; Christensen *et al.*, 2002; Langlois, 2002; Ethiraj and Levinthal, 2004), their emergence (Langlois, 1992a, 2002) as well as their current and expected future prominence (Langlois and Robertson, 1989; Langlois, 2003, 2004, 2006), the interplay of product modularity and firm boundaries is more blurred. While the (near) decomposability of products achieved through modularity is argued to foster the emergence of independent producers and thereby greater disintegration (Sanchez and Mahoney, 1996; Baldwin and Clark, 1997; Chesbrough and Kusunoki, 2001; Christensen *et al.*, 2002),[1] others maintain that modular products require some firms acting as "systems integrators" for coordinating sub-product manufacturers and to enable innovation in the product architecture itself (Brusoni and Prencipe, 2001; Langlois, 2002; Sturgeon, 2002; Dosi *et al.*, 2007).

Empirically, both structures have been observed. Industries have shifted from disintegrated to more integrated settings and back throughout their evolution (Christensen *et al.*, 2002). In some instances, a shift towards more integrated modes of organization was caused in response to competitive pressures rather than changes in the product's architecture (e.g., in several Italian industrial districts, Guerrieri *et al.*, 2001; Paniccia, 2002; Cainelli and Zoboli, 2004). Another interesting observation put forth by Christensen *et al.* (2002) and to some extent Deakin *et al.* (2009) is that in some industries, modularity and disintegration were found to reduce product differentiation. The issue that remains open in these investigations is whether it is modularity causing this or its combination with disintegration. Put differently, how does (dis)integration in the organizational architecture affect the benefits to modularity?

[1]This is in line with related findings in organization studies, where (nearly) modular production processes benefit firms with very independent departments (Frenken *et al.*, 1999; Marengo *et al.*, 2000; Simon, 2002; Dosi *et al.*, 2003).

While the benefits of modularity for product variety through mix-and-match are best achieved in disintegrated settings with very flexible producer relations, overall product quality may well require some degree of integration to ensure coordination between sub-product manufacturers. With more stable producer relations, less mixing and matching may occur at the expense of overall product variety. The question investigated here is the effect of coordination versus mix-and-match achieved in integrated and disintegrated settings for overall product quality and diversity. To study this aspect, Sections 2 and 3 develop a model analyzing the relative efficiency of (dis)integrated structures in manufacturing products with different degrees of modularity. Both settings are archetypal and developed to emphasize the benefits of *coordination* versus *mix-and-match*. In contrast to most of the literature, we measure efficiency through product quality and variety, thereby also investigating under which conditions disintegration and the associated mix-and-match dynamics lead to greater product differentiation.

As a result, we obtain a model where the stylized dynamics of coordination or mix-and-match yield better performance depending on product architecture. This enables us to give a more precise answer about when modularity befits (dis)integration. Moreover, we are able to investigate, in how far the benefits for product quality and variety suggested in the literature are delivered. The model confirms existing arguments (Section 4) insofar as modularity is required for disintegration and mix-and-match dynamics to achieve better *quality*. For very interdependent product architectures, quality is instead improved by integration and coordination. However, modular products manufactured in the disintegrated setting are only more *varied*, if there is entry and exit. Without entry and exit, the coordination provided by more integrated organizational structures provides greater variety for both low and high levels of modularity.

2. The model

We start by modelling a product through its production process. Both are treated as interchangeable in the following. It is argued that any particular part in the product has its equivalent in the production process, i.e., each of the N activities in the production process contributes to one particular feature in the final product. While this is a simplification of actual production processes, some level of modularity in both product and production process is required to allow for disintegration at the organizational level. Without both aspects, producers of product component would not be able to operate independently and could not offer distinguishable sub-products. Therefore, the following arguments about the structure of the production process are equivalent to the architecture of the final product.

Each of the N production activities (x_n) can be conducted in a specific way represented by its state a_n. For simplicity, activities can only take states 0 or 1 here. The

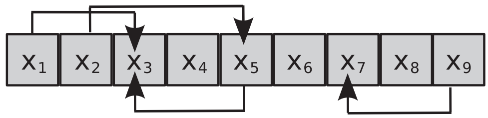

Figure 1 A product represented by $N = 9$ production activities.

full set of production activities $Y = x_1x_2...x_n$ then corresponds to the entire production process and thereby the final product (Figure 1). Depending on the activity states chosen, the production process and thus the product has a specific configuration of 0 and 1 labeled $C = a_1, a_2...a_n$.

The success of conducting an activity in a particular way ($a_n = 0$ or 1) can differ, i.e., each activity state has a "fitness value" (w_n) associated with it. Moreover, production activities can be interdependent, i.e., the fitness of one activity (w_i) hinges on the choice made for the state of another (a_j). This is illustrated by the arrows in Figure 1. Fitness values are assigned through a random draw from a uniform distribution between 0 and 1 as in the *N*/*K* model (Kauffman, 1993). Higher w_n denote higher fitness values of the corresponding state a_n. In case of interdependent activities, one w_n is drawn for each possible combination of activity states.

From the states and fitness values of all activities, one can derive the fitness of the current configuration of the production process. It is equal to the average of the fitness values of all production activities and represents product quality:

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

The product's architecture is implemented as follows: the production process is split into subsets 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, or tires. We represent this by partitioning production into I equally sized modules $Y = X_1X_2...X_I$. Each module then gives rise to one sub-product (Figure 2).

The partition is implemented such that each production activity is on one module only, i.e., there is no overlap between modules as far as production activities are concerned. However, splitting the production process can generate interdependencies between sub-products, which are labeled external dependencies. In Figure 2, for example, splitting Y into $X_1 - X_3$ leads to two internal dependencies [between activities (1, 3) in X_1 and (9, 7) in X_3]. Two other dependencies [between activities (2, 5) and (5, 3)] are now external insofar as they connect modules X_1 and X_2.

The share of these external dependencies (α) proxies the degree of non-modularity by defining to what extent sub-products depend on each other. With $\alpha = 0$, modules are fully independent, corresponding to a modular production process with no external dependencies. For the process in Figure 2, we find two

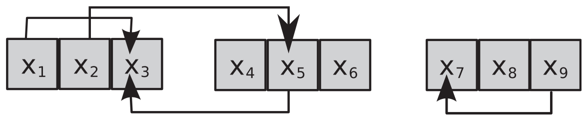

Figure 2 The product from Figure 1 is split into $I = 3$ modules. Now, we can differentiate between internal $\{(x_1, x_3), (x_9, x_7)\}$ and external $\{(x_5, x_2), (x_5, x_3)\}$ dependencies.

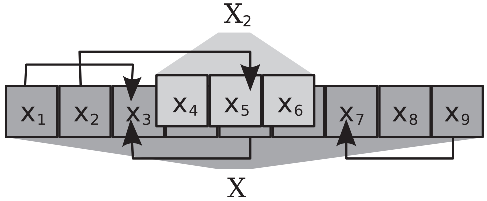

Figure 3 To assess the quality of sub-product X_2, we need a context $Y = (X_1, X_3)$ as there is an external dependency (x_2 to x_5) influencing the fitness of X_2.

internal, two external, and four dependencies in total. The share of external dependencies would be $\alpha = 0.5$ (50%), making this process lean towards the non-modular end of the spectrum.[2]

Similar to overall product quality, sub-product quality $W(X_i, Y)$ is equivalent to the average of the fitness values of all activities in that sub-product.

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

Due to the possibility of having external dependencies, $W(X_i|Y)$ reads as the quality of X_i in the context of a product with overall configuration Y. The context is essential for the value of X_i. Since w_n is drawn for every possible combination of interdependent activities, knowing the fitness value associated with a state a_n in sub-product configuration X_i, requires knowledge of the states of any a_i that a_n is interdependent with. To obtain the quality of sub-product X_2 in Figure 3, we have to set it in the context of a final product Y in order to know the states of interrelated activities in other sub-products.

To include several products and producers into the model of an industry, we assume that there are J final products, leading to $J \times I$ sub-products. Each

[2]The degree of non-modularity (α) is an independent variable in our model. Unlike some other studies using the *N/K* framework (Marengo *et al.*, 2000; Dosi *et al.*, 2003; Ethiraj and Levinthal, 2004; Marengo and Dosi, 2005), we do not investigate what the best decomposition of the process is or whether rationally bounded firms can "find" it. Moreover, thanks to our model setup, we can directly influence α making it independent from the exact partition of the production process.

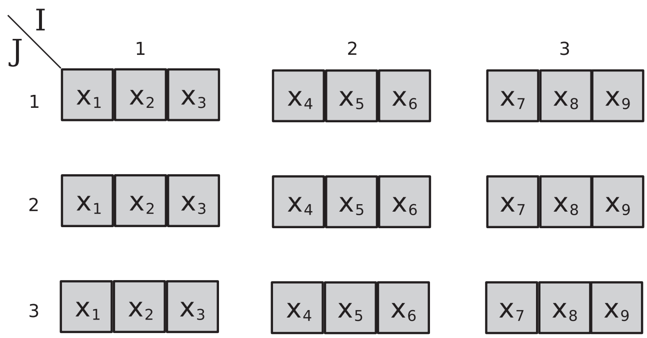

Figure 4 An industry with J agents each producing one of the I sub-products. Columns are groups of sub-product manufacturers, while lines correspond to one final product.

sub-product is manufactured by one agent. Figure 4 depicts a setting, where $I = J = 3$. $X_{i,j}$ then denotes the activities of the j-th agent manufacturing sub-product i. In the figure, $X_{1,3}$ refers to the activities of the third agent manufacturing the first sub-product (at the bottom of the first column).

The question of the relative advantage of (dis)integration comes into play when looking at different ways of organizing production at the industry level. On the one hand, one could imagine that each product is made in a firm-like setting (*integration*). In this case, sub-products are manufactured by departments and final product assembly is fixed (Figure 5A). On the other hand, sub-products could be made by different producers that interact in a market-like setting to assemble the final product (*disintegration*). In this case, each producer develops her sub-product independently and then combines it with complementary sub-products from other manufacturers (Figure 5B).

In the following, we ask how the benefits of (dis)integration relate to the degree of product (non)modularity (α). The answer will depend on (i) the relative advantage of fixed or flexible product assembly and (ii) the behavior of manufacturers and firm departments. Both are described in more detail in the following section.

3. Model dynamics: industry organization and efficiency

To evaluate the relative performance of (dis)integrated settings for different product architectures, we use product quality (proxied by fitness) and differentiation (proxied by the differences in product configurations). Both measures highlight to what extent the benefits ascribed to modularity (better and more differentiated products) are delivered by the (dis)integrated setting.

In contrast to many existing papers using the N/K framework, quality (=fitness) is relative in our analysis. We are not concerned with whether agents do or can develop

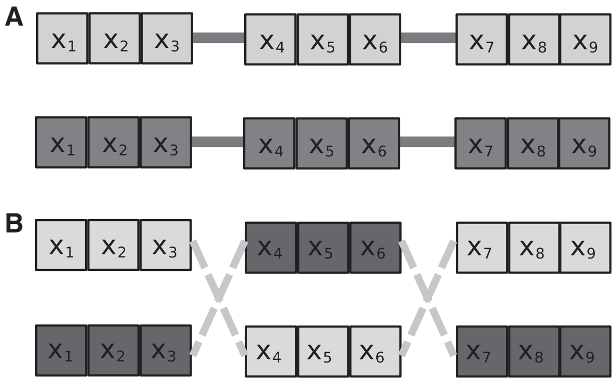

Figure 5 Organizing production. (**A**) In the integrated case, sub-product combinations are fixed. (**B**) In the disintegrated case, different sub-product combinations are possible.

the best possible product (the globally optimal configuration). Instead, we focus on whether they can find better qualities for their products than other agents in the industry. As a result, the relative performance of (dis)integration matters rather than whether either setting would (theoretically) be able to develop the best possible product.

3.1 Search

To start the model, agents (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. The tentative configuration $\tilde{X}_{i,j}^{(t+1)}$ thus differs in one activity state from the previous one $X_{i,j}^{(t)}$. Moving from 010 to 011 would be an example. Search activity takes place in *each* simulation step and is conducted in parallel by *all* agents.[3]

Search activity is identical, implying that departments and independent manufacturers have the same capabilities for developing their sub-product. While this may be a heavy simplification of real life, the focus of the present analysis is on the relative advantage of (dis)integration. Endowing agents with different search capabilities would introduce another parameter that is not of direct relevance to the question addressed here. In addition, it is difficult to justify an advantage of firm departments

[3]Search parameters (e.g., the number of activity states changed or the number of activities per agents) are key to performance in the *N*/*K* framework (Kauffman, 1993; Auerswald *et al*., 2000; Kauffman *et al*., 2000; Press, 2006). As search is identical in both setups, this does not interfere with our results. We tested this notion by implementing different search mechanisms (see Section 4.1), which did not modify the qualitative nature of the results.

or independent manufacturers in sub-product development: the latter enjoy a specialization benefit since they focus on a subset of the production process (Marshall, 1920; Paniccia, 2002), whereas the former enjoy 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 difference between (dis)integration then arises from the adoption of new sub-product configurations (due to 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 final products are assembled flexibly. A "good" manufacturer of one sub-product can therefore search for "good" manufacturers of complementary sub-products. However, this freedom means greater uncertainty about the partners with whom one will assemble a final product. The future configurations of other sub-products are thus unknown, implying that 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 adoption and assembly dynamics.

Through search, all manufacturers arrive at a tentative sub-product configuration $\tilde{X}_{i,j}^{(t+1)}$. *Adoption* then determines, whether the tentative configuration is chosen over the current one. As agents are autonomous, they make opportunistic decisions: they select the alternative that optimizes the quality of their sub-product. If the tentative configuration is better than the previous one, it will be adopted. Otherwise, manufacturers stick with their existing sub-product.

As there may be external dependencies, manufacturers need a context to assess sub-product quality (see Section 2). In the present setting, we assume that relationships among manufacturers are extremely flexible in order to maximize the mix-and-match dynamics associated with modularity and disintegration. This implies that assembly of the final product takes place through spot transactions among manufacturers. As a consequence, manufacturers do not know *ex ante*, which complementary sub-products they can acquire. In addition, higher product quality is assumed to be rewarded by consumers. All manufacturers would therefore like to be part of the best product currently known in the industry.[4]

If manufacturers seek to be part of the best known product in the industry (Y^*), they should develop sub-products suited for it. Unfortunately, due to the extreme mix-and-match dynamics, manufacturers do not know what the configuration of the relatively best product will be in $t+1$. Therefore, the current best product $Y^{*(t)}$

[4]Again, the "best" product refers to the configuration with the currently highest fitness value and not to the overall optimal product (which may well be beyond agent's reach).

becomes the common benchmark, meaning that each manufacturer evaluates her old and new sub-product configuration as if they were to be integrated in the relatively best product at time *t*. In doing so, the manufacturer obtains an expected quality for her tentative configuration $W(\tilde{X}_{i,j}^{(t+1)}, Y^{*(t)})$ as well as for the old one $W(X_{i,j}^{(t)}, Y^{*(t)})$. She adopts the new configuration, if it provides a higher expected quality:

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

For product architectures with high modularity, this mechanism ensures relatively accurate manufacturer decisions: since there are few or no external dependencies, expected product quality will be relatively close to actual product quality. With lower modularity (higher α) the errors in assessing sub-product configuration become more extreme, thereby decreasing the accuracy of manufacturer decision-making.

Given the adoption of sub-product configurations, final product *assembly* is complicated by the flexibility in relationships between manufacturers. We assume that a "market-like mechanism" matches sub-product manufacturers. Its logic is straightforward: agents take the expected quality of their adopted configuration $W(X_{i,j}^{(t+1)}, Y^{*(t)})$ to signal to others. Manufacturers with high expected qualities make attractive assembly partners able to choose other high quality manufacturers (and vice versa). As a result, we rank agents according to their expected quality. All manufacturers with the best, second-best, third, etc. expected qualities get matched to assemble a final product (Figure 6).

An alternative approach to *assembly* lies in a sequential implementation of the market-like mechanism. This would find producers of modules one and two signaling their expected quality to each other with manufacturers being matched based on their ranking. In a second step, the matched configurations of modules one and two are re-assessed regarding their expected quality and then ranked again to be matched with producers of module three. Our findings revealed that this does not alter the

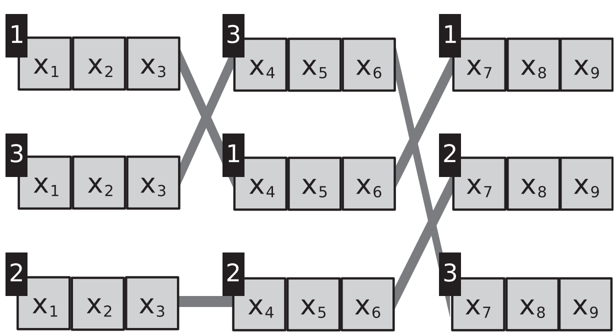

Figure 6 Product assembly in the disintegrated case: all firms are ranked (1–3) by their expected sub-product quality. Firms with the same rank contribute to one final product.

relative performance of the (dis)integrated setting. Opportunities for "bad" matches still exist in the early stages of the value chain, which implies that the greater certainty of more downstream fitness values does not offset the higher quality of decision-making in the integrated setting.

3.3 Integration

The integrated setup lacks the freedom of flexible assembly 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. At the same time, department decisions are not based on assumptions about the activities of others as a control instance enables coordination. These aspects map out as follows.

The modelling of the integrated setup is based on Siggelkow and Rivkin (2005). As was explained earlier (Section 3.1), each department generates a tentative alternative $\tilde{X}_{i,j}^{(t+1)}$ to its current configuration via search activity. It presents the current and tentative configuration to a coordinator, which could be the CEO. The coordinator then has 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 randomly combines old and new sub-products into a tentative configuration of the final product $\tilde{Y}_j^{(t+1)}$.[5] This configuration is tested against the status quo ($Y_j^{(t)}$) and the one with the higher quality is *adopted*:

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

Based on the coordinator's decision, 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 fixed *assembly* is illustrated in Figure 7.

While the thus assembled final product is certain to have a higher quality than the previous one, the integrated setup will tend to be slower in improving its products as improvements have to be obtained for the entire production process rather than for one sub-product. Moreover, fixed assembly can lead to lock-in with a specific configuration if the number of elements required to be changed for greater quality exceeds the search range of all departments taken together. As a result, the integrated setting will tend to be slower than the disintegrated one in improving product quality and may well lock-in with sub-optimal product configurations. At the same time, its lack of speed and flexibility may well be compensated for through a greater certainty about product quality, especially when the level of modularity is low (high α).

[5]Old ($X_{i,j}^{(t)}$) and new ($\tilde{X}_{i,j}^{(t+1)}$) sub-products enter with equal probability $P=0.5$.

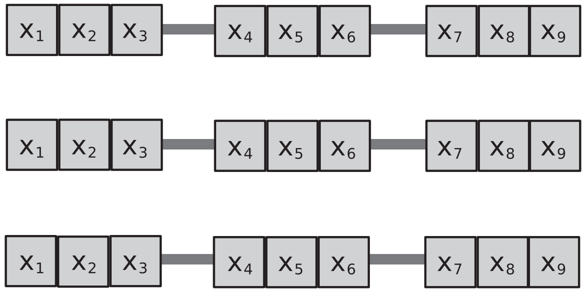

Figure 7 Product assembly in the integrated case: firm departments (rows) contribute to one final product.

4. Results: modularity and (dis)integration

In the disintegrated and integrated setting, search, adoption, and assembly lead to J final products with configurations $Y_j^{(t)}$ in each simulation step. Based on these configurations, product quality and differentiation are measured at the industry level to assess the relative performance of (dis)integration. In this section, we discuss the simulation setup and results. We start by explaining the independent and dependent variables (Section 4.1). Next, we present the results of the baseline case (Section 4.2) and then add entry and exit to the model (Section 4.3).

4.1 Parameter settings

The model was implemented[6] as follows. We use the degree of non-modularity (α) and the type of industry organization [(dis)integrated] as independent variables. We simulate a production process with $N = 64$ activities split into $I = 8$ sub-products of unit size $n = 8$. Each sub-product is manufactured by $J = 10$ agents, bringing the total number of agents to 80. Regarding interdependence, we used an average of $K = 4$ dependencies per activity. The share of external dependencies encompasses fully modular ($\alpha = 0.00$) and non-modular processes ($\alpha = 0.50$) with intermediate stages set in steps of $\alpha = 0.1$.[7] We changed this setup to include simulations with different numbers of agents ($J = 5$) or dependencies ($K = 2$ and $K = 8$), as well as varying sizes of the production process ($N = 32$) and its modules ($I = 4$). Moreover, we implemented simulations with other search mechanisms. While one-bit mutation constituted the baseline, we also included "probabilistic search", where each activity

[6]The model was implemented in Java. To obtain 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.

[7]An α-value of 0.25 thus means that one-quarter of all dependencies in the production process span sub-products. With an average of $K = 4$ dependencies per activity, each activity would then be linked (on average) to one activity outside its sub-product and to three activities within the same sub-product.

in the sub-product could be changed with varying likelihood (P). The relative performance of the (dis)integrated setup (Sections 4.2 and 4.3) was not sensitive to these changes as the decisive factors for relative performance are selection and assembly dynamics (with search being identical in both settings—see Section 3.1—it shifts overall results but not relative performance). All results are based on 500 simulation runs for each α-value.

To know which form of industry organization is better for a certain degree of modularity, we measure *average* product quality in the industry ($\bar{W}$).

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

Furthermore, we measure product diversity, i.e., *diversity in product configurations.* To evaluate this, we measure the difference between products by calculating the aggregate Hamming distance of their production processes. This assumes that differently configured production processes lead to products with different characteristics. To arrive at this measure, we start by calculating the mutual Hamming distances. For two processes $A = a_1 \ldots a_N$ and $B = b_1 \ldots b_N$, it is defined as:[8]

$$H(A, B) = \sum_{x=1}^{N} \begin{cases} 1 & \textit{if } [a_x \neq b_x] \\ 0 & \textit{otherwise} \end{cases} \tag{6}$$

To measure total diversity, we use the aggregate Hamming distance $\bar{H}$, i.e., the average of the mutual Hamming distances between all products. The higher $\bar{H}$, the higher diversity.

$$\bar{H} = \frac{1}{J^2}\sum_{m=1}^{J}\sum_{n=1}^{J} H(Y_m, Y_n). \tag{7}$$

4.2 Industry organization and efficiency

The relative performance of the (dis)integrated setup is determined by the degree of (non-) modularity. When plotting average quality in two sample runs (Figure 8a and b), the disintegrated setting outperforms the integrated one only if the product is relatively modular (here $\alpha = 0.1$). However, repeating the simulations 500 times shows that on average (Figure 8c and d), the integrated setting delivers higher quality in the long run, regardless of the level of modularity. While the more speedy optimization in the disintegrated setting delivers an initial quality advantage for relatively modular products (low α), with time the benefits to coordination start to overwhelm those of mix-and-match (Figure 8c).

[8]The Hamming distance 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.

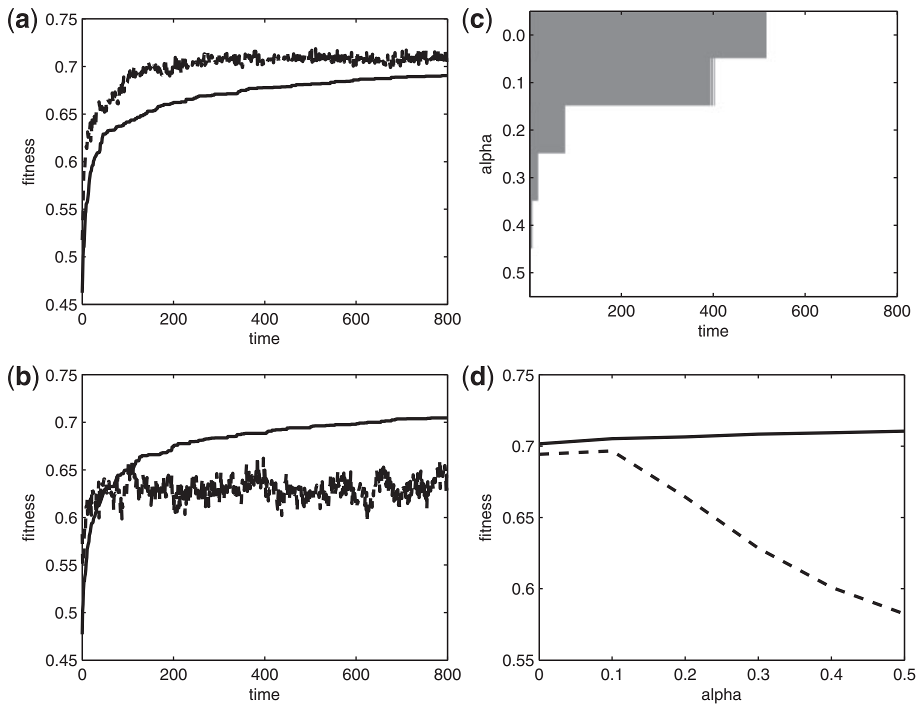

Figure 8 Product quality in the disintegrated and integrated setting over time and for different values of α. Figure (a) shows the evolution of quality in a sample run with $\alpha = 0.1$. The disintegrated case (dashed) delivers higher quality. Figure (b) contains a sample run with $\alpha = 0.3$ where the integrated case (solid) performs better in quality. Figure (c) highlights quality at each simulation step averaged over 500 runs. Grey areas correspond to higher average quality in the disintegrated case, which is most prominent in early simulation stages and for low α values. White areas denote higher average quality in the integrated setting, which concentrates on later simulation stages and higher α values. Figure (d) compares average quality values at the last simulation step with the integrated setting (solid) delivering better average quality.

The long-term advantage of the integrated setting stems from two aspects. First, product architectures that are not fully modular convey a benefit to coordinated decision-making as it accounts for all external dependencies. As mentioned earlier (Section 3.3), coordination reduces the speed to quality improvements, thereby conveying a speed benefit to the disintegrated setting. The effect of integration is thus akin to the results described by Marengo *et al.* (2000) as coordinated decision-making eliminates the errors caused by a lack of accounting for external dependencies in the disintegrated setting. However, this rationale cannot explain why the long-term performance of the integrated setting exceeds that of the disintegrated one in fully modular product architectures. The reason for this finding is instead tied to the results on product diversity.

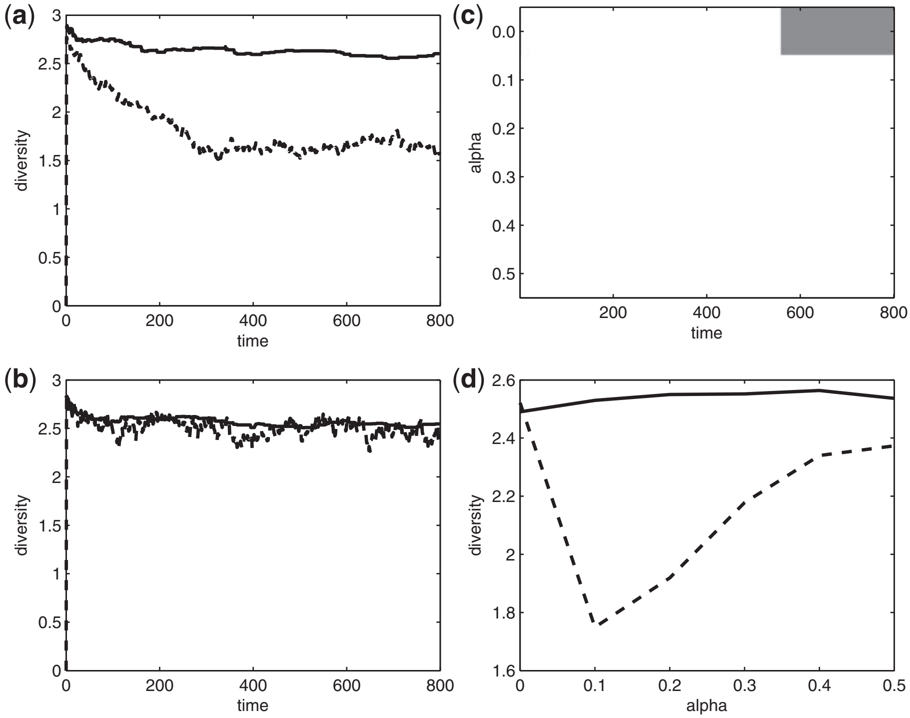

Figure 9 Product diversity in the disintegrated and integrated setting over time and for different values of α. Figure (a) shows the evolution of diversity in a sample run with $\alpha = 0.1$. The integrated case (solid) delivers higher diversity. Figure (b) contains a sample run with $\alpha = 0.3$ where both settings deliver similar diversity levels. Figure (c) highlights diversity at each simulation step averaged over 500 runs. Grey areas correspond to higher average diversity in the disintegrated case, which only occurs at late stages of simulations with low α values. White areas denote higher average diversity in the integrated setting, which corresponds to early simulation stages and higher α values. Figure (d) compares average diversity at the last simulation step with the integrated setting (solid) delivering higher average diversity if $\alpha > 0$.

When considering product diversity, the integrated setting delivers greater variety, especially for relatively modular products (Figure 9a versus b). As can be obtained from Figure 9c, the integrated case generally delivers greater diversity. The only exception to this are settings with fully or highly modular products where in the long run, diversity increases in the disintegrated setting. This finding is opposed to conventional wisdom, where modularity and disintegration are argued to be accompanied by greater product variety. Instead, the disintegrated setup shows a sharp decrease in diversity for low levels of α (Figure 9d).

The push towards more homogeneous products in the disintegrated setting is caused by the adoption mechanism. All manufacturers strive to be part of the best currently known product (see Section 3.2). For low levels of α, the activities of one manufacturer have only limited effects on others, resulting in low mutual disturbance. Therefore, agents would settle with one sub-product configuration relatively soon and optimization dynamics cease. This effect is also responsible for the lower long-term quality as compared to the integrated case, where optimization is less prone to lock-in.

Since the evaluation of these sub-product configurations is done in the same context, each group of sub-product manufacturers would come up with similar configurations, thereby reducing product variety and increasing the likelihood of lock-in. In situations with higher α, this effect no longer holds, as the greater mutual disturbance between agents produces more and more changes in sub-product configuration. This effect reduces the tendency of having homogeneous configurations in each group of manufacturers and thereby increases diversity of final products. In the fully or very highly modular case ($\alpha = 0.00$), diversity ends up being higher since agents are free to choose any sub-product configuration—the configurations of other sub-products are irrelevant for their quality. As a result, different configurations may be optimal (due to internal dependencies), thereby giving rise to greater product diversity.

Summing up, the present model confirms the discussion in the existing literature insofar as modularity allows for disintegration and disintegration delivers more speedy improvements of product quality. 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 nature of the matching process in the disintegrated case, it does propose a rationale for the observation of less product diversity in modular industries. If producer relations are extremely flexible and all strive to be part of the best currently known product, modularity and disintegration may increase product homogeneity. However, these results are set in a situation where bad producers stay active in the industry. Section 4.3 therefore benchmarks them against those of a model with selection.

4.3 The role of entry and exit

The previous findings are based on a model where low-quality producers stay active in the industry. This could distort the results on relative performance with respect to quality. To account for this aspect, we included entry and exit to the model by implementing a selection mechanism. Selection is modeled 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 agent is replaced with a perfect copy of the top performing one. This mimics a dynamics where industry entrants imitate the top performer or where the best performing companies expand production capacities.

We are aware that the assumption of perfect imitation is a strong one [especially against the research of Rivkin (2000) or Nelson and Winter (1982)]. Reducing the

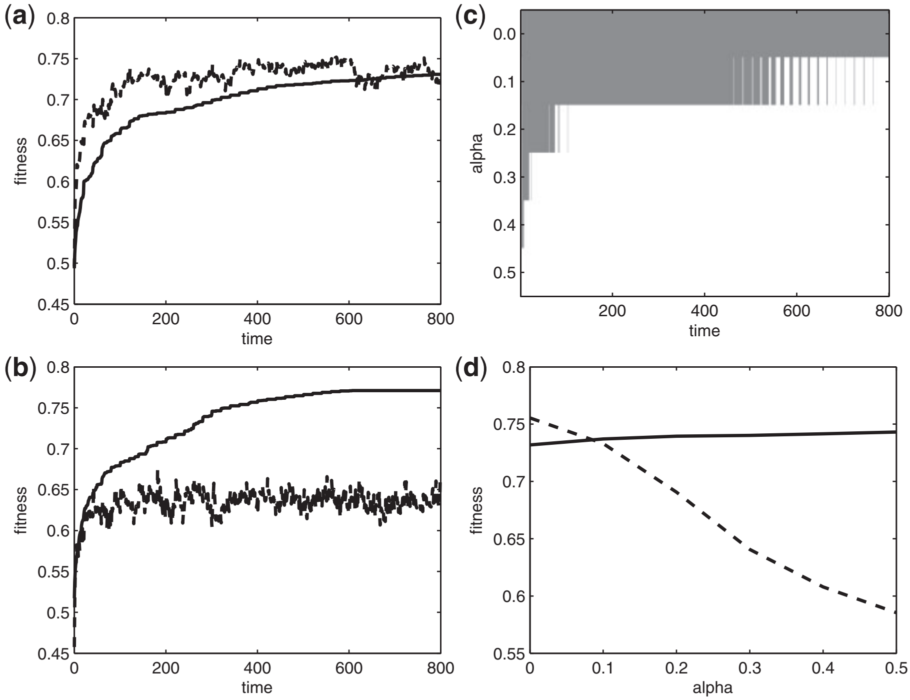

Figure 10 Product quality in the disintegrated and integrated setting over time and for different values of α including entry and exit. Figure (a) shows the evolution of quality in a sample run with $\alpha = 0.1$. The disintegrated case (dashed) initially delivers higher quality. Figure (b) contains a sample run with $\alpha = 0.3$ where the integrated case (solid) performs better in terms of quality. Figure (c) highlights quality at each simulation step averaged over 500 runs. Grey areas correspond to higher average quality in the disintegrated case, which is concentrated with lower α values. White areas denote higher average quality in the integrated setting, which relates to higher α values. Figure (d) compares average quality values at the last simulation step with the integrated setting (solid) delivering better average quality if $\alpha > 0.1$.

goodness of imitation reduced the effect of selection but did not alter the qualitative nature of the results presented here. This is due to the fact that the important dynamics for quality and differentiation reside in product assembly rather than imitation itself. In the disintegrated setting, the new entrant corresponds to several sub-product manufacturers that may well be matched with other agents in the following simulation steps. In the integrated setting, the new entrant corresponds to a new organization that will seek to improve upon the whole production process in subsequent steps. As a result, the effect of entry and exit for the industry differs.

In the integrated setting, entry and exit increase average quality up to a point as copies of the currently best organization are being introduced. This is illustrated by the gradual yet steady increase of product quality (Figure 10a and b). However, entry and exit decrease product variety for the very same reason: copies of the currently best organization are introduced (Figure 11a and b). Especially with time, improvement on these configurations becomes more difficult implying that all firms eventually lock-in with the same configuration (Figure 10d). In contrast to the previous setting where optimization started and proceeded from very different product configurations, entry and exit homogenize the starting-point for optimization in the integrated case, thus implying that organizations finally lock-in the same configuration. As this effect starts to materialize in early stages of optimization, it inhibits the integrated setting from developing more differentiated products in case of (nearly) modular production processes. Put differently, the long-term performance advantage of coordinated decision-making is eliminated for (nearly) modular products. This is also illustrated in the phase diagram (Figure 10c), where the disintegrated setting always delivers higher diversity in the long run.

The effect of selection on diversity in the integrated setting is stronger for less modular products (high α), i.e., diversity decreases more quickly. This is due to the fact that more modular products (low α) have fewer external dependencies, i.e., individual departments are more likely to find improvements to the benefit of the entire firm. In these cases, there will be more changes in configuration over time than in less modular ones. Therefore, selection may work to copy different current best organizations over time. While diversity always goes to zero in the long run, more modular product architectures have less stability in their current top product implying that homogeneity takes longer to be established.

In the disintegrated setting, selection introduces a copy of the currently best manufacturers, which may however be matched to different sub-products in the following simulation steps. This effect works to increase overall product quality. When selection occurs at time t, there is at least one product with configuration $Y^*(t)$ in $t+1$, namely the newly introduced copy. This increases the quality of decision—making of agents with configurations suited to the last "best" product of the industry [which usually correspond to those producers that were part of $Y^*(t)$ at time t as they have no or fewer modifications to perform in order to obtain a suitable sub-product configuration]. This effect gives optimization a (short-lived yet repeated) boost that is also evidenced by the pronounced quality "jumps" in the sample runs (Figure 10a and b).

Overall, selection works to increase product quality (albeit through different mechanisms) in the disintegrated and the integrated case (compare panel (d) in Figures 8 and 10). Moreover, selection decreases variety for both settings (compare panel (d) in Figures 9 and 11). However, product variety now becomes relatively higher for the disintegrated case (Figure 11a and b), which is more in-line with the theoretic predictions on the joint effect of modularity and disintegration. This shift in relative performance is due to the fact that diversity converges to zero in the integrated setting while surviving at a lower level in the disintegrated one thanks to the aforementioned mix-and-match dynamics. This implies that long-term

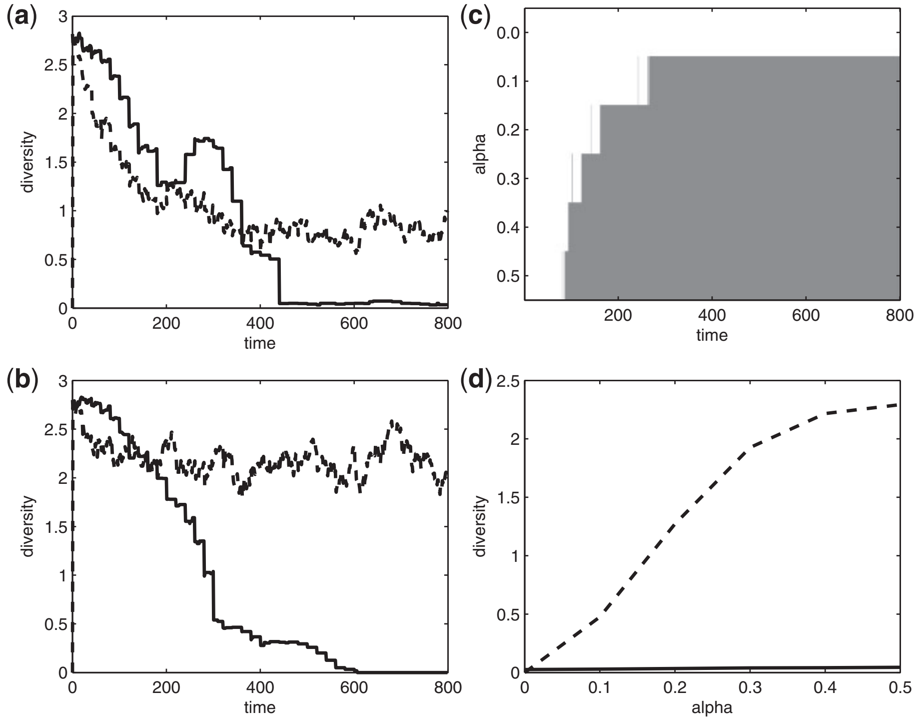

Figure 11 Product diversity in the disintegrated and integrated setting over time and for different values of α including entry and exit. Figure (a) shows the evolution of diversity in a sample run with $\alpha = 0.1$. The disintegrated case (dashed) delivers greater diversity in the long run. Figure (b) contains a sample run with $\alpha = 0.3$ where the disintegrated case (dashed) performs better overall. Figure (c) highlights diversity at each simulation step averaged over 500 runs. Grey areas correspond to higher average diversity in the disintegrated case, occurring for higher α values and in later simulation stages. White areas denote higher average diversity in the integrated setting, occurring in early simulation stages and for very low α values. Figure (d) compares average diversity at the last simulation step with the disintegrated setting (dashed) delivering higher diversity if $\alpha > 0$.

diversity is always higher in the disintegrated case (Figure 11c). The only time when mix-and-match does not work to produce greater variety for the disintegrated setting are fully modular product architectures ($\alpha = 0.0$). Here, the homogenizing effect of adoption decisions sets in (Section 4.2), bringing variety to zero in the disintegrated case. In the integrated case, variety survives as the independence of sub-product quality implies that firm departments can encounter beneficial modifications for a more extended time, thereby shifting the configuration of the leading firm that is copied through selection. In this one case, variety seems to last longer in the integrated case, although at the end, it also converges to zero (compare Figure 11 panel c and d).

In sum, selection increases quality and reduces diversity for the integrated and the disintegrated setting. However, the aforementioned dynamics imply that with selection, the joint benefits of modularity and disintegration materialize as predicted in the literature, provided that product architectures are nearly modular. The benefits to modularity and disintegration that are emphasized in the literature thus depend on the extent of entry and exit in the industry. If both are strong, they materialize more strongly than in cases with little or no selection.

5 Conclusion

In this article, we studied the link between product modularity, (dis)integration and the benefits to product quality and variety proposed in the literature. We started by developing a model able to assess, for which degrees of modularity in products and production, (dis)integration produces better quality and more differentiated products. In line with existing work (Sanchez and Mahoney, 1996; Baldwin and Clark, 1997; Langlois, 2002), a minimum degree of modularity is required for obtaining a higher quality with a disintegrated organization of production. For non-modular products, integration of production within a firm achieves better qualities. Beyond this, the article showed that the benefits to modularity and disintegration (namely greater product quality and in particular *variety*) are conditional on the existence of entry and exit. In absence of both, integration delivers more differentiated products. As a result, we can conclude that (nearly) modular products favor disintegration but that greater product differentiation is then conditional on entry and exit.

While the model mechanisms of modifying and assembling products constitute a heavy simplification to real-world production processes, there may be some industries exhibiting similar dynamics. For instance, industries with strong on the spot "winner takes all" dynamics (e.g., creative industries like advertising where competition for projects is strong). Such industries could—in a disintegrated setting—exhibit the effect of everyone wanting to be part of the currently best project in the industry as described by the model. In case of very flexible producer relations, such industries may witness a decrease in product differentiation provided that there is limited entry and exit. More stable producer relations or leading companies acting as systems integrators would work to offset these effects and thereby contribute to obtaining the benefits to modularity. In this vein, the stratification of the disc-drive industry described by Christensen *et al.* (2002) could—alongside the more technological reasons given in the paper—also have contributed to the resulting loss of product variety.

While more extensive empirical analysis would be required to determine the role of industry-specific aspects in generating these findings, we argue that the link between product modularity and (dis)integration is more nuanced than often acknowledged.

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References

Auerswald, P., S. Kauffman, J. Lobo and K. Shell (2000), 'The production recipes approach to modeling technological innovation: an application to learning by doing,' *Journal of Economic Dynamics and Control*, **24**(3), 389–450.

Axelrod, R. and M. D. Cohen (1999), *Harnessing Complexity: Organizational Implications of a Scientific Frontier*. The Free Press: New York.

Baldwin, C. Y. and K. Clark (1997), 'Managing in an age of modularity,' *Harvard Business Review*, **75**(5), 84–93.

Brusoni, S. and A. Prencipe (2001), 'Unpacking the black box of modularity: technologies, products and organizations,' *Industrial and Corporate Change*, **10**(1), 179–205.

Cainelli, G. and R. Zoboli (eds) (2004), *The Evolution of Industrial Districts: Changing Governance, Innovation and Internationalisation of Local Capitalism in Italy*. Contributions to Economics. Physica: Heidelberg, New-York.

Chesbrough, H. W. and K. Kusunoki (2001), 'The modularity trap: innovation, technology phase shifts and the resulting limits of virtual organizations,' in I. Nonaka and D. J. Teece (eds), *Managing Industrial Knowledge: Creation, Transfer and Utilization*. Sage: London, pp. 202–230.

Christensen, C. M., M. Verlinden and G. Westerman (2002), 'Disruption, disintegration and the dissipation of differentiability,' *Industrial and Corporate Change*, **11**(5), 955–993.

Coase, R. H. (1937), 'The nature of the firm,' *Economica*, **4**(16), 386–405.

Deakin, S., A. Lourenco and S. Pratten (2009), 'No "third way" for economic organization? Networks and quasi-markets in broadcasting,' *Industrial and Corporate Change*, **18**(1), 51–75.

Dosi, G., A. Gambardella, M. Grazzi and L. Orsenigo (2007), Technological revolutions and the evolution of industrial structures. Assessing the impact of new technologies upon size, pattern of growth and boundaries of the firm. LEM Working Paper Series 2007/12. Sant'Anna School of Advanced Studies, Pisa.

Dosi, G., D. A. Levinthal and L. Marengo (2003), 'Bridging contested terrain: linking incentive-based and learning perspectives on organizational evolution,' *Industrial and Corporate Change*, **12**(2), 413–435.

Ethiraj, S. K. and D. A. Levinthal (2004), 'Modularity and innovation in complex systems,' *Management Science*, **50**(2), 159–173.

Frenken, K., L. Marengo and M. Valente (1999), 'Interdependencies, near-decomposability and adaptation,' in T. Brenner (ed.), *Computational Techniques for Modelling Learning in Economics*. Kluwer Academic Publishers: Boston, pp. 145–165.

Guerrieri, P., S. Iammarino and C. Pietrobelli (eds) (2001), *The Global Challenge to Industrial Districts: Small and Medium Sized Enterprises in Italy and Taiwan*. Edward Elgar: Cheltenham, UK.

Kauffman, S. A. (1993), *The Origins of Order: Self-organization and Selection in Evolution*. Oxford University Press: Oxford, New York.

Kauffman, S. A., J. Lobo and W. G. Macready (2000), 'Optimal search on a technology landscape,' *Journal of Economic Behavior and Organization*, **43**(2), 141–166.

Langlois, R. N. (1988), 'Economic change and the boundaries of the firm,' *Journal of Institutional and Theoretical Economics*, **144**(4), 635–657.

Langlois, R. N. (1992a), 'External economies and economic progress - the case of the microcomputer industry,' *Business History Review*, **66**(1), 1–50.

Langlois, R. N. (1992b), 'Transaction-cost economics in real time,' *Industrial and Corporate Change*, **1**(1), 99–127.

Langlois, R. N. (2002), 'Modularity in technology and organization,' *Journal of Economic Behavior and Organization*, **49**, 19–37.

Langlois, R. N. (2003), 'The vanishing hand: the changing dynamics of industrial capitalism,' *Industrial and Corporate Change*, **12**(2), 351–385.

Langlois, R. N. (2004), 'Chandler in a larger frame: markets, transaction costs, and organizational form in history,' *Enterprise and Society*, **5**(3), 355–375.

Langlois, R. N. (2006), 'The secret life of mundane transaction costs,' *Organization Studies*, **27**(9), 1389–1410.

Langlois, R. N. and P. L. Robertson (1989), 'Explaining vertical integration - lessons from the American automobile industry,' *Research Policy*, **49**(2), 361–375.

Langlois, R. N. and P. L. Robertson (1992), 'Networks and innovation in a modular system-lessons from the microcomputer and stereo component industries,' *Research Policy*, **21**(4), 297–313.

Mahoney, J. T. (1992), 'The choice of organizational form: vertical financial ownership versus other methods of vertical integration,' *Strategic Management Journal*, **13**(8), 559–584.

Marengo, L. and G. Dosi (2005), 'Decentralization and market mechanisms in collective problem-solving,' *Journal of Economic Behavior and Organization*, **58**(2), 303–326.

Marengo, L., G. Dosi, P. Legrenzi and C. Pasquali (2000), 'The structure of problem-solving and the structure of organisations,' *Industrial and Corporate Change*, **9**(4), 757–788.

Marshall, A. (1920), *Principles of Economics*. 8th edn. Macmillan: London.

Nelson, R. R. and S. G. Winter (1982), *An Evolutionary Theory of Economic Change*. Harvard University Press: Cambridge, MA.

Paniccia, I. (2002), *Industrial Districts: Evolution and competitiveness in Italian Firms*. Edward Elgar: Cheltenham UK.

Prencipe, A., A. Davies and M. Hobday (2003), *The Business of Systems Integration*. Oxford University Press: Oxford.

Press, K. (2006), *A Life Cycle for Clusters? The Dynamics of Agglomeration, change and Adaptation*. Springer: Heidelberg.

Rivkin, J. W. (2000), 'Imitation of complex strategies,' *Management Science*, **46**(6), 824–844.

Robertson, P. L. and R. N. Langlois (1995), 'Innovation, networks, and vertical integration,' *Research Policy*, **24**(4), 543–562.

Sanchez, R. and J. T. Mahoney (1996), 'Modularity, flexibility, and knowledge management in product and organization design,' *Strategic Management Journal*, **17**, 63–76.

Siggelkow, N. and J. W. Rivkin (2005), 'Speed and search: designing organizations for turbulence and complexity,' *Organization Science*, **16**(2), 101–122.

Simon, H. A. (2002), 'Near decomposability and the speed of evolution,' *Industrial and Corporate Change*, **11**, 587–599.

Sturgeon, T. J. (2002), 'Modular production networks: a new American model of industrial organization,' *Industrial and Corporate Change*, **11**(3), 451–496.

Williamson, O. E. (1991), 'Comparative economic organization: the analysis of discrete stuctural alternatives,' *Administrative Science Quarterly*, **36**, 269–296.