Journal of Engineering and Technology Management 47 (2018) 81–95

Contents lists available at ScienceDirect

Journal of Engineering and Technology Management

journal homepage: www.elsevier.com/locate/jengtecman

Grounding the “mirroring hypothesis”: Towards a general theory of organization design in New Product Development

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ARTICLE INFO

Keywords:
Product architecture
Organizational architecture
Social network
NK-model
New Product Development (NPD)

ABSTRACT

The similarity between product architecture and organization design has become known as the “mirroring hypothesis”. We present a theoretical model of new product development using the NK-model, in which we represent organization design with varying degrees of mirroring. The main result holds that perfectly mirroring organizations only perform well in designing products with many components and low complexity, while imperfectly mirroring organizations do better in designing product with few components and high complexity. Our theoretical model can inform future empirical research, which hitherto lacked a common representation framework for organization design.

1. Introduction

Ever since the topic of modularity emerged in management science and innovation studies (Henderson and Clark, 1990; Langlois and Robertson, 1992; Ulrich, 1995), a central hypothesis holds that a modular product architecture is likely to be reflected in a modular organization design (Sanchez and Mahoney, 1996; Baldwin and Clark, 2000). This hypothesis later became known as the ‘mirroring hypothesis’ (Colfer and Baldwin, 2016). Since the product architecture pre-specifies the design specifications to which modules have to adhere, each module can be developed and produced independently from the other modules. Hence, the product development and production process requires less coordination, allowing the firm to grant substantial autonomy to its divisions, or even to outsource module design and production to other companies. Reversely, more integrated product architectures would require more centralized organization design with few options for outsourcing.

Criticisms of the mirroring hypothesis exist, based on empirical evidence (Brusoni et al., 2001; Ernst, 2005; Frigant and Talbot, 2005; Cabigiosu and Camuffo, 2012; Furlan et al., 2014). One of the main critiques has been that product architectures are not necessarily stable, and hence co-evolve with organizational processes. At the same time, empirical evidence also supports the mirroring hypothesis for cases where product architectures remained fixed, even if most evidence is limited to the computer and software industries (Sosa et al., 2004; Hoetker, 2006; MacCormack et al., 2012; Baldwin et al., 2014).

Notwithstanding the insights gained from empirical studies, and the auxiliary hypotheses that followed from the original hypothesis, the mirroring hypothesis itself has remained underexplored theoretically. It seems self-evident that the organization design is directly related to the exact nature of interdependencies, given that human organizations primarily exist to deal with interdependencies (Langlois, 2002). More specifically, modular product architectures are expected to be reflected in modular organizations, a conjecture going back to Simon’s (1962) work on nearly decomposable systems. Hence, it seems that the intuitive appeal of the mirroring hypothesis may explain the lack of further theorizing.

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https://doi.org/10.1016/j.jengtecman.2018.01.001
Received 21 July 2016; Received in revised form 20 December 2017; Accepted 7 January 2018

Given that the mirroring hypothesis lacks a precise theoretical foundation, further hypothesis-driven empirical research could benefit from a general theoretical framework. Such a framework could bring together and stimulate dialogue among current “supporters”, “opponents” and “contingents” of the mirroring hypothesis, as identified by Sorkun and Furlan (2017), under a single analytical umbrella. The model that follows is a first attempt to come to a model of mirroring between organization design and product architecture. Our model is a general model, in that it is not limited to modular architectures, but includes any architecture that can be expressed as a Design-Structure Matrix (DSM) (Baldwin and Clark, 2000). This allows us to understand, theoretically, whether the mirroring hypothesis is a general hypothesis, or one that is specific to a subset of product architectures. Consequently, this research is consistent with the call made by Cabigiosu and Camuffo (2012) for a shift from research focused on assessing the hypothesis' mere existence to research focused on the conditions under which the hypothesis is valid.

Here, we go beyond solely focusing on modular designs, and ask the general question whether any organization design mirroring a product design would result in the development of the best design. To this end, we adopt the NK-model as first introduced in the social sciences by Levinthal (1997) and later adapted as a model of artefact evolution by Frenken and Nuvolari (2004). We supplement the standard NK-model with an organization design layer that determines the decision-making structure of agents. A perfect mirroring between the product and organization designs means that all interdependencies between the product's components are reflected by collective decision-making structures at the organizational level. Following this definition, any other decision-making structure can then be expressed by their difference from the perfectly mirroring decision-making structure as the number of dependent components that are being ignored when a particular agent carries out a mutation. Hence, our model is a general model in which any organization design can be modelled as expressed by any directed communication network among organization members, hence going beyond existing models that reason solely from non-overlapping firm divisions (Rivkin and Siggelkow, 2003, 2007; Baumann, 2015). The advantage is to avoid any strict assumptions about the level of technological decomposability: complex, near-decomposable or modular systems can be implemented within this modelling framework.

The model flexibility is particularly relevant to provide a more systematic perspective on New Product Development. We assume that deviations from perfect mirroring happen when the organization lacks technological knowledge about the new product in development (including the architecture of technological interdependences). Technological knowledge improves during the development process when alternative component technologies are implemented and their effects on the global product are compared. Given the myopic nature of search in our model, search processes do not necessarily end up in a local optimum in which single agents can no longer improve their individual fitness (Nash equilibrium). Instead, search may well continue endlessly, thus requiring a deadline in the organization to settle on a New Product Design, once the search has produced different prototypes that can be evaluated by comparison with each other. This is why we will compare the search result of different decision-making structures by measuring the overall fitness of the best product design ever found during a fixed time period. This implies that some agents, who could have improved their component's performance by mutation of the best design, will be less satisfied by the final choice of design. We consider this a second relevant assessment criterion of an organizational structure, since the internal support and commitment to the new product design not just depends on some objective fitness criterion relevant to the firm as a whole, but also on the prestige that all individual agents experience for their contribution to the selected product design (Guth and MacMillan, 1986).

We proceed as follows. After a literature review in Section 2, we present the NK-model as a model of New Product Development (NPD) in Section 3. In Section 4, we extend the model by representing organization designs by the organization's decision-making structure. In Section 5, then, we present simulation results and we end with a discussion about the theoretical, empirical and managerial implications of our work.

2. The mirroring hypothesis

The mirroring hypothesis emerged out of an older literature on modularity in the early 1990s (Henderson and Clark, 1990; Langlois and Robertson, 1992; Ulrich, 1995). One of the key hypotheses that has emerged from this literature holds that an organizational design is expected to mirror its product's design (Colfer and Baldwin, 2016; MacCormack et al., 2012). Hence, one would expect that the more modular the product of a firm, the more likely that this firm has a decentralized organization design, either in terms of having semi-autonomous departments each responsible for a module, or in terms of being a system integrator with supplier firms each producing a module.

Compared to more centralized forms of organizing production, a decentralized organization can have mainly two advantages (Baldwin and Clark, 2000). First, the overhead costs can be much lower as little explicit coordination is needed during the production process. Second, each module can be adapted to changing circumstances (e.g., prices, consumer tastes), without the need to re-design the whole product also known as inter-temporal economies of scope (Helfat and Eisenhardt, 2004).

The reduced coordination, however, generally come at a cost: (i) higher development costs due to the additional need of interface standardization (Sanchez and Mahoney, 1996); (ii) the risk of losing component-specific knowledge needed for effective outsourcing (Takeishi, 2002); (iii) lower overall performance as complementarities (“synergistic specificity”) between product components remain underexplored as strict interfaces do not allow so (Schilling, 2000; Fleming and Sorenson, 2001); and (iv) the risk of getting locked into a product architecture and its accompanying organization design preventing firms to effectively develop radically new architectures (Henderson and Clark, 1990; Brusoni et al., 2001). Hence, depending on the relative importance of costs and benefits, there is a theoretically-optimal level of modularity for each technology.

Apart from advantages in production, modularity also generates advantages in New Product Development (NPD). Indeed, the mirroring hypothesis was first and foremost a hypothesis about the design of NPD organizations. In its earliest formulation, also known as Conway's Law, it was argued that “organizations which design systems (…) are constrained to produce designs which are copies of the communication structures of these organizations" (Conway, 1968, p. 31). To improve communication structures in NPD, it is pivotal that interfaces between modules are pre-specified *ex ante*, and remain rather stable during the product development process itself (Cabigiosu and Camuffo, 2012; Magnusson and Lakemond, 2017).

The mirroring hypothesis in NPD itself has rarely been tested. Indeed, most of the empirical research on modularity has focused on the effects of modularity (e.g., consumer satisfaction, loss of dynamic capabilities, supplier survival rates, etc.) (for a review, see Campagnolo and Camuffo, 2010). The few studies directly testing the existence of the mirroring hypothesis have compared the modularity of product architectures developed by NPD organizations with different organization designs. MacCormack et al. (2012), for example, found that software products with the same function but designed by more decentralized organizations (open source communities), were much more modular than those designed by more integrated organizations (commercial firms). Another study, by Baldwin et al. (2014) looked at Design-Function Matrices of 1286 software releases, and found that those designed by commercial firms had a much bigger set of tightly connected core components than those designed by an open and distributed platform. There is an older study by Hoetker (2006) on the computer industry looking at component renewal and outsourcing, which tested the hypotheses that firms that design more modular products, also tend to renew their components more often and to outsource the production of its components more often. This study found evidence for the first hypothesis, but failed to find evidence for the second hypothesis. Finally, the study by Sosa et al. (2004) looked at the design of an aircraft engine development organization, and found a high level of mirroring: 90 percent of the technical interdependencies were matched by team interactions within the NPD organization.

Ethiraj and Posen (2013) emphasize that the literature related to the mirroring hypothesis regards product architectures as being exogenous to the firm. By studying the specific circumstances of the existence of the mirroring hypothesis, we are matching different types of product architecture with different structures of decision-making. Our model thus adds managerial and economic prescriptions to this literature by showing how the firm creativity can be improved (or deteriorated) by using the right (or wrong) combination of product architecture and organization design, making the issue of mirroring a more endogenous lever for the firm.

3. Product architecture: the NK-model

A standard way, by now, to represent architecture as a complex system of interconnected components is Kauffman's (1993) NK-model. This model originated from biology to model the evolution of genotypes through mutation in genes leading to changes in the phenotype as expressed by each gene's fitness level. In management science, Levinthal (1997) introduced the NK-model as a way to model organizational attributes and has been widely applied to address a range of questions in the strategy literature (for a review, see Ganco and Hoetker, 2009).

Here, we use the NK-model to represent the component technologies and the product architecture that specifies the interdependencies between these component technologies (Kauffman et al., 2000; Simon, 2002). As a complex system, the fitness of each component i depends not only on the state of the component technology itself, but also on the state of a subset of K other components: $\{i_1,\ldots,i_K\} \subset \{1,\ldots,i-1,\ i+1,\ldots,N\}$, which is equivalent with specifying a Design Structure Matrix (Steward, 1981; Baldwin and Clark, 2000).

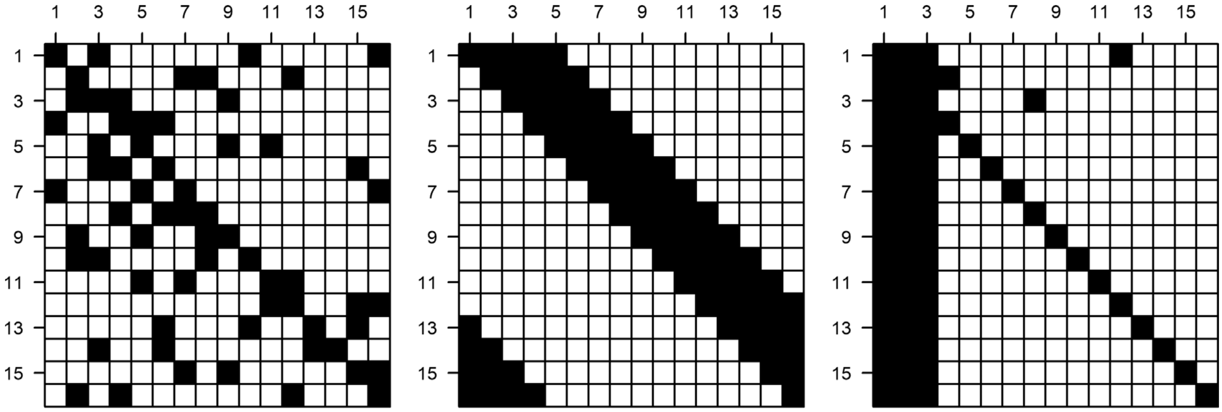
The set of technical interdependencies characterizing a product architecture can equally be understood as a directed network where an arc between component i to j implies that a change in component i influences the fitness of component j. Following the NK-model logic, the arcs are created in such a way that K arcs are directed to end on each component, i.e., the indegree of each component is exactly K for all components. On the other end of the arcs, the subset of influencing components being selected randomly, the outdegree equals K only on average. Henceforth, we will describe a product architecture as a "technology network" which is expressed by the binary matrix of size $N \times N$ and a density of $(K+1) \times N$. By using networks of agents and components, we adopt a representation that is more abstract, but more flexible than the Design Structure Matrix. The DSM logic is focused on the clustering of tasks and individuals, making decomposability a very strong assumption of this approach (Browning, 2016). Our objective is to move the focus away from decomposability. By studying situations where the technological interdependences are not fully revealed to the firm, the search cannot be optimized.

Without loss of generality, we follow the standard assumption that each component can be designed in two ways, which implies we have a binary "design space" of size 2^N. The global fitness of a product design $F(x)$ is the average of the fitness contribution of every component F_i, which is given by a random number drawn from a uniform distribution between 0 and 1. This means that component i has a unique and uncorrelated fitness value for each different design of component i and of all K components $\{i_1,\ldots,i_K\}$ influencing the fitness of i. Hence, we have:

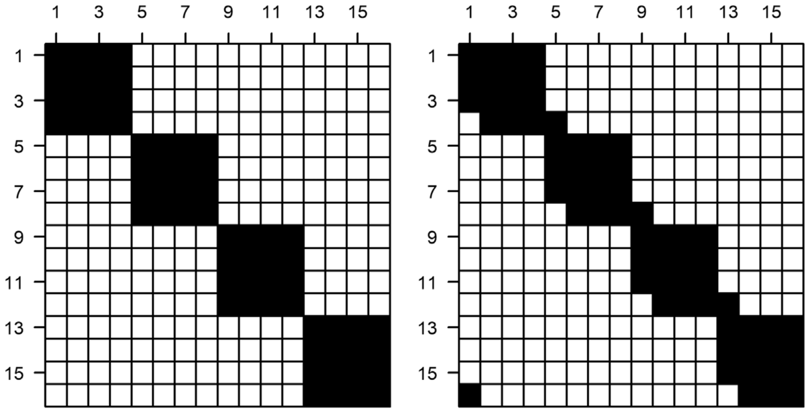
$$F(x) = \frac{1}{N}\sum_{i=1}^{N} F_i\left(x_i;\, x_{i_1},\ldots,x_{i_K}\right) \tag{1}$$

Search takes place by the mutation of components, i.e. flipping their state from 0 to 1 or vice versa: $x_i \in \{0,1\}$ and $x = \{x_1,\ldots,x_i,\ldots,x_N\} \in \{0,1\}^N$. Zero and one can be understood as "absence or presence of the component", as well as "the component relates to technology zero or to technology one". We assume that a NPD organization searches for better product designs by mutating only one element at the time. Though this assumption is a simplification, it has been considered more legitimate than assuming that organization can engage in global search (and hence, in global optimization) as the latter strategy is much more expensive than the local search strategy (Simon, 1962).

To test the mirroring hypothesis, we will examine a number of archetypal product architectures (cf. Rivkin and Siggelkow, 2007).



Standard NK Regular Core-Periphery



Perfectly Decomposable Nearly Decomposable

Fig. 1. The architecture of technological networks.
For a given product architecture defined in this example by $N = 16$ and $K = 3$, there is a technological interdependency (black cell) when the component on the row influences the component on the column.

These structures are identical to Design Structure Matrices as employed in the literature to represent complex interdependences between elements in an artefact (Baldwin and Clark, 2000). We will consider the following product architectures (Fig. 1):

- A *standard NK* architecture: following Kauffman (1993), the technical interdependencies are chosen randomly with the only restriction that the indegree of each component in the technology network equals K.
- A *regular* architecture, in which each component is influenced by the K components located after itself, in a circular structure. Unlike the standard-NK architecture, the indegree and the outdegree of each component are equal, producing a regular pattern (Watts and Strogatz, 1998; Rivkin and Siggelkow, 2007).
- A *core-periphery* architecture, which core is made of K components that influence every other component and K components from the periphery influence the core to maintain the NK density (Rivkin and Siggelkow, 2007; Baldwin et al., 2014).
- A *perfectly decomposable* architecture which is perfectly broken down in $N/(K + 1)$ modules of size $K + 1$. All the components influencing a given component belong to the same module (Frenken et al., 1999; Ethiraj and Levinthal, 2004).
- A *nearly decomposable* architecture, where the last component of a module influences the first component of the next module, instead of influencing the first component of its own module (Frenken et al., 1999; Ethiraj and Levinthal, 2004).

All these archetypal product architectures can be constructed for particular K-values, except for the maximum K-value (being $N - 1$), which corresponds to a fully connected product architectures where all structural distinctions have vanished. Besides providing a way to compare different product architectures, the K-value is also an indicator of technological complexity: generally speaking, the higher K, the lower the decomposability of the product's components.

For each K-value, we then perform simulations with different degrees of mirroring. In the case of perfect mirroring, each social tie in the organization design coincides with each technical interdependency among components in the product architecture (in both cases K per agent-component). Imperfect mirroring is operationalized by randomly removing social ties from the organization design such that the number of ties per agent goes down first by one ($K - 1$), then two ($K - 2$), et cetera. The most imperfect mirroring of an organization design vis-à-vis the product's architecture, then, is reached when the number of social ties per agent has reached 0.

4. Organization design as a decision-making network

As members of a NPD organization work on different components of a product, the question is how to organize the decision-making procedures regarding the mutation proposals of different agents controlling different components. We assume that there are as many agents in the organization as components in a product (N), and that each agent i controls the state of component i and only component i.

An organization design, then, specifies how an organization evaluates a change in a product design, which here means a mutation in one of its components. A fully centralized ("hierarchical") organization design can be understood as an organization where each mutation is evaluated with reference to its effect on the global fitness (Rivkin and Siggelkow, 2003). In such an organization, the agents have no autonomy, because any mutation proposal will only be accepted by a principal who looks at whether the global fitness – computed on the basis of the mean fitness of all components – will increase. In a fully decentralized organization, by contrast, all agents have full autonomy, and any mutation proposal is accepted if the component fitness will increase (Mihm et al., 2010).

Intermediate organizational designs are those combining some degree of autonomy with some degree of hierarchy. This is apparent in organization where teams are created to control a non-overlapping subset of components. In such organizations, a mutation proposal done by a team member is accepted if and only if the mean fitness of components, which fall under the control of the team, increases (Kauffman and Macready, 1995; Rivkin and Siggelkow, 2003).

The literature on organization using the NK-model, has so far only explored these three categories of organization design, ranging from hierarchical, team-based, to fully decentralized organizations. These can be shared under one dimension that specifies the team size, with organizations with team size of N being fully centralized, with team size of 1 being fully decentralized, and with team size in between 1 and N being 'team-based' (Rivkin and Siggelkow, 2003).

However, the team size parameter is too limited as a representation of the possibility space in organization design, nor does it allow one to model perfectly mirroring designs. If team size would be the only variable that can be tuned to design a NPD organization, mirroring between an organization design and a product architecture can only be achieved in the hypothetical situation that a product architecture happens to be fully decomposable in subsystems of size corresponding to department sizes (Frenken et al., 1999; Marengo et al., 2000; Marengo and Dosi, 2005).

A generalized model of organizational design would be one that comprises all possible decision-making network configurations that can exist between members of an organization, where the network relations of an agent specify the subset of agents whose fitness is taken into account in the evaluation of a mutation proposal. A mirroring organization design, in our model, is a specific case of organization design where all the technical interdependencies are reflected in an organization design such that a component technology influenced by K interdependent components in the technology network is controlled by an agent who has social ties with the K agents in charge of the K interdependent components. In reality, there may also exist social ties that do not mirror any technical interdependency. However, such a social tie would not have any effect on decision-making, because the component controlled by an agent who has a social tie with another agent but is nevertheless technically interdependent from that agent, will not be influenced by a mutation from that agent. Hence, we can neglect any social ties between agents whose components are technically independent.

Recall that the set of technical interdependencies characterizing a product architecture can be understood as a directed network where an arc between component i to j implies that a change in component i influences the fitness of component j. This "technology network" is expressed by the binary matrix of size $N \times N$ and of density $(K + 1) \times N$. Along the same lines, an organization design can be expressed as a directed network where an arc from agent j to agent i, then, means that if i mutates its own component i, it takes into account the consequences for the fitness of component j as well. Hence, in our model, the fitness function for an agent is expressed in terms of the mean fitness of components controlled by herself and all her network neighbors.

A "perfectly mirroring organization design" can then be understood as the decision-making network with the exact same matrix that characterizes the technology network. Thus, for each agent i controlling component i that is influenced by K components$\{i_1, ..., i_K\} \subset \{1, ..., i - 1, i + 1, ..., N\}$, in Eq. (1), the fitness function at the component level becomes:

$$F_i(x) = \frac{1}{1 + g_i}\left(U\left(x_i; x_{i_1}, ..., x_{i_K}\right) + \sum_{j \in G_i} U\left(x_j; x_{j_1}, ..., x_{j_K}\right)\right) \tag{2}$$

with $x_i \in \{x_{j_1}, ..., x_{j_K}\}$, and G_i is the set of components j influenced by component i (g_i is the number of components in this set) and $U\sim$ uniform random distribution on [0,1]. Search in a perfectly mirroring organization takes place in a decentralized but "networked" manner. When an agent mutates its component, it collects the fitness values of all the components affected by the mutation. Then, the agent checks whether the mean of fitness values increases, and only if this is the case, the mutation is accepted. Note here that the results for perfect mirroring necessarily correspond to the results of centralized search. In the latter, each mutation is evaluated on the basis of whether the mean fitness of a product increases, which is the same as a perfectly mirroring organization, where each mutation is evaluated on the basis of the mean fitness of all the components affected by the mutation.

Once we have been able to specify a perfectly mirroring design, we can compare the fitness level achieved by this organization design compared to imperfectly mirroring organization designs. We will test the range of organization designs from the perfectly mirroring organization (all K social ties being present), to imperfectly mirroring organizations in which some of the agents affected by a mutation are ignored (some of the K social ties being present), to the organization design where mirroring is completely absent, that is, agents ignore any effect a mutation may have on the fitness levels of other agents in the organization (none of the K social ties being present). In Eq. (2), this procedure consists in altering the set G_i from agent i's perspective. Concretely, when evaluating the fitness of its mutation, the agent i will only take into account the new fitness from the subset $\widetilde{G_i} \subset G_i$ of components influenced by the mutation. In the appendix, we provide the example of $N = 3$ and $K = 2$, and with varying levels of mirroring ranging from perfect mirroring to complete absence of mirroring. Here, the boundaries of the subset $\widetilde{G_i}$ are only represented at the lower horizontal level (i.e. a set of agents in charge of individual component technologies). However, this subset can also be interpreted as the horizontal projection of a vertical hierarchy, where the fitness values of interest are collected by vertical intermediaries and transferred to an upper-level manager for the final decision.

5. Simulation

5.1. Simulation set-up

At each repetition of the simulation, a fitness landscape is created following parameters N, K, and the product architecture in question. The N agents start searching from a randomly chosen string. At each simulation step, one agent – chosen *at random* – mutates its bit and evaluates according to its fitness function F_i, whether the mutation is fitness-improving. Then, at the next step, again an agent is randomly chosen among the agents who have not yet evaluated their own mutation since the last modification of the product. The length of the simulation thus corresponds with the number of mutations tried.

Note that given the myopic nature of decision-making, the collective search process does not necessarily reach equilibrium, that is, a string for which no agent can improve its fitness by mutation (Nash-equilibrium). Quite often, search continues during the whole simulation, as at least one of the agents is able to improve its fitness. In addition, since the agent's opportunity to evaluate a mutation happens in a random order, a variety of exploration paths are visited. Along these paths, identical designs may reappear several times, without necessarily coming from or leading to the same paths that designed them originally. That is why we collect, at the end of each simulation, the highest mean fitness ever achieved. In reality, this corresponds to a principal allowing its agents working in the NPD organization a certain amount of resources (e.g. a time span), and once the resources are exhausted, the principal collects the best fitness solution achieved in that time.[1] This means that we assume that the principal, as are the designers, is able to observe the fitness values of components as to be able to select the design with best mean fitness. Hence, we abstract here from any strategic principal-agent problems that may arise within an organization.

The decentralized nature of search also implies that New Product Development processes can be assessed not just in terms of the fitness of the best design found, but also in terms of the level of satisfaction among the agents regarding this design. Satisfaction refers to the share of agents who could have improved their individual fitness by mutation of the best-fitness design. If many agents can have done a better individual job by mutating their component in the best design, they could have achieved a higher level of prestige for their individual contribution. As this negatively affects their individual reward either within the organization (as a signal affecting their pay) or outside the organization (as a signal adding to their reputation) such agents will be less satisfied than other agents (Guth and MacMillan, 1986; Athey and Roberts, 2001). Thus, the more agents are not satisfied with the final choice of design, as their individual contribution could have been higher by a simple mutation of that design, the lower the internal support for the further development of this design into a marketable product.

The simulations are repeated over a large set of values for N, K and the number of steps with $N = \{8, 16, 32, 64\}$, $K = \{0, 1, 3, 7, 15, 31{,}63\}$ for $(K < N)$ and the number of steps $=\{200, 4000, 800, 1600\}$. As explained, each simulation is first carried out assuming perfect mirroring where the number of social ties agents have corresponds to the K interdependencies between a product's components. Then, we repeat the simulation for the same landscape assuming ever decreasing levels of mirroring until the agents have no social ties at all. Each of these simulations is replicated 1000 times with different random number streams.

5.2. Results for the standard NK architecture

Fig. 2 reports, for different K-values, the percentage of mirroring technical interdependencies and social ties required to achieve the best fitness value. It indicates the highest optimal level of mirroring, above this level of mirroring the fitness is lower, and below this level the fitness is similar or lower. The mirroring axis ranges from 0 percent (fully decentralized decision-making, ${}^{0}\!/_{K} = 0\%$) to 100 percent (perfect mirroring hypothesis, ${}^{K}\!/_{K} = 100\%$). Fig. 3 reports on the same results, but now showing the mean fitness values and levels of satisfaction. The subfigures increase in size with N because a higher N means more levels for K. Each subfigure reports the values of two variables of interest (Best Fitness and Satisfaction) on the top half. The values of these variables depends directly on the values of two parameters of the simulations (K and Mirroring) on the bottom half, as well as they depend on the third parameter N.[2]

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[1] As a robustness check, we performed all the simulations for different amounts of time, ranging from 200 steps to 1600 steps. Obviously, more time means that the fitness achieved is higher overall runs. Yet, differences are small. From these results, one can also deduce the degree of stability of the solution: a difference of fitness between different amounts of time reflects an inability to reach a stable solution.

[2] Using the network analogy detailed in Sections 3 and 4, the parameter K sets the level of complexity of the 'technology network' (i.e. the product represented as a set of interdependent components). Hence, each vertical solid line isolates individual technology networks for which we decrease the level of Mirroring from perfectly mirroring (left side, Mirroring = K, i.e. the technology and decision-making networks are identical) to fully decentralized (right side, Mirroring = 0, i.e. the decision-making network is an empty network without any arcs between the agents-components). In other words, each curve inside a rectangular frame represents the outcome of product developments by different organizations characterized by different levels of mirroring.

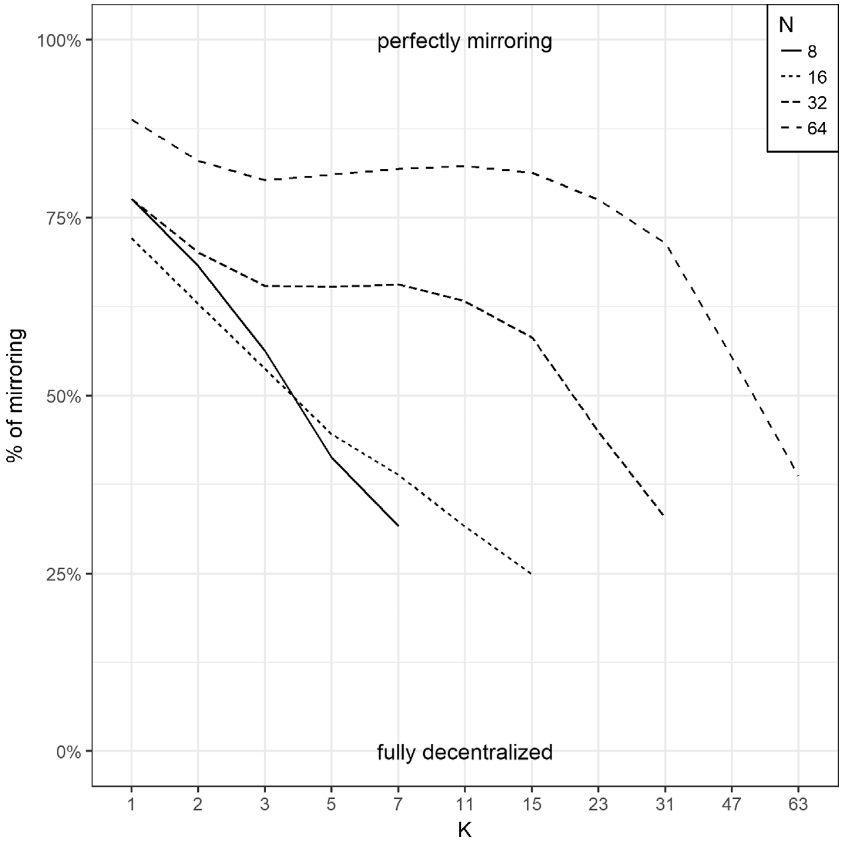


Fig. 2. Percentage of mirroring for best fitness.
For the standard NK architecture, the figure shows the percentage of ties necessary to achieve best fitness, given a pair of N and K values. For instance, for $K = 11$ and $N = 64$, on average 9.05 ties are necessary to achieve best fitness, making a percentage of mirroring equals to $^{9.05}/_{11} = 82\%$.

Starting with the *standard NK* architecture (Figs. 2 and 3) and using the Best Fitness as a measure of performance, the first important observation holds that perfectly mirroring does not outperform imperfect mirroring. Perfectly mirroring organizations perform relatively well in designing products when $K \ll N$ (left side). However, for increasing K values, better designs are being discovered by lower degrees of mirroring. That is, it pays off to ignore some of the technical interdependencies among the product's components in the organization design. This positive effect of "ignorance" is increasing with K, but decreasing with N. A second observation (Fig. 3) holds that there is an optimal level of mirroring in-between perfect mirroring and complete absence of mirroring (an inverted-U shape).

The Satisfaction measures the percentage of agents who are satisfied by the best-fitness situation, i.e. those agents who have no gain in making a mutation. Satisfaction is always a hundred percent in the case of perfect mirroring, since a mutation is only accepted if the mean fitness of all the components/agents affected by the mutation, increases. The downside of perfect mirroring can be understood from the fact that perfect mirroring puts hard requirements for any mutation to be accepted. By ignoring some of them, more mutations are accepted and a larger part of the design space is effectively explored by the NPD organization. And, the higher the complexity K of a product, the more constraining mirroring is, since very few mutations will results in an increase in the mean fitness of all those concerned. In all, perfect mirroring is especially detrimental for products with few components or high complexity. This suggests that to construct an effective organization design, one can first mirror a product architecture as a baseline, and then ignore a substantial (random) part of interdependencies. The fact that the Satisfaction decreases immediately once we depart from a perfectly mirroring organization tells us that convergence (or lock-in) is unlikely to occur since at least one agent is not satisfied by the situation and will propose a mutation. Meanwhile, the level of satisfaction is superior to 95% for most of the levels of imperfect mirroring that outperforms the perfectly mirroring organization in terms of Best Fitness.

5.3. Results for alternative NK architectures

Figs. 4–7 repeat the simulations reported in Fig. 3, with each figure displaying the results of one of the four alternative product architectures (regular, core-periphery, decomposable, nearly decomposable). Note that the results for maximum K-values ($K = N - 1$) necessarily produce identical results whatever the architecture, because every component influences every other. That is why we have only reported the results for maximum K-values in Fig. 3.

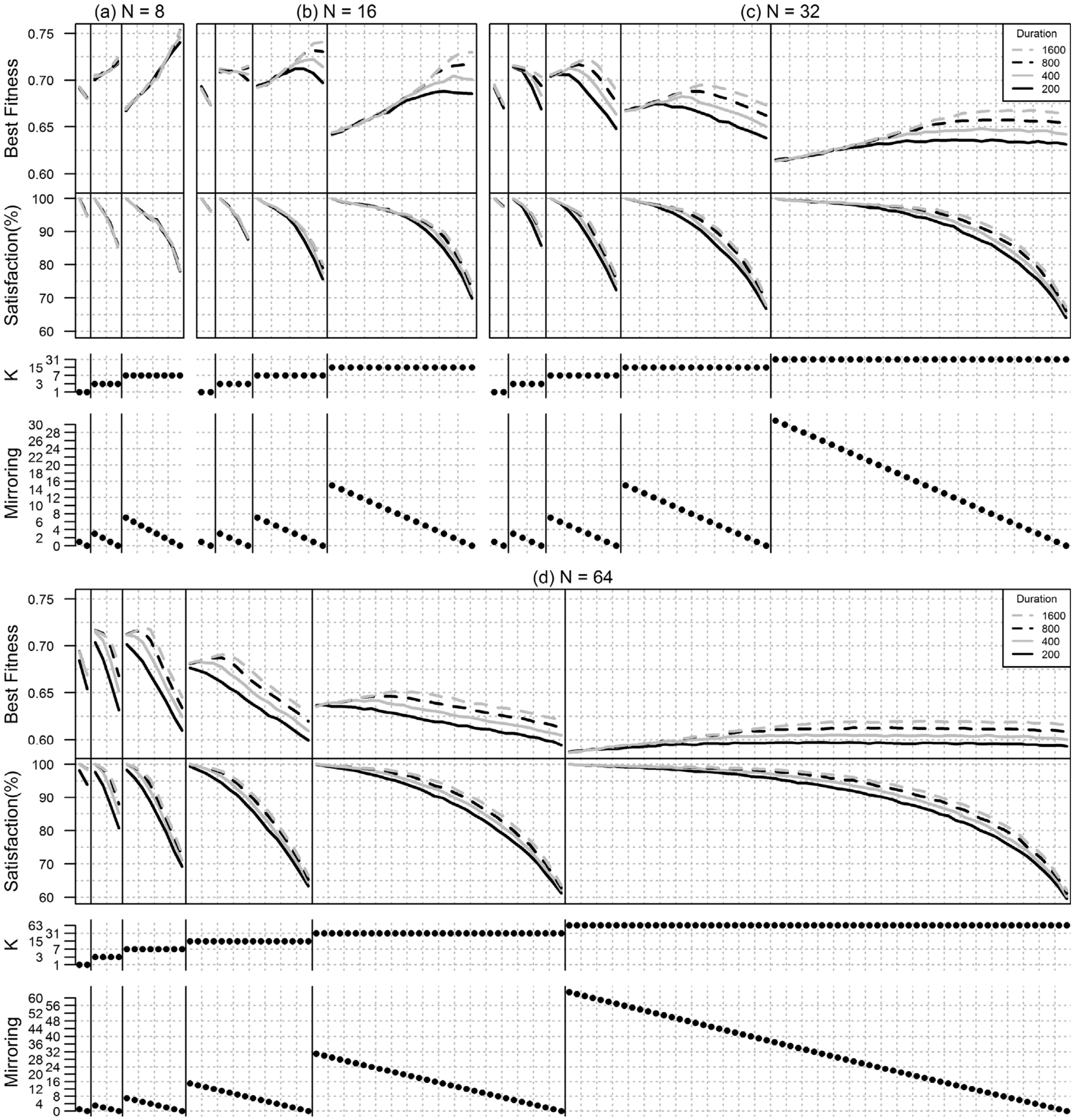


Fig. 3. Results for a standard-NK technological architecture.
For a given N, K and number of ties (lower quadrant), the upper quadrant shows the best fitness and the satisfaction achieved by an organization, from perfectly mirroring (left, mirroring = K) to fully decentralized (right, mirroring = 0). These results are reported for 4 different durations of exploration (the number of steps).

Going to the *regular* architecture (Fig. 4), we see very little differences in the results compared to the standard NK-model. Again, we observe that perfect mirroring performs especially poor for high K-values and low N-values. Furthermore, as for the standard NK-model, an optimal fitness is achieved with an intermediate level of mirroring.

The *core-periphery* architecture (Fig. 5) also shows the value of ignoring some of the product's interdependencies in an organization design, as the highest fitness values tend to be found for intermediate levels of mirroring. However, different from previous results, the differences in fitness levels are less pronounced. Hence, it appears that a mirroring organization is an appropriate organization design whatever the exact size and complexity of the product architecture in question.

Finally, we look at *decomposable* and the *nearly decomposable* architectures (Figs. 6 and 7). Indeed, the literature of mirroring has primarily centered on the question of product modularity, and whether this modularity is reflected in decentralized organization designs. The overall results are very similar to the results for the other architectures. Perfect mirroring is not the optimal organization design for large K or small N. Reversely, for small K and large N perfect mirroring does a very good job, similar to other architectures.

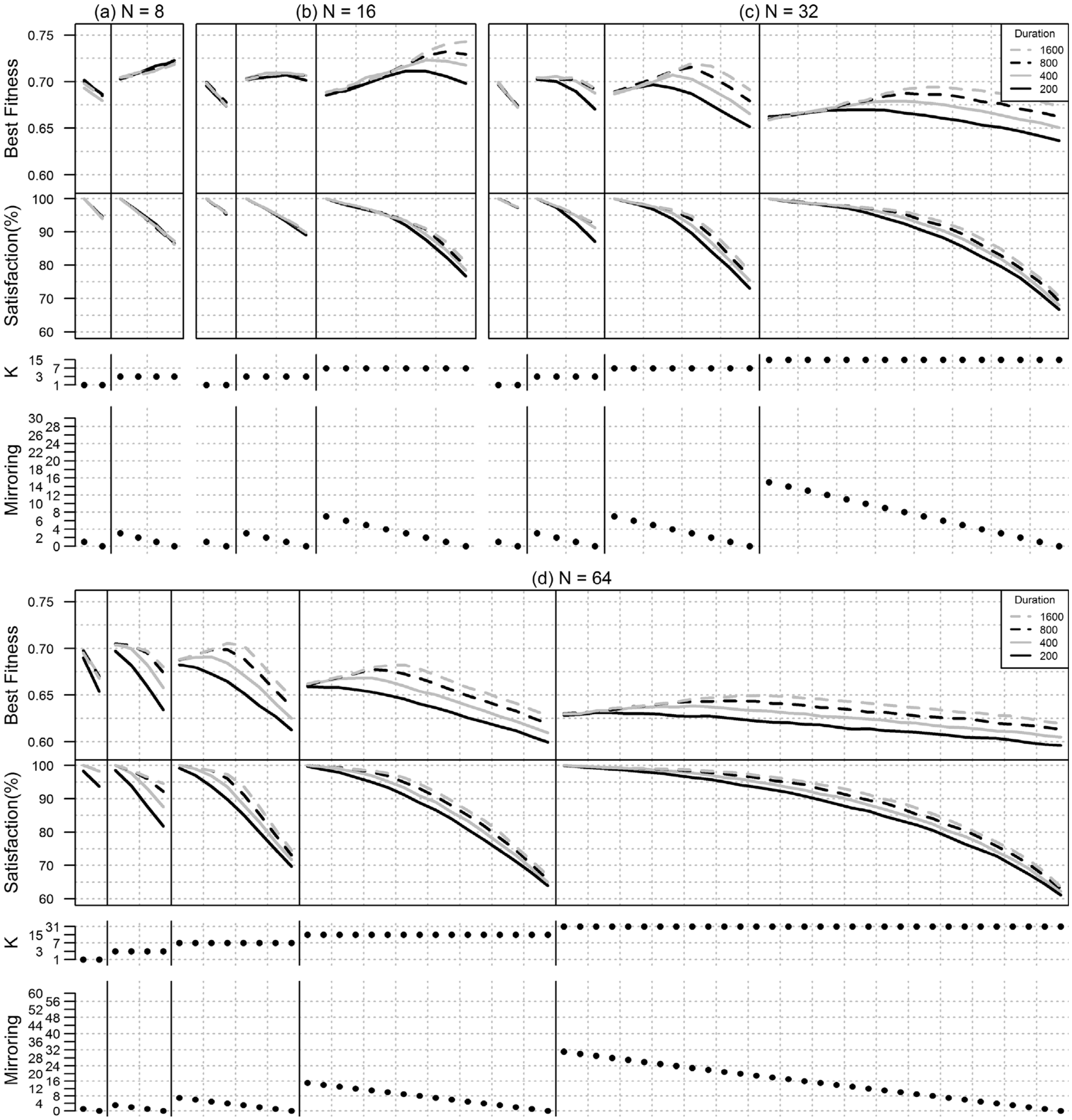


Fig. 4. Results for a regular architecture.
Same structure as Fig. 3.

Furthermore, we can observe little differences between decomposable and nearly decomposable architectures. As already pointed out by Simon (1962, 2002), these two product architectures can be considered very similar.

To summarize, we have three key results that apply to all the architectures implemented in this experiment. *First*, perfect mirroring is not necessarily the optimal organization design. This is an important theoretical result. The widespread intuition that technical interdependencies should all be reflected in the design of an NPD, is proven false given our definition of mirroring. *Second*, complete ignorance of the interactions between components in one's organization design is not rewarding, particularly when the number of components (*N*) increases. For small *N*, the number of technological combination is relatively limited, so it is easier to find some very good optima by chance. When *N* increases, some degree of coordination within an NPD is necessary. *Third*, for $K \ll N$, perfect mirroring often turns out to be the optimal design, whatever the exact architecture underlying the product technology. *Fourth*, mirroring does especially well for core-periphery architectures, even for systems with small *N* and large *K*.

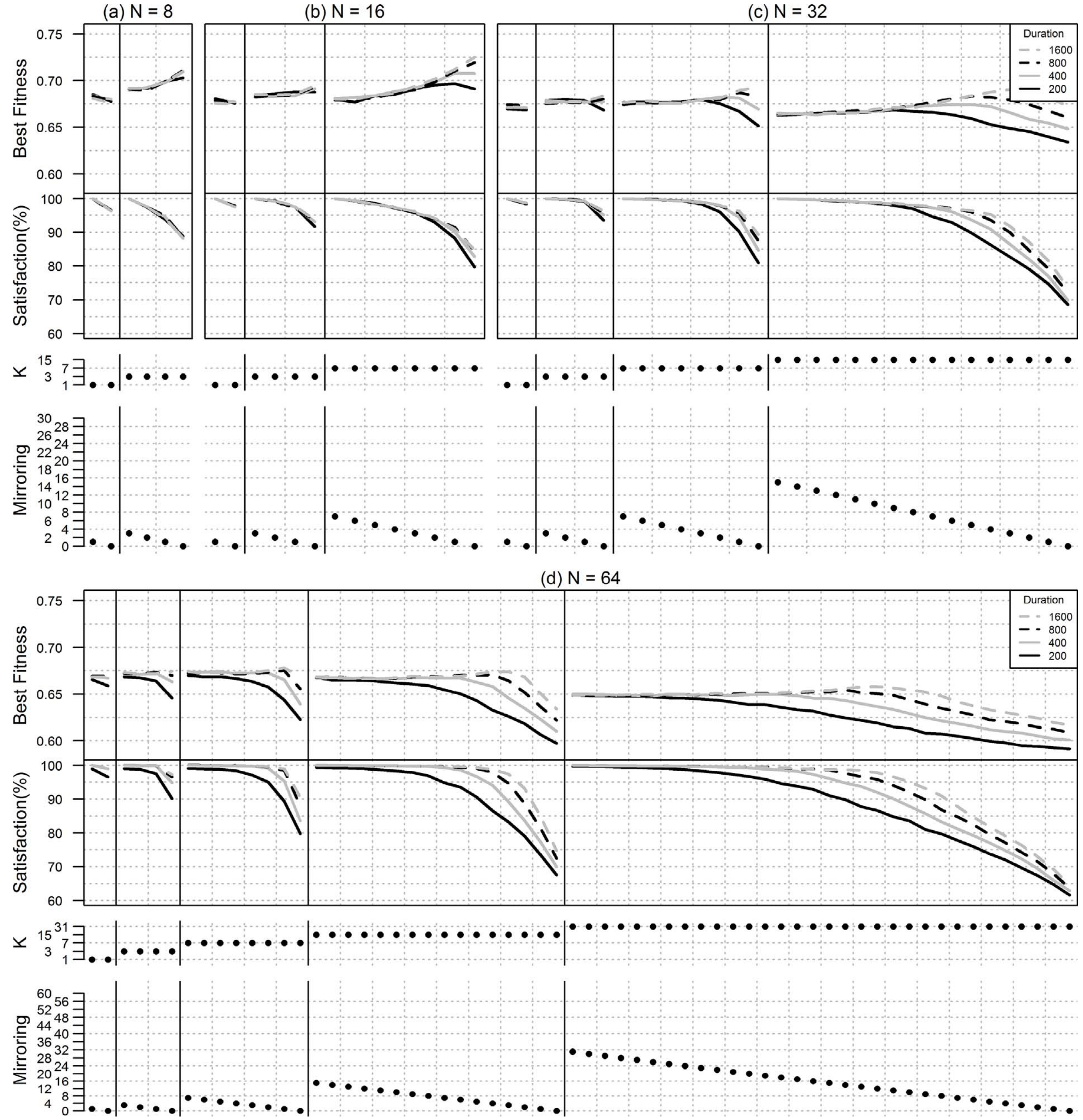


Fig. 5. Results for a core-periphery architecture.
Same structure as Fig. 3.

6. Discussion

We presented a theoretical model of organization design that mirrors the architecture of the product being designed. In a perfectly mirroring organization design, the network of agents is such that each agent accepts a mutation of its own component by taking into account all consequences throughout the whole organization. This model is a generalization of previous models that were limited to the study of team-based organization designs. The generalized representation allowed us to come up with a theoretical model of the mirroring hypothesis, which hitherto was lacking.

Our main result has been to show that the mirroring hypothesis holds for large systems with only few interdependencies among its components ($K \ll N$). Thus, although we found theoretical support for the mirroring hypothesis only for specific parameter settings (large systems with low complexity), one can argue that these exact parameter settings are most representative for real-world technologies. Indeed, most technologies contain many components and relatively few interdependencies (Baldwin and Clark, 2000).

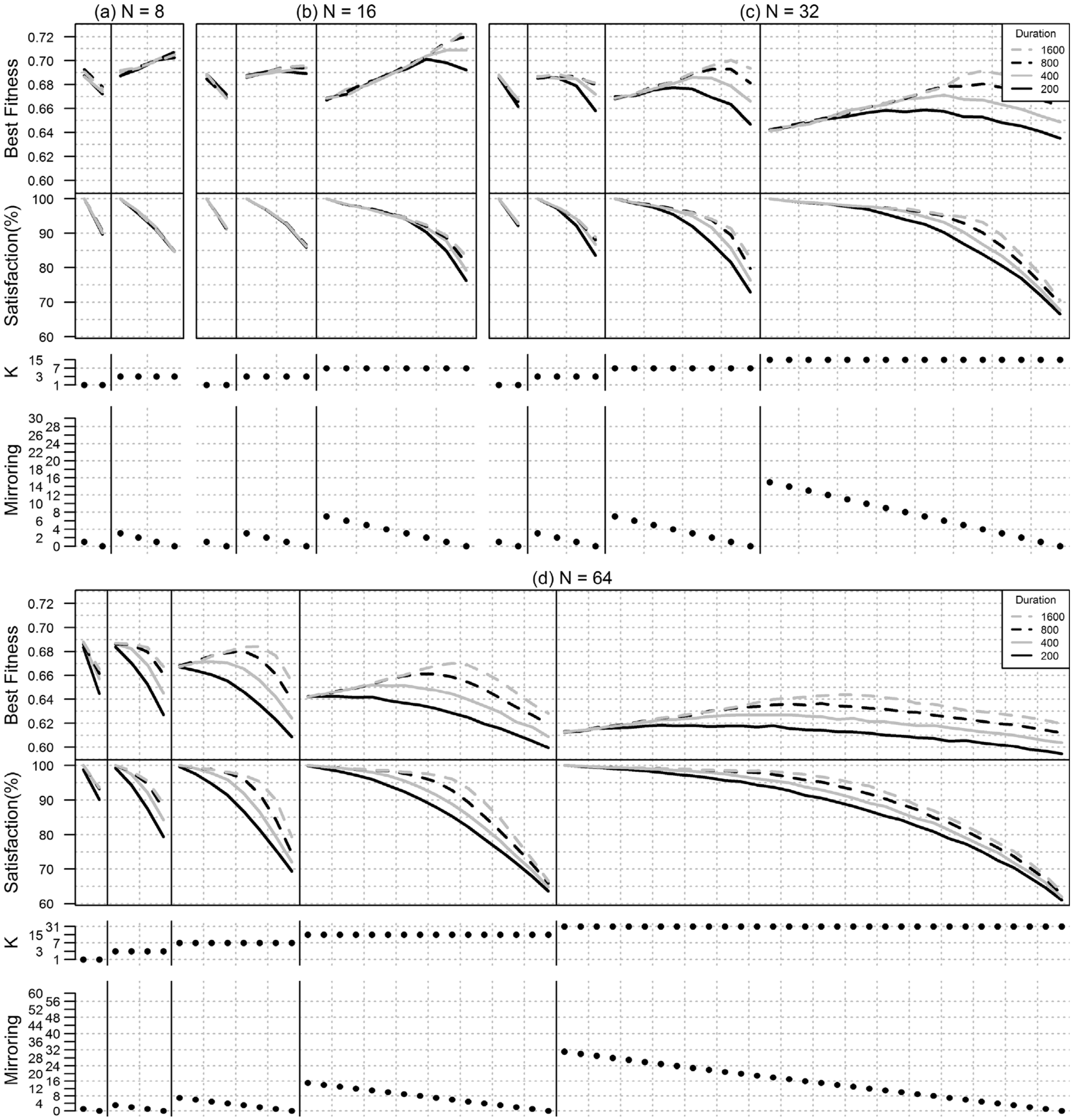


Fig. 6. Results for a perfectly decomposable architecture.
Same structure as Fig. 3.

This is also apparent from the empirical work on Design-Function Matrices on aircraft engines (Sosa et al., 2004) and computers and software (Baldwin and Clark, 2000; MacCormack et al., 2012; Baldwin et al., 2014) as well as NK-inspired statistical analysis of steam engines (Frenken and Nuvolari, 2004) and energy technologies (McNerney et al., 2011). Hence, though theoretically not valid for the full range of parameters, the mirroring hypothesis can be expected to be predictive in many empirical contexts.

Furthermore, we found that mirroring organizations perform especially well in designing products with a core-periphery architecture. Again, there is evidence that many products are designed according to a core-periphery architecture (Baldwin and Clark, 2000; Sosa et al., 2004; Baldwin et al., 2014), in particular, designs that have become dominant designs as defined by the choice of technologies for core components (Murmann and Frenken, 2006).

In future work, our model can be used to further probe the expanding empirical literature on the mirroring hypothesis. Some of the conflicting results may be attributed to exactly those parameters in our model that specify when mirroring performs well and when mirroring performs poorly. In particular, as noted before, one expects the mirroring hypothesis to hold for very large products

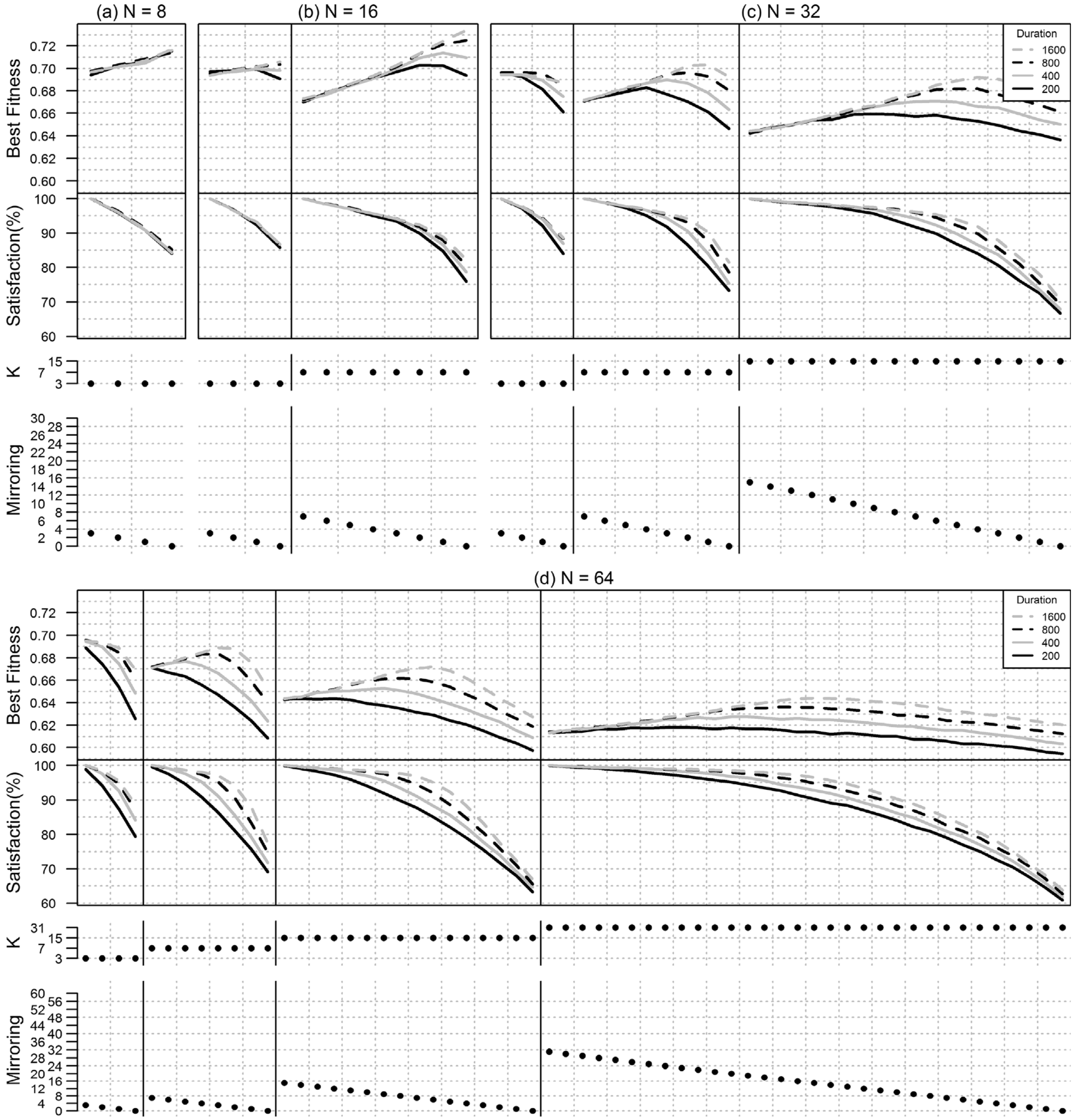


Fig. 7. Results for a nearly decomposable architecture.
Same structure as Fig. 3.

with relatively few interdependencies (such as technologies based on computer sciences), while it may not hold for products with much higher complexity and few components (such as technologies based on chemical engineering).

Besides the mirroring hypothesis, this model contributes to the literature on knowledge diffusion and innovation networks by providing a very flexible tool to understand the communication process of complex decision makings in inter- and intra-organizational settings. For instance, our results put into perspective the results obtained by Lazer and Friedman (2007). Using an NK-model, they simulate an inter-organizational network of innovators who explore independently a complex landscape, but are connected by flows of knowledge communication giving them an opportunity for imitation. They find also an inverted-U relationship between the connectedness (flow of knowledge) and the performance of the exploration. Methodologically, our model extends these findings by demonstrating how this inverted-U relationship happens for specific forms of product complexity in a network of interdependent innovators. While these authors emphasize the trade-off between information diffusion and diversity, our work put forward the economics of attention perspective. Based on our results, one can claim that the inability to access or process all the available information in the innovation networks can be rewarded by greater discoveries.

Our results also provide two thoughts for organizational governance. First, tempering the willingness of individual teams to provide the greatest features on their individual components can eventually lead to a greater product overall. In fact, the high level of satisfaction achieved in our simulations tells us that asking a team to temporarily alter a component in order to further the exploration will eventually lead both to a better product and to a better component. Second, our results show that organizations do not need to optimize forcefully their decision-making structure when they start developing a new product. In other words, the informal relationships or long term collaborations that contribute to an organization structure can subsist and provide great discovery, even if they do not mirror all the technological interdependences of the new product in development.

7. Limitations and future extensions

The main limitation of the model is that the decision-making structure of a NPD organization is a fully decentralized one, in which each component is controlled by a single agent. This prevents search to take place in “long jumps” involving multiple mutations at the same time (Levinthal, 1997). Especially for modular products, long jumps are feasible given that one module can be completely redesigned (involving many simultaneous mutations), while necessitating no – or very few – adjustments in other modules. One promising extension of the model is to allow for such longer jumps, and then compare the performance of mirroring organizations compared to other organizations.

Another assumption we followed holds that the principal in the organization is able to perfectly observe the fitness values of components and, on this basis, to select the design with highest performance. We thus abstracted from any strategic principal-agent problems that may arise within an organization. Future modelling efforts on product design and the mirroring hypothesis may pick up the challenge to integrate principal-agent theory within a model of decentralized design.

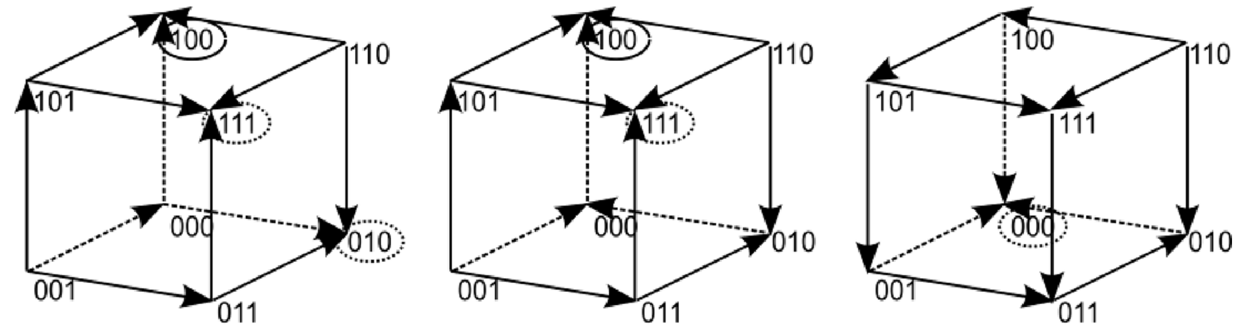
Another limitation of the model holds that we assume that the firm’s environment is stable. One way to introduce environmental dynamics is to let some of the fitness values change as to represent an external shock. In such contexts, modular product architectures are said to be advantageous, since each module can be adapted, without the need to re-design the whole product. The question that follows is whether such inter-temporal economies of scope (Helfat and Eisenhardt, 2004) are better realized by perfectly mirroring organizations or imperfectly mirroring organizations.

A final limitation of the model is the exogenous nature of network structures. That is, we have compared the performance effects of alternative organization designs, expressed as decision-making network structures, in terms of product fitness and agents’ satisfaction. However, even if network structures have been imposed exogenously by the organization onto the agents, the effective use of such communication channels by agents may still be limited as agents can strategically provide inaccurate information about technology choices that may affect others.

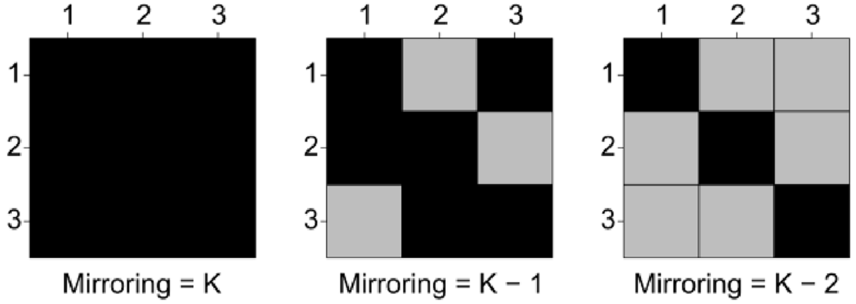
These extensions, and possibly others, can all be accommodated rather easily within the flexible modelling structure of the NK-model. In this way, one can make models that are more specific to particular technological or organizational contexts, and provide managerial implications for specific firms and organizations. In doing so, we hope to contribute to the further development of our understanding of the mirroring hypothesis, as well as of the wider literature of New Product Development, both in terms of theoretical consistency and clarity and in terms of its manifold applications in empirical research and strategic management.

Appendix A

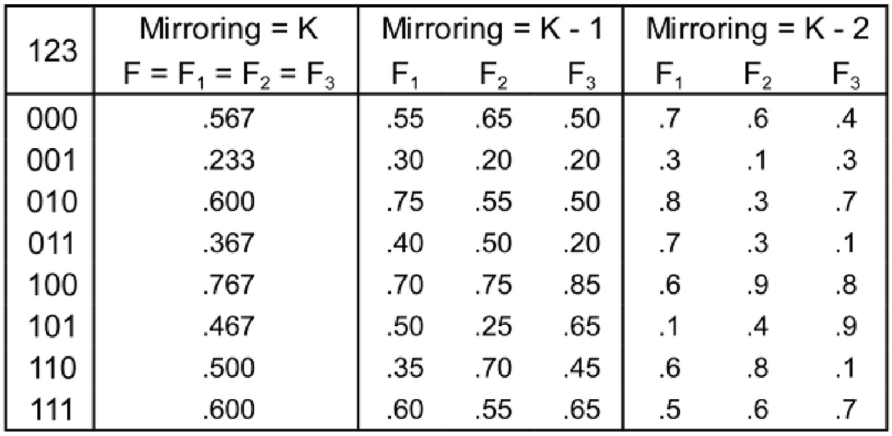
Example of fitness landscape for $N = 3$ and $K = 2$. (a), (b) and (c) represent the fitness-increasing mutations in design space. When mutations converge to a single design, this is a local equilibrium, where no agent desires to make a mutation; (d) shows for each agent (rows) the technological interdependences that are not acknowledged by the organization design (in gray); (e) shows the fitness values F_i evaluated by each agent for each product design in each organization design.



(a) Perfectly mirroring (Mirroring = K) (b) Incompletely mirroring (Mirroring = K - 1) (c) Absence of mirroring (Mirroring = K - 2)



(d) Technological interdependences and social ties



123	Mirroring = K	Mirroring = K - 1			Mirroring = K - 2		
	$F = F_1 = F_2 = F_3$	F_1	F_2	F_3	F_1	F_2	F_3
000	.567	.55	.65	.50	.7	.6	.4
001	.233	.30	.20	.20	.3	.1	.3
010	.600	.75	.55	.50	.8	.3	.7
011	.367	.40	.50	.20	.7	.3	.1
100	.767	.70	.75	.85	.6	.9	.8
101	.467	.50	.25	.65	.1	.4	.9
110	.500	.35	.70	.45	.6	.8	.1
111	.600	.60	.55	.65	.5	.6	.7

(e) Fitness landscape

- In a perfectly mirroring organization (a), search may end up in three designs (100, 111 and 010), including the global optimum 100. For all three designs, it holds that F cannot be improved by mutation.
- By reducing the level of mirroring by one (b), search may end up in two designs (100 and 111), including the global optimum 100. For both designs, it holds that F_i cannot be improved by mutation.
- Without any mirroring (c), search ends up in design 000, which is suboptimal from a global perspective. Only for this design, it holds that F_i cannot be improved by mutation.

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