On ignorance in organizational design: A generalized model of decentralized search

Adrien Querbes-Revier
TU Eindhoven
School of Innovation Sciences
a.querbes@tue.nl

Koen Frenken
TU Eindhoven
School of Innovation Sciences
k.frenken@tue.nl

Abstract
In this paper, we propose a formal model of decentralized search. In particular, we aim to understand how ignoring some pieces of information during technological search is rewarding for the development of radically new products. To do so, we propose an agent-based model of simulation including both product and organization structure. The NK model is used to represent a directed ?technology network?, producing a rugged fitness landscape. Organizations are represented by a directed ?social network?, where communication links are the counterpart of the technological interdependences. By simulating different density of the social network (from a perfectly mirroring organization to an organization made of fully autonomous agents), we find that a relative ignorance related to the effect of technological decision (on the dependent component technologies) can be rewarded by technological breakthroughs. This is particularly true when the complexity and the number of components of the products are high.
ABSTRACT: In this paper, we propose a formal model of decentralized search. In particular, we aim to understand how ignoring some pieces of information during technological search is rewarding for the development of radically new products. To do so, we propose an agent-based model of simulation including both product and organization structure. The NK model is used to represent a directed “technology network”, producing a rugged fitness landscape. Organizations are represented by a directed “social network”, where communication links are the counterpart of the technological interdependences. By simulating different density of the social network (from a perfectly mirroring organization to an organization made of fully autonomous agents), we find that a relative ignorance related to the effect of technological decision (on the dependent component technologies) can be rewarded by technological breakthroughs. This is particularly true when the complexity and the number of components of the products are high.

KEYWORDS: product architecture, organization design, NK-model, new-product development, mirroring hypothesis, social network.
1. Introduction

Designing an organization to produce the next technological breakthrough is a goal shared by many managers. In the race for radical innovations, new solutions are introduced to organize new-product development projects inside or outside the boundaries of a single firm, or even calling on the ‘wisdom of crowds’. However, for the development of complex technological artifacts, this search of creativity is counterbalanced by constraints on the product architecture. Product architecture is generally defined as the set of technical dependencies between product parts (Henderson and Clark, 1990; Ulrich, 1995). Changes in one part have implications for other parts as well (Simon, 1969). This is why coordination is needed, so that changes in components are made in the context of their consequences for other components. Coordination in the design of complex artifacts requires therefore the close correspondence of organization and product architecture. For instance, the “mirroring hypothesis” suggests in organization design that the organization of a new product development project will correspond closely to the product architecture (Colfer and Baldwin, 2010). The organization, which specifies the communication structure between designers of different components of an artifact, can therefore correspond to the product architecture of technological interdependencies that exist between components of the product.

The aim of this paper is then to assess how much the organizational structure should mirror the technological interdependencies, in the context of radically new-product development projects. Thanks to a systematic review of the empirical evidence on the mirroring hypothesis, it is suggested that, indeed, organizational and technological designs often coincide, but also that notable exceptions remain (Colfer and Baldwin, 2010). Importantly, this does not favor a particular causal arrow. The correspondence between organizational and technological structure can stem from the organizational structure such that independent teams are likely to build a modular architecture, while a single integrated team is more likely to opt for an integrated architecture. Or, correspondence can stem from physical constraints such that the physical properties of technologies render particular architectures most efficient with the organization mirroring this architecture. Obviously, the two logics can also operate simultaneously.
In the specific context of new-product development, we must take into account that “thinking of invention as a process of recombinant search over an interdependent landscape provides a more complete and causal explanation of the technological sources of the life-cycle, from birth by synthesis, growth and productivity through initial modularization, eventual exhaustion from complete modularization, and rebirth through new interdependent syntheses” (Fleming and Sorenson, 2001, p. 1037). Consequently, on the technology side, the new synthesis produces technological interdependences unknown or unobservable by the product designers. On the organization side, routinized communication structures curb equally the alignment between technology and organization. Exploring the whole technological potential of a new product requires specific organization designs (Rivkin and Siggelkow, 2006), far from structured processes and market concerns (Veryzer, 1998).

Our aim is then to develop a theory of organization and product design, where organization design is as diverse as the innovative combination of component technologies. This is the reason why we build upon the previous theoretical work analyzing decentralized search by non-overlapping teams (Kauffman and Macready, 1995; Rivkin and Siggelkow, 2003; Siggelkow and Levinthal, 2003). In our model, we generalize the theory of decentralized search in such a way that we can model the performance of any organization design that can be expressed as a directed social network between the members of the organization. In such a model, non-overlapping teams constitute a special case of a social network. Hence, our contribution is to provide a generalized framework for decentralized search in complex systems in which any networked organization can be assessed in terms of its innovative performance.

In the sections 2 and 3, we present successively the NK-model as a representation of complex technological artifacts and how we use networks to produce a generalized model of organization design. In section 4, we show how our simulations put together a given form of organization design with a given product architecture. In this section, we develop our representation of ignorance in organization design in term of incomplete networks of communication between agents in the organization. Equally, we show our formalization of the new-product development process as a trials and errors process. In section 5, we present the results of the simulation, which can be summarized as an inverted-U relationship between
ignorance in the communication network and creativity in the product development. In the final discussion, we explain how this result can be used by managers.

2. Product architecture: the NK-model

A standard way, by now, to represent product architecture as a complex system, 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 dependencies between these component technologies (Kauffman et al., 2000; Simon, 2002a; Frenken and Nuvolari, 2004). As a complex system, the fitness of each component depends not only on the state of the component technology itself, but also on the state of \( K \) other components. Thus, for each component \( i \), its fitness depends on a subset of \( K \) components: \( \{ i_1, ..., i_K \} \subset \{ 1, ..., i-1, i+1, ..., N \} \), using the formulation proposed by Altenberg (1997).

The set of technical dependencies 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 \( j \). The parameter \( K \) then equals the indegree of each component, while the outdegree can vary between 0 or higher, and on average equal to \( K \). Henceforth, we will describe a product architecture as a “technology network” which is expressed by the binary matrix of size \( N \times (N-1) \) and a density of \( K \times N \).

Without loss of generality, we follow the standard assumption that each component can be designed in two ways (i.e. there are two technological options for each component), which implies we have a binary state 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:

\[
F(x) = \frac{1}{N} \sum_{i=1}^{N} F_i(x_{i_1}; x_{i_2}, \ldots, x_{i_K})
\]

Search takes place by the mutation of components, i.e. flipping their state from 0 to 1 or vice versa (0 and 1 can be understood as “absence or presence of the component”, as well as “the component relates to technology 0 or to technology 1”). If search proceeds in only one component at the time (local search), and mutation proposals are accepted on the basis of global fitness, we have a model of product innovation that is formally equivalent to Kauffman’s (1993) biological model of natural selection. We will hold on the assumption that a new product development (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, 1969).

3. Organization design: a 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 individuals controlling different components. For the sake of writing, we assume that there are as many individuals in the organization as components in a product \( N \), and that each individual \( i \) controlling 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 component. A hierarchical organization 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 a hierarchical organization individual designers have no autonomy; hence any proposal for mutation will only be accepted if the global fitness -- computed on the basis of the fitness of all components -- will increase.
Another organization design is one where each individual would be free to mutate its component. In such a design, each individual tries to optimize the fitness of its component only. Each mutation proposal will be evaluated against the fitness of this component. Hence, in a fully decentralized organization individual designers have full autonomy, and any proposal for mutation will only be accepted if the component fitness will increase. Mihm et al. (2010) show that such a structure produces an oscillation of the global fitness.

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 sub-set 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).

The literature on organization using the NK-model, has so far only explored these three categories of organizational 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 hierarchical, 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. If departmental size would be the only variable that can be tuned to design a NPD organization, a correspondence between organization and 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; Simon, 2002). The consequence of these approaches is that decentralized organization design works only for clearly modular artifacts (Sanchez and Mahoney, 1996) and reciprocally, hierarchy is necessary for not fully decomposable products (Siggelkow and Levinthal, 2003).

A generalized model of organizational design is one that comprises all possible social network configurations that can exist between members of an organization, where the network relations of an individual specify the subset of individuals whose fitness it 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 technical interdependencies are reflected in an organization design such that a component technology influenced by $K$ neighboring components in the technology network, is controlled by an individual who has social ties with the $K$ individuals in charge of the $K$ neighboring components. Social ties outside the set of the $K$ individuals may be realistic, but they have no effect on the decision, because these components are not influenced by the mutation. They can be omitted in our model.

### 4. A model of search of radical innovation by a decentralized organization

Recall that the set of technical dependencies 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 $N \times (N - 1)$ and of density $K \times N$. A mirroring organization design can hence be understood as “social network” with the exact binary matrix that characterizes the technology network. An arc in the social network from individual $j$ to individual $i$, 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, there are as many fitness functions as there are individuals (and, to repeat, there are as many individuals as there are components, with each individual $i$ controlling the state of component $i$ and only $i$).

For each individual $i$ controlling component $i$ that is influenced by $K$ components $\{i_1, ..., i_K\} \subset \{1, ..., i - 1, i + 1, ..., N\}$, the corresponding fitness function becomes:

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

with $x_i \in \{x_{i_1}, ..., x_{i_K}\}$, because $G_i$ is the set of components $j$ influenced by component $i$ ($g_i$ is the number of components in this set) and $U \sim \text{uniform random distribution on } [0,1]$.

Search takes place now in a decentralized but “networked” manner. When an agent mutates its component, it collects the fitness values of the components influenced by the mutation.
The aim of our simulations is then to compare the ability of a social network to improve a complex technological system, while ignoring (or not) the global effect of the decision. We test then a range of agent’s social outdegree between the perfectly mirroring organization (agents take into account the fitness of all the components influenced by the mutation before changing their technologies) and an organization of independent individuals (agents change their technologies if their component fitness increase, regardless the effect on the other components). By this method, we model a set of ignorance levels, where agents realize their innovations by taking into account a more or less incomplete set of information. Then, we assess the creativity related to this ignorance by looking at the technological combination which gives the best fitness over a fixed period of exploration.

This development process is consistent with the development of radically new products. On one hand, when developing a radically new product, the firm can only estimate the superiority of a combination over another by comparing a large set of combinations. Equally, while some development projects will reach a local optimum where all the agents consider that a mutation will be decreasing the fitness they observe, some other projects -- in particular, those where agents ignore a large part of the outcome of their decisions -- are oscillating. Development projects are increasingly benefiting from advances in prototyping (computer simulation, 3D printing …), making trials and errors faster and cheaper. This is why we assume that trials and errors is the more efficient process of technological exploration (Sommer and Loch, 2004), but thanks to the amount of generated versions of the artifact, firms have the knowledge to extract the best product instead of an only satisfactory solution (Fleming, 2002; Girotra et al., 2010).

On the other hand, to discover and to make optimal use of synergies, a technological option which was discarded for a given technological state of the components, has to be reevaluated once the influential components have changed. Instead of linear and sequential development processes, the development of radically new product involves concurrent engineering, as well as waterfall or iterative development.

For Rivkin and Siggelkow (2006, p.611), “the key to successful strategizing may lie in organizing to manage the transition from search to stability, and back to search should an environmental change require renewed adaptation.” This is why we focus on the creativity as
a technological achievement. The search for speed and stability -- which needs communication and hierarchy (Mihm et al., 2003, 2010; Rivkin and Siggelkow, 2003) and is, therefore, adverse to ignorance -- corresponds to the next stages of the product evolution and commercialization (Veryzer, 1998). Ignorance is not yet related to myopia, delays or opportunism in our model. In fact, we assume that when technological options are assessed, perfect information about the outcomes of these changes are disclosed by the member of the social network. We can imagine that agents unable to disclose perfect information or untrustworthy does not belong to the social network. This does not change our results, as long as the various degrees of ignorance tested in our model (the agent’s social outdegree) can relate, without distinction, to the ignorance of the technological interdependence as well as the ignorance of the effect of this interdependence due to myopia, delay, opportunism and so on.

5. Simulation

In our model, at each simulation step, one agent (chosen randomly) has the opportunity to test a technological mutation and to implement it if this mutation improves the fitness of its social network (i.e. the agent and its neighbors). There is neither delay nor myopia regarding the transmission of information inside this network, i.e. everyone is perfectly informed. Hence, the agent can compare the fitness value of its social network, with or without mutation.

The simulations are performed over a large set of values for \( N \) and \( K \), with \( N = \{8, 16, 32\} \), and \( K = \{0, 1, 3, ..., N - 1\} \) (for \( K \neq 0 \), we consider only positive odd numbers). Following Kauffman (1993), the technical interdependencies are chosen randomly with the only restriction that the indegree of each component in the technology network equals \( K \). For each value of \( N \) and \( K \), we performed several simulations. One simulation represents the case of “perfect mirroring” between the technology and social networks. Then, the simulations are repeated, and for each repetition, each agent “destroys” one of the \( K \) social ties, such that the density of the social network is reduced from \( N \times K \) to \( N \times (K - 1) \), and then from \( N \times (K - 1) \) to \( N \times (K - 2) \), et cetera. Hence, for the first simulation, each mutating agent takes into account the changes of fitness of all its \( K \) social neighbors, for the second simulation the changes in fitness of \( K - 1 \) neighbors, for the third simulation the changes in fitness of \( K - 2 \) neighbors, and so on, until the last simulation where all the social links have disappeared. For
a system with complexity $K$, we simulate $K + 1$ social networks ranging from the social network with indegree $k = K$ that perfectly mirrors the technology network to a fully decentralized network with indegree $k = 0$. 

(a) $N=8$

(b) $N=16$
Figure 1 shows the results of the simulations. In order to test the performance of the organization (regarding a given technological design), we let the organization trying to improve its technological system over 200 simulation steps, then we save the system’s best fitness value over this period. For a given level of $N$ and $K$, the Figure 1 shows a curve, the extreme left point (highlighted by a red dotted line) is the perfectly mirroring organization where the number of neighbors ("social link") is strictly equals to $K$ and each point on its right shows another organization with a decreasing number of neighbors disclosing their fitness value. For instance, for $N = 8$ and $K = N - 1 = 7$ (the extreme right curve of Figure 1a), the perfectly mirroring organization is an organization where each agent chooses to mutate depending on the fitness value of their component technology after the mutation, as well as the effect on the 7 other component technologies they influence. The best system produced by this organization has a fitness value of 0.659. On its right, there is an organization where only 6 agents disclosed their component technology’s fitness value over

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1 On the Figures, "K link" quadrant shows the value of $K$, i.e. the technological complexity. "social link" quadrant shows the value of $k$, i.e. the number of neighbors providing their fitness information.
the 7 agents influenced by a given component technology. This organization has developed a system which has reached a fitness value of 0.664. And so on.

The first result that we can observe is for very simple systems (small number of $K$ links), i.e. when $K = \{1\}$ for $N = 8$ and $K = \{1,3\}$ for $N = \{16,32\}$ ($K = 0$ is only represented to show the fitness level of a system without interdependences). In these cases, ignoring the fitness of dependent technologies is wrong. The highest fitness values are reached by organizations with a full set of social ties (i.e. “mirroring organizations”). This is wrong because of the very limited number of synergies between components. Concretely, $K$ being the number of components influencing a given component, we can expect (on average) that $K$ is the number of components dependent of a given component as well. When an agent tests a change for its component, if it ignores its influence on other components, this agent is only looking at an alternative between two fitness values (one for the state 0 and one for the state 1). On the contrary, by not ignoring the influence on other components, the agent has potential fitness values for its component. These fitness values being drawn uniformly between 0 and 1, it increases the chance to draw a large fitness value. This is how the NK-model produces potential technological synergies among interdependent components.

The second result is that the chance to benefit directly from these synergies decreases when $K$ increases. In fact, when $K$ increases the changes tend to be neutral because the synergies between some interdependent components are counterbalanced by negative interactions between other components. This is the reason why, for higher complexity, the technological artifact reaches rapidly a local optimum, where all the next mutations will decrease the global fitness. However, by ignoring some information, the agents will move the technology from this optimum and may eventually reach a better one.

Finally, a third result is that a complete ignorance of the interactions between component is not always rewarding, particularly when the number of components ($N$) increases. For small $N$, the number of technological combinations is relatively limited, so it is easier to find some very good optima by chance. When $N$ increases, some degree of coordination is necessary,

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2 The tests showing the robustness of these results can be found in Annex.
because the organization cannot develop very good artifacts (i.e. find interesting local optimum) based solely on completely random changes.

6. Discussion and conclusion

In our simulation model, we have generalized the existing work on team-based organization, via a network approach. By this way, we have represented a network of actors who can capture exactly the complexity of interdependences at the technological level. By introducing some degree of ignorance related to the performance of technological decisions, our general result is that the creativity -- the discovery of technological breakthroughs -- will increase when the agents ignore some outcomes of their decisions. This interesting property of a decentralized technological exploration is particularly robust when the complexity (defined as the number of interdependencies between components, i.e. $K$) and the size (defined as the number of component technologies, $N$) increase. The reason is that when the number of agents involved in a technological decision grows, their aggregated opinions about a potential change tend to be against this change. Consequently, the product will only benefit from few technological changes and reach quickly a local optimum on the fitness landscape, where there are no more rewarding mutations. However, even if removing social links reduce this inertia, it also increases to produce uncooperative decisions detrimental for the performance of the product: it happens when agents make completely autonomous decisions, their outcome being immediately lost by the conflicting decision of another autonomous agent and so on.

Regarding the development of radically new products by networked organizations, this emergent property of complex technological artifact is particularly interesting when we take into account the cognitive and communication constraints, as well as the governance of such projects. For organization design, “human attention, not information, is the scarce factor -- the essential design constraint” (Simon, 2002b, p. 614). Hence, our results may give security to the designers of components facing the difficulties to gather and compute all the information related to their technological decisions. Equally, there is uncertainty about unexpected interdependences discovered when exploring the potentials of a new product -- as a new combination of component technologies. Our findings show that ignoring these interdependences is, therefore, not completely harmful for the development project.
Particularly, by using a standard NK-model with random interdependences, we show that it is not necessary to introduce modularity or quasi-decomposability (Mihm et al., 2003, 2010; Rivkin and Siggelkow, 2003) to find good solutions, when the organization is neither completely hierarchical nor completely decentralized. Knowing the cognitive limitations of the human’s ability to coordinate (Heat and Staudenmayer, 2000), accepting this ignorance might as well be more cost effective than designing a multi-layered hierarchical structure or introducing incitation methods.

Our results reinforce also the idea that lucky -- or “lone” (Singh and Fleming, 2010) -- inventors are unlikely to make the major discovery, particularly for large and complex technological artifacts. In the same line, we show that organizations should integrate a degree of independence between agents to maximize the creativity. This is consistent with Lazer and Friedman (2007) who find an inverted-U relationship between connectedness of the agent’s network and performance of the exploration, using a different method. On the other extreme of our representation of organizations, we can also propose a candidate explanation for a notable exception of the mirroring hypothesis: organizations with few ties between the stakeholders by comparison with the complexity of the technology they develop. This form of coordination can therefore be advantageous to discover better technological combination. Then a perfectly mirroring organization exhibits too much inertia to make these discoveries for very complex technologies. For simple (modular) technologies, an alternative is to redesign the team-based (modular) organization. In fact, creating new ties at the organizational level is a solution to discover technological synergies unexpected by a modular organization.

An extension of the model would be to analyze how these best artifacts -- developed according to various degrees of ignorance -- correspond to Nash equilibrium. More precisely, because we cannot expect a general agreement for a given solution due to the decentralization, it would be interesting to know the proportion of agents who consider useless to change the best artifact. Such an index gives a complementary idea of the relevance of a hierarchical organization design. Another limitation of this model is to focus only on random networks for organization and product designs, in respect of the standard version of the NK-model. Consequently, a next step of the simulation is to use different patterns of organization design (cf. Rivkin and Siggelkow, 2007) to compare with organization mirroring.
the random structure of technological interdependences (this technological structure still based on standard NK-model). Particularly, we can start from small world or clustered networks, mimicking an existing organization design which may have to evolve in order to increase the creativity for new product development.
References


Annex
Description of Figure 2: for a given $N$ and a given $K$, this figure shows the $p$-values of the Student’s t tests comparing the best fitness obtained by each form of incompletely mirroring organization with the best fitness obtained by the perfectly mirroring organization. The alternative hypothesis being “the incompletely mirroring organization has an inferior best fitness value than the perfectly mirroring organization”, we can consider that the more the $p$-value is superior to 0, the more we can reject this hypothesis and, therefore, the more we can consider that the incompletely mirroring organization provides a better (or equivalent) best fitness value.