Computational & Mathematical Organization Theory 3:1 (1997): 43–66

Simulation of Learning in Supply Partnerships

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Abstract

A model is designed and used to simulate how partners in a supply relationship identify and reach a common target in the form of an ideal end product. They cooperate fully and share returns. They learn by interaction, as follows. From their different perspectives, they complement each other's identification of the target. They adapt their productive competencies to the target, in order to conform to demand (quality), and to each other, in order to achieve efficient complementarity in production (efficiency). As they approach the target, their accuracy of identifying the target increases. Also, their speed of adaptation increases, and thus they can be said to be learning by doing. The model allows two different patterns of acceleration: a routine and a radical type of development. At some distance from the target they start to produce. A longer distance from the target yields earlier returns, but also entails a greater compromise on quality and thereby yields lower returns. Unpredictable changes in market and technology yield random shifts of the target. In the analysis, the returns from single and dual sourcing are compared under different parameter settings. The simulations show that in line with expectations dual sourcing can be more advantageous if development is of the radical type. However, the advantage only arises if conditions of market and technology are neither too volatile nor too stable.

Keywords: inter-organizational relations, adaptive learning, simulation models, subcontracting, organizational learning, uncertainty, market

1. Introduction

Developments in technology and global markets have accelerated, and this has increasingly turned competition into a race in innovation and market penetration. In order to stand a chance in these races, to achieve rapid switches to novel opportunities and conditions, and to deal with increasing complexity, firms must concentrate on core competencies (Prahalad and Hamel 1990). This entails the need to outsource activities, even when they are strategic in the sense that they have a large share in costs, are sensitive to quality and entail specific competencies. Rather than claiming to have full competence in all dimensions of their products and production processes, firms should make use of the specific competencies of suppliers, not only in production, but also in the process of research and development. Rather than making blueprints of required inputs that are "thrown over the wall" to suppliers, there should be early supplier involvement in the design process (Helper 1991; Lamming 1993). Supply relations must be managed to yield both high product quality, in a close fit to market requirements, and low-cost, efficient production. This requires supply relationships in which partners utilize complementarities in perception of market demands and technical competencies, and adapt to each others' competencies in design and production.

Often, from the perspective of transaction cost economics (TCE), studies have concentrated on the problems of mutual dependence ("hold-up") as a result of transaction specific investments, which raise complicated issues of governance of relations between formally independent but materially dependent firms, in forms of organization "between market and hierarchy" (Williamson 1985). This certainly forms an important issue, which deserves all the attention it has received. For a recent model of governance that proposes an integrated framework, including elements from outside TCE (such as trust next to opportunism, see Nooteboom 1996a). But in the context set out above, innovation and learning form a crucial dimension of supply relations, and TCE does not deal with it, as Williamson (1985) himself admitted[1] (Nooteboom 1992).

Our basic purpose is to develop a better understanding of the conditions that determine whether single or multiple sourcing is better in supply partnerships, while focusing not on issues of governance but on issues of learning and innovation in the interaction between buyer and supplier(s). In order to limit the complexity of the model, we assume that issues of governance are taken care of in such a way (for example: by symmetry of mutual dependence) that cooperation in a long term relation is ensured[2].

The perspective on knowledge (epistemology) that we take can be characterized as pragmatist and social constructivist (Nooteboom 1992, 1996b). Pragmatist in the tradition of American pragmatism (Peirce 1957) that knowledge (on the level of both people and organizations) is seen as the ability to perform a practice, and adequacy of knowledge is judged by the success of performance. Social constructivist in the sense that cognitive competencies such as perception, understanding and evaluation are based on categories that are developed in interaction with the world and particularly with other agents. As a result, cognitive competencies are path-dependent and to some extent idiosyncratic: different agents perceive, interpret and evaluate the world differently to the extent that they have had different experiences, in different contexts. This perspective highlights the importance of cognitive complementarities between different agents. Thus learning is seen here as an adaptation of cognitive and productive competencies to goals, on the basis of experience in applying those competencies (learning by doing) and interaction with other agents (learning by interaction).

We want to model radical uncertainty, in the sense that agents (people and firms) have a limited cognitive capacity: they can only perceive, interpret and evaluate a limited range of phenomena. In line with our epistemological perspective, to a greater or lesser extent they do so differently from others (Dearborn and Simon 1958; Kahneman, Slovic and Tversky 1982; Walker 1985). Organizations may react to uncertainty in several ways. For example, they may try to seal off, smoothen or buffer external influences (Thompson 1967; Pólos 1995). They may bet on generalism (Freeman and Hannan 1983; Péli 1997) or follow an "r-strategy" going for short term advantages (Brittain and Freeman 1980). In cooperative relations, firms may try to increase their engagement in their existing exchange relations or look for new partners with similar status (Podolny 1994).

Uncertainty is reduced by learning in two ways: learning by doing and learning by interacting. In line with our epistemology, learning by doing entails that one improves task perception, and the ability to produce in accordance with it, by accumulating experience in striving after one's goal. Learning by interacting profits from the complementarity of the different perspective and competence of a partner (Hakansson 1986). Both processes entail not only information acquisition, but also adaptation of cognitive and productive competencies.

We consider two kinds of organizational agents that join their efforts to develop and produce a new product. The first agent is the user who decides what to produce, and in view of its core competence (and transaction cost considerations) decides which part to produce itself and which part to obtain from suppliers. To limit complexity, we assume a single product. The user looks for partners who can provide or develop the missing competencies (Schrader 1991). The second kind of agent is the supplier that joins the user. Suppliers have more specialized knowledge and competencies than the user concerning the required input materials, components, technology and methods, but these need to be adjusted to the purpose of cooperation with the user. This entails specific investments, but we assume that the resulting complications for governance are taken care of so that full and ongoing cooperation is ensured. The user has a certain capacity to *absorb* inputs from suppliers (Cohen and Levinthal 1990).

The non-trivial task of selecting appropriate partners (Hamel 1991; Teece 1986) is beyond the scope of the present simulation. Our story begins when the market, the product to be developed and the cooperative relation are already given and partners set to work.

We assume that there is an imperfectly perceived optimal competence set for the manufacturing of user's chosen product, given technology and market structure[3]. A product "distant" from a supplier in terms of the required production skills is perceived less accurately than a "proximate" one. The goal for the suppliers is to achieve the competence configuration ideal for the production of the given product. As suppliers adapt, i.e., they bring closer their actual competence offer to the ideal, their knowledge on the location of the optimum gradually improves (learning by doing). Meanwhile, the user has to bring its absorptive capacity close to the actual skill offer of the supplier (learning by interaction). When getting closer to the optimal competence configuration, the quality of the product improves. Here quality is literally taken according to the definition of quality as conformance to requirements of demand. When user and supplier get closer to each other, the efficiency of production improves due to better mutual adjustment. Thus we model the three central goals required by competitive conditions: utilization of complementary core competencies, high product quality and low-cost, efficient production.

A crucial feature of the model is the possibility of using not one but multiple suppliers with specializations in different directions, thus increasing the variety of sources (Nonaka 1991; Nooteboom 1992). Attacking the problem with two or more cooperating suppliers with different perspectives and competencies enhances the accuracy of their joint perception. Also, a specialized supplier can adapt more quickly to the perceived goal in the direction of its specialization. A further advantage for the user of having multiple suppliers is dealing with external turbulence. Turbulence comes into the model as random shifts of the ideal product requirements (and so, of the corresponding ideal competence configurations) due to changes in market conditions. By maintaining two, differently positioned suppliers instead of a single one, the user hedges risks against random shifts in product requirements. However, the user has to face the trade-off between that advantage and the complication of maintaining relations and making mutual adaptations with several partners. The model serves to explore the trade-off under different conditions represented by different parameter settings.

As indicated, we do not include problems of governance due to dependence as a result of specific investments, on the assumption that they are satisfactorily dealt with[4]. But a few remaining strategic aspects of interaction need to be mentioned. One is that an agent may opportunistically choose to switch to a more attractive partner that appears on the scene. A partner may also drop from the scene due to bankruptcy or take-over. Our model does not deal with these issues. Multiple sourcing has the additional function of hedging against such risks, or improving one's bargaining position with the threat of switching to an alternative partner. Another aspect is spill-over: intensive exchange of knowledge between partners carries the risk that through the partner it may spill over to a competitor (Teece 1986). This risk increases as the number of partners increases. We do not model the appearance and disappearance of actual or potential partners and processes of switching between them. We only study the trade-off between single and dual sourcing as a function of the shifts of the goal, perception of the goal, speed of adaptation to the goal and mutual adaptation between user and supplier(s). But one point remains: in case of two suppliers, to what extent will they be prepared to adapt competencies to a common goal, in the interest of the user, if this makes them close mutual competitors? There are probably limits to this: two suppliers will not be prepared to come closer to each other in competence than some minimal distance. The effect of this restriction is considered in the appendix.

The paper is organized as follows. Section 2 is about model construction: how some crucial elements of joint production and mutual adaptation are represented in the simulation model, the motivations for certain technical solutions, what has been left out or simplified. Model construction is based on an initial design by Nooteboom (1994, 1995). Section 3 offers the simulation results. Three hypotheses are formulated that are plausible under certain ceteris paribus conditions. The simulations show what comes out if we let conditions vary and interact, for different parameter settings.

Section 4 provides a discussion and summary of the findings.

2. Model Specification

2.1. The Scenery

This first subsection provides a picture which is still static: it serves to specify how the agents and their targets are represented in space.

The model is set up on the basis of movements in a Euclidean space, called competence space. Learning is seen as such changes of competence. Since we look at outsourcing, the dimensions of the competence space stand for the outsourced production competencies that the user needs to obtain from suppliers. To keep the representation simple and to be able to plot movements visually, the model handles two competence dimensions. We assume an *ideal point* (*IP*) in the competence space, which represents the ideal competence configuration for the product that user intends to manufacture in cooperation with supplier(s). This competence set is necessary to achieve the optimal product specifications, that is, to produce maximal quality. Since the same output may be produced by different underlying technologies that require somewhat different combinations of competence, a given product may in principle have multiple ideal points in the competence space (or in different, partly overlapping competence spaces). To limit complexity, we assume a single ideal point at each time step.

Changes of technology and other features of market conditions are modeled by ideal point shifts: new technologies and products usually require new configurations of competence. We model cases when the change is punctuated: technological breakthroughs or market changes occur suddenly after relatively quiet periods. Therefore, a parameter is introduced that measures the elapsed time between subsequent ideal point shifts, reflecting market stability (*Mstab*). Since market conditions are assumed to be externally given, *Mstab* is an independent variable in the model.

Organizational agents are characterized by the actual competence configuration they possess. A supplier position in space (S) indicates its competence to *produce* a certain input for the user. The user's position (U) indicates its competence to *absorb* the input offered by the supplier (Cohen and Levinthal 1990). The joint goal of user and supplier is to minimize the Euclidean distances between the ideal point and the supplier(s) (to achieve optimal quality), and also between the user and its supplier(s) (to achieve efficient production).

Some assumptions concerning competencies are implied in the chosen Euclidean framework. First, the fact that competence types are represented as orthogonal axes of the space implies that the skills are independent from each other, a condition not always met in reality. A second assumption follows from the isotropy of Euclidean space: there is no preference for directions. A consequence of this property is that higher competence values are not necessarily better. The ideal point of the product represents the optimal set of competence values, and overshoot is as bad as shortfall. For some products an overshoot is indeed bad: a coat can be too long, a drink too sweet, a car too large. But what is the problem with too high competencies? If a smart operator can produce well, a smarter operator can produce superbly. But the maintenance of high competence levels carries a cost. Beyond a certain limit, more competence does not improve product quality enough to counterbalance extra investments in skill improvement. Note that a similar practice is used in the so-called address type models of product differentiation in the industrial organization literature (Eaton and Lipsey 1989). There demand of a consumer is represented as a point in a *Lancasterian* product characteristics space, which is also Euclidean.

2.2. Movement

This subsection is about dynamics: our agents and targets move, representing adaptive efforts and market change, respectively.

Each agent follows an adaptive path to fit competencies to the target. Two aspects of cooperation that influence the outcome are addressed. The distance between the agents and the ideal point (*IP*) in competence space serves as a measure of product *quality*; the distance between user (U) and supplier (S) serves as a measure of *efficiency* of production, since it reflects the mismatch between supplier's ability to produce an input and user's ability to absorb it. When S reaches *IP*'s position along a dimension of competence, this means that the optimal degree of competence along that dimension has been achieved. Proximity between *S*'s competence offer and *U*'s receptive ability means good mutual fit, which enhances efficiency. Goal perception depends on distance: the closer is an agent to its goal in a dimension, the more accurately it perceives the goal's position on that dimension.

Being in the space of *outsourced* competencies, the ideal point's position is characterized with supplier skills. It is the supplier's task to figure out the *IP* coordinates in the outsourced dimensions, and to approach them. User's job is to bring its absorptive competence close to *S*'s productive competence position. *U* may opt for different adaptive strategies. It may give preference to rapid improvements in cooperation and approach *S* immediately. Then, user follows a moving target, namely, the actual supplier coordinates. Then distance between the partners may reduce rapidly, but *U* moves along a detour of mutual adaptation before all partners end up at *IP*. Alternatively, *U* can move towards *IP* directly, anticipating that *S* will arrive there as well. Then, priority is given to minimalization of detours, with the disadvantage of a slower improvement of cooperation. Intuition suggests that the latter option is superior, and some preliminary test runs confirmed this intuition. Therefore, the following simulations go on with a user that approaches its supplier by moving towards *IP*, in anticipation of *S*'s getting there as well.

Now we consider how agents' adaptive speeds change as they approach their targets. Since movement is a vector, with direction and length, the positive effects of agents' improving task perception on performance are twofold. The first concerns spatial orientation. Having a clear picture of the target allows for moving straight towards its *de facto* position[5]. The precision of perception is modeled by the width of an error range around the goal on each competence dimension. Being a linear function of the distance from the goal, the perception error decreases to zero as agents approach their targets. As a result, the zigzags of the adaptive path gradually smoothen out. Task perception is re-evaluated after each simulation step. Technically, the target's perceived position is randomly given within the (narrowing) error range.

Second, the *magnitude* of adaptive speed also reflects agents' perception. Actors cannot change their competencies arbitrarily rapidly. But possessing precise task information makes the adjustment faster. In model terms: adaptive movements accelerate with the agents getting closer to their targets. The *pattern* of acceleration depends on the novelty of the product under development. Two acceleration patterns were studied that reflect different dynamics of competence adaptation (learning). Let's call them *routine type* and *eureka type* development patterns, respectively: refinement of an existing technology or invention of a new one (Levinthal and March 1981). Or in other words: *cumulative* versus *radical* innovation.

A *routine type* development pattern involves a task where competence development is gradual and cumulative. The resulting product is an enhanced version of similar ones that have been manufactured before. Think of a new model of a successful family car or a new version of a text editor software. There are no or only few brand new technological elements in the R&D process. The outcomes of the R&D are to a large extent predictable; the adjustment process is gradual and subject to reliable timing. In model terms: adaptive speed increases linearly as the agent approaches its goal (figure 1(a)).

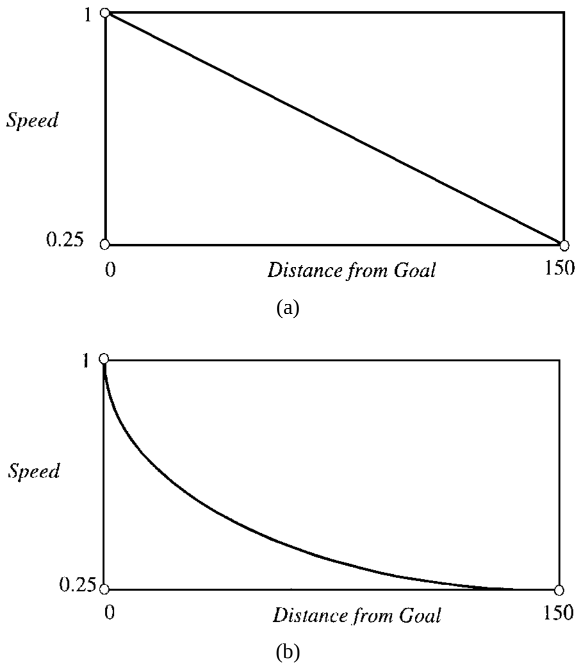


Figure 1. Patterns of adaptive speed change. (a) Routine development task, constant acceleration with distance (b) Eureka development task, changing acceleration with distance.

An *eureka type* development pattern is about the construction of a brand new product or production technology that constitutes a break with respect to previous practice. Uncertainty is high, the research begins “in the dark”. Think of a car with a new type of propulsion principle, or a new generation computer operation system. The beginning is slow because there is less to build on. But after an incubation, a breakthrough occurs, and once one has a grip on the subject, task knowledge grows rapidly, without delays due to the need to maintain continuity with previous practice. Speed increases slowly far from *IP*, and but increases steeply near the target (figure 1(b)).

The distinction between the two development patterns can be seen as different positions along the exploration/exploitation trade-off (March 1991): exploration dominates in the eureka type developments, while the exploitation of mainstream methods and technologies prevails in routine developments.

2.3. Diversity

Having the actors and their movements, now the trade-off is introduced between having one or more suppliers. A crucial question is addressed: how to represent the beneficial effects for the cooperation of having more diversity of competence by having not one but two suppliers, and how to account for the drawbacks arising from coordination in such triads.

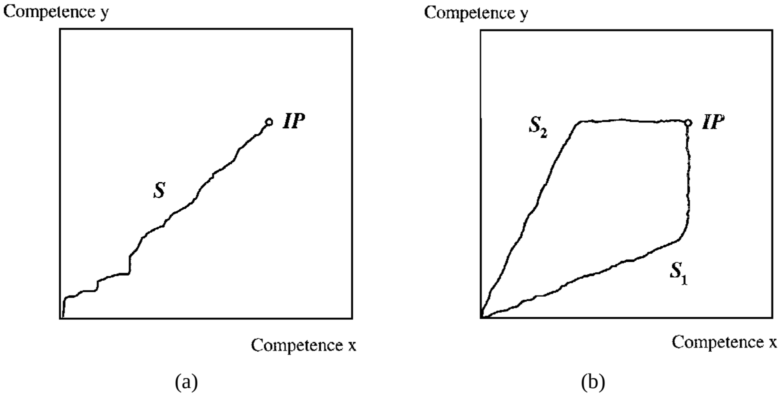


Figure 2. Supplier trajectories. (a) Single supplier (b) Two suppliers.

This setting requires some new denotations. In the following, U denotes a user with a single supplier S, and U_{12} denotes a user with two suppliers, S_1 and S_2. Similarly, let C and C_{12} denote the cooperation with one and with two suppliers, respectively.

Multiple sourcing may be superior to single sourcing for several reasons. Here, we focus on the consideration that the abilities and task perceptions of the contributors differ, yielding wider information diversity. The question is whether the beneficial effects counterbalance the costs of obtaining and processing the more diverse information, and accomplishing mutual adaptation between three instead of two agents.

Now two suppliers, S_1 and S_2, have to provide the necessary complementary competencies for user U_{12} to manufacture a product (*IP*). Both suppliers have to adjust their competencies to *IP*, that is, they have to identify and approach the *IP* coordinates. How can one represent the effect of greater information diversity resulting from the different angles from which a target is approached? In a spatial framework, a feasible solution is to assign different adaptive trajectories to S_1 and S_2. We assume a systematic difference in suppliers' developmental orientation. Although their objective is to adjust all of their competencies to *IP*, they are biased in skill development; they specialize in adjustment of one skill relative to the other. In simulation terms, adaptation on the specialized competence dimension is systematically faster. Consequently, the suppliers' routes toward *IP* will differ, even in case of a common departure point (figures 2(a) and (b)).

Let S_1 be specialized in adaptation along competence x, while S_2 is better in developing competence y. These specializations are represented by higher adaptive speed components along the pertaining dimensions. In mathematical terms, each supplier's speed vector is decomposed unevenly to horizontal and vertical components. The ratio of the two components $(v_x : v_y)$ serves as a measure of specialization. In the given case, we set $2:1$ for S_1 and $1:2$ for S_2. As a consequence, S_1 and S_2 do not approach the ideal point directly, but they make detours. These detours stand for extra coordination efforts under specialization. Note that while suppliers specialize in one dimension, they still have to mutually adapt in the other dimension.

The advantages of multiple supply are modeled as follows. S_1 has a good chance to approach the ideal point early on dimension x and to provide precise data on IP_x. Similarly,

S_2 will typically serve reliable estimates on IP_y. Focusing search efforts on one direction enhances adaptation speed along the pertaining competence. We model full cooperation where partners disclose all relevant information to each other. So, S_1, S_2 and also their user can use the best available estimate on *IP*'s position at each simulation step. Moreover, if a supplier is temporarily inactive, then the other may partially take over its task in supplying inputs to the user. The negative side of multiple sourcing comes in the form of adaptive detours (figure 2(b)). These bypasses represent the costs of specialization. Moreover, it is difficult for U_{12} to adapt to suppliers of different inclinations simultaneously; the bigger the difference between S_1 and S_2, the more problematic to cooperate with both of them. Having only a single supplier yields less varied knowledge but fewer troubles of adaptation.

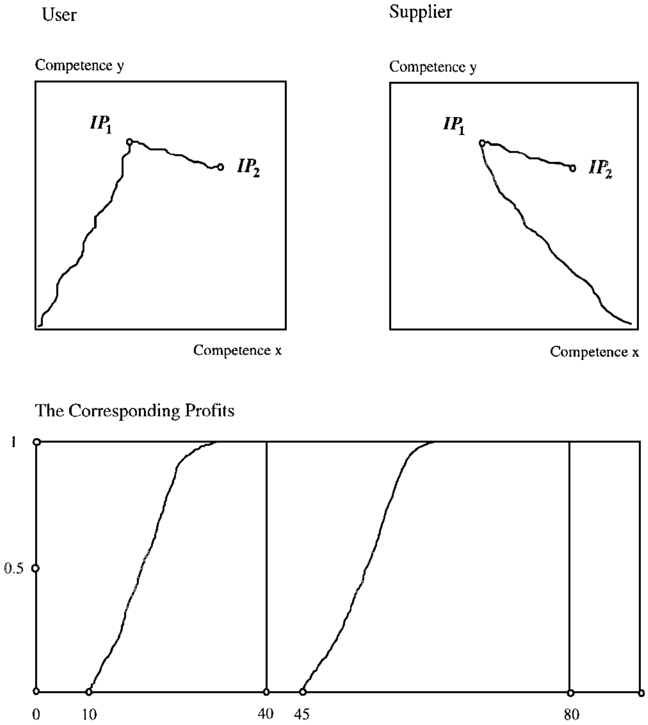
2.4. *Profits*

The three previous subsections specified the actors, their movements and the role of diversity. The last step in the construction of the model is to specify the net outcome of revenues and costs, in a profit function. As in real life, the best choice (having one or two suppliers) depends on a set of conditions.

The magnitude of profit achieved in cooperation varies with time: some cooperations set off production early, yielding an early stream of profits, while others start production only after longer preparations, but then achieve a higher rate of profits. The performance of a partnership can be correctly evaluated only by taking into account *cumulative* profit, i.e., the summation of profit over a sufficiently long time period. Therefore, we measured success by the accumulated profit that a cooperation achieved during the whole time span of the simulation. The relative success of the two cooperation forms is measured by the *ratio* of accumulated C_{12} and C profits (*Profit ratio*): if the variable $\textit{Profit ratio} > 1$ then multiple sourcing C_{12} is superior, while values less than 1 indicate that single sourcing C is better.

The profit during periods of production is the product of two factors. One represents quality: the fit of competencies used with the optimal competencies required. This component decreases linearly with the distance between *S* and *IP*. The second factor represents the efficiency of production: are productive competencies properly aligned? This component decreases linearly with the distance between *U* and *S*. The multiplicative specification of the profit function reflects a crucial assumption: none of the partners can produce the end product on its own, and close mutual fit of competence (efficiency) alone is not enough for success. On the other hand, a close fit to market requirements (quality) alone is not enough either. High quality at zero efficiency is as useless as high efficiency at zero quality. The profit rate is normed to be unity at its maximum, i.e., when both *U* and *S* positions coincide with *IP* (figure 3). To make single and multiple sourcing comparable, we assume that the profit rate of dual sourcing is the mean of the rates of the two component cooperations, U_{12}-S_1 and U_{12}-S_2.

Production and sales usually start later than the cooperation itself: partners do not release a product until being sufficiently close to the goal of quality. The model assumes no contribution to production from a supplier that stays beyond a certain maximum tolerance distance ($Tdist = 10$) from the ideal point: then quality is too low. Moreover, when *U*



IP_1 and IP_2 denote, respectively, the ideal point positions in the [0; 40) and [40; 80) time intervals. Zero profit is produced in [0;10] and in [40; 45], because agents are farther from *IP* or from each other than *Tdist*.

Figure 3. Agents' trajectories and the obtaining profits.

is farther from *S* than *Tdist*, then efficiency is too low to produce. An advantage of dual supply is that production capacity can be partially taken over from an inactive supplier by the active one. Due to switching costs and costs of maladaptation, substitution is not perfect; the proportion of transfer decreases linearly with increasing distance between S_1 and S_2.

Note that if we assume a single producing agent instead of separate suppliers and user (no outsourcing), then we are back at the so called "first mover versus efficient producer" dilemma (Williamson 1975; Hannan and Freeman 1989; Péli and Masuch 1997). First movers are characterized by early production involvement (high *Tdist*), which slow down their adaptive speed. Efficient producers begin production only after achieving a better fit of skills (low *Tdist*), maintaining a high adaptive speed for a longer period of time.

The degree of market stability (*Mstab*) represents the speed of environmental change. This degenerated version of the model reproduces Hannan and Freeman's basic claim, namely that first movers are better if environmental change is rapid, while slow change favors efficient producers (Péli and Nooteboom 1995).

3. The Model at Work[6]

3.1. *Cooperation with Single and with Multiple Suppliers*

We offer three crude hypotheses on the relative success of C and C_{12}. They are crude in the sense that they indicate how single parameters of the model affect relative success, under *ceteris paribus* conditions (other parameters remaining the same). These hypotheses express common sense knowledge in the economic and organization science literature. The reader may ask why we make such extensive efforts to model evident truths. The answer is that *a priori* it is hard to predict the interaction effects: what happens if we vary the parameters simultaneously. The simulation takes into account opposing tendencies: some favor single supply while others favor dual supply. The question is that what happens when we mix them?

Hypothesis 1 is about the effect of the two development patterns on success. Routine development does benefit much from extra information diversity; eureka type, radical innovation does.

Hypothesis 1. Routine development tasks favor single supply, eureka type developments favor dual supply.

The second hypothesis is about the effects of market stability (*Mstab*). Information acquisition is especially important if market conditions are volatile. Multiple suppliers provide bigger information diversity, so:

Hypothesis 2. Rapidly changing market conditions favor multiple supply, slow market change favors single supply.

The third hypothesis is about the effect of early *versus* late production. Strict tolerance limits (low *Tdist*) pose strict quality and efficiency requirements as a precondition for the beginning of production. In case of dual sourcing, there is a bigger chance that at least one supplier meets the strict product requirements to offer sufficient quality. On the other hand, to improve efficiency is more difficult in C_{12}, because user may have to adjust to remote partners. If *Tdist* is large, then production can begin early, even when S_1 and S_2 are diverging (figure 2b), causing a relative disadvantage for C_{12}. Therefore:

Hypothesis 3. Loose production requirements favor single supply, tight requirements favor dual supply.

Now how about mixing these effects? What outcome should one expect, for example, in case of routine development tasks with rapidly changing market conditions? Then, Hypothesis 1 suggests that C is better, while Hypothesis 2 predicts C_{12}'s superiority. The simulation runs suggest answers to these questions, clarifying the interplay of opposing effects that shape the fortune of the two supply forms. The findings are listed in Table 1.

Table 1. The summary of simulation results.

Routine development		Eureka development		
H1	+	−	+	−
H2	−	−	+	+
H3	−	−	+	−
		0–20	30	40–60
			Mstab	
		Extremely rapid change	Modestly rapid change	Slow change

We conducted a series of sensitivity analyses with the variables mentioned in the hypotheses: development pattern, market stability and minimum production requirements. To achieve reasonably stable results, we employed rather long runs: 5000 simulation steps for each parameter combination. Simulation steps represent elementary time intervals. After each step, agents update their knowledge on the location of the ideal point and move into the direction of their perceived goals in the next step. To make the comparison of results easier, the ideal point, the suppliers and the users had, respectively, the same initial positions at each run. The random walk of the ideal point was also the same at each sensitivity analysis run.

3.1.1. Routine Type Development. Table 2 presents the sensitivity run data, and figure 4 plots the results in a three dimensional diagram for routine type developments. Single sourcing C is superior (*Profit ratio* < 1) at all parameter settings. However, the gap between the performance of C and C_{12} strongly varies with the frequency of market change. C is much better if *Mstab* is low (10), because then S_1 and S_2 do not have enough time to achieve high speed, the bonus for their detours (figure 2(b)). C_{12}'s disadvantage gradually lessens as market conditions get more stable. Note that a very high stability in conditions (*Mstab* $= 60$) minimizes the winner's advantage, whoever it is, because finally all agents approach the goal and reach close to maximum profit. The longer this maximum production state persists,

Table 2. Profit ratios, routine development task.

	Mstab					
Tdist	10	20	30	40	50	60
5	0.75	0.77	0.85	0.96	0.93	0.95
10	0.55	0.75	0.82	0.88	0.92	0.94
15	0.6	0.73	0.80	0.87	0.90	0.92
20	0.67	0.69	0.78	0.86	0.90	0.92
25	0.7	0.69	0.77	0.85	0.89	0.91
30	0.72	0.69	0.77	0.85	0.89	0.91

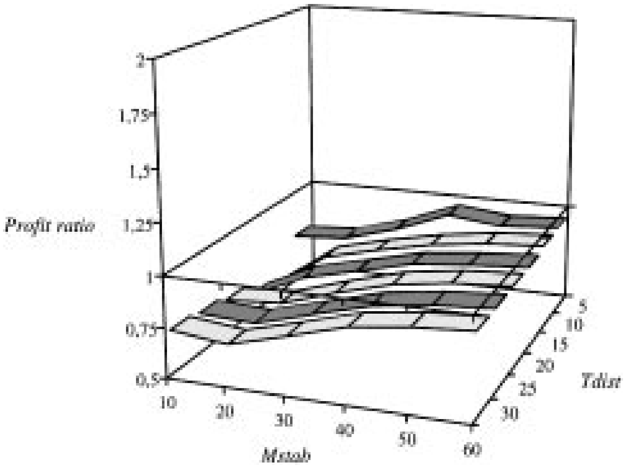


Figure 4. Routine development.

the smaller the effect of the initial adaptation period on the outcome. Therefore, *Profit ratio* converges to unity (Table 2).

These outcomes support Hypothesis 1: having multiple suppliers for the same task is not a good strategy in routine product development. Then, extra knowledge is not that important, therefore the disadvantages of having two partners with different specializations outweigh the benefits of having extra information. The claim that information acquisition is not crucial in routine problems has not much novelty. However, the fact that the model provides appropriate predictions in well-understood cases may increase the confidence in its reliability when less straightforward results obtain.

Dual supply is especially useless when market conditions are volatile ($Mstab = 10$), and C_{12}'s extra search efforts have no time to reach results: Hypothesis 2 is falsified in case of routine development tasks.

Tdist (the minimally required distance from optimal production) has a weak influence on the results: C_{12}'s relative performance improves with 5–10% as the tolerance limit becomes more strict. This finding is in line with Hypothesis 3, but the effect is not strong enough to yield a clear justification (Table 1).

3.1.2. Eureka Type Development. While the routine development case led to uniform or only smoothly changing outcomes, a radical non-monotonicity occurs in the results when the eureka type development (uneven adaptive speed enhancement) applies. C_{12} performs very much better than C in a certain parameter range (figure 5), so Hypothesis 1 is at least partly justified for non-routine development tasks. Surprisingly, the range where C_{12} is better is quite narrow; the advantages come only in case of *modestly* rapid market change ($Mstab = 30$). However, in this parameter setting C_{12} is much better in most of the cases.

What is the explanation of the peak in figure 5? If market conditions change often (*Mstab* is 10–20), then dual supply has no time to achieve its potential advantage since S_1

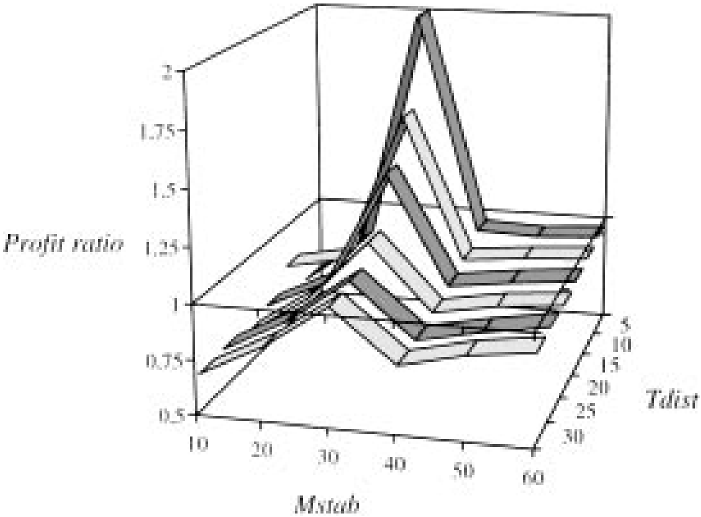


Figure 5. Eureka development.

and S_2 diverge in the early phase of adaptation. Therefore, single supply is better. If, on the contrary, market stability is very high (*Mstab* is 40–60) then the transitory effects of different adaptation routes are immaterial. Both cooperations assume close-to-maximum profit most of the time, consequently the gap between their performances gradually goes away (Table 3). But between slow and very fast market change, there is a range where, on the one hand, C_{12} has enough time to enjoy the returns of extra search efforts, on the other hand, a single supplier has still not enough time to approach *IP*. Thus, Hypothesis 1 is partly justified in case of non-routine development tasks: modestly rapid market change is advantageous for dual supply. Hypothesis 2 (on the effects of market stability) is also supported for the cases of modestly rapid and slow market change: the former supports C_{12}, the latter is better for C. However, Hypothesis 2 is falsified for extremely fast market change (*Mstab* < 30), then single supply performs better (Table 1).

Table 3. Profit ratios, eureka development task.

	Mstab					
Tdist	10	20	30	40	50	60
5	0.64	0.86	2.01	0.96	0.95	0.97
10	0.80	0.86	1.57	0.9	0.93	0.95
15	0.69	0.83	1.37	0.86	0.9	0.93
20	0.65	0.84	1.13	0.83	0.88	0.91
25	0.68	0.83	1.04	0.8	0.86	0.91
30	0.67	0.82	1.02	0.79	0.86	0.90

The difference between the two cooperations' performance strongly depends on the *timing* of production: the later it begins (the lower *Tdist* is), the bigger C_{12}'s advantage at medium market stability. The reason for this is that low *Tdist* values behave like a filter, they cut out production in the early phase of adaptation. In this early period, S_1 and S_2 are still involved in specialization and stay apart from each other (figure 2(b)), and therefore they have no chance to yield profit. So, a strict tolerance limit does not kill any opportunity for C_{12}. But, C could have a chance to produce some profit even in this early phase, since the single supplier moves steadily toward *IP* (figure 2(a)). A strict production tolerance limit (low *Tdist*) kills this first mover opportunity, increasing the relative advantage of C_{12} over C. In other words, dual supply is especially favored under a tight quality regime, when production does not start until competencies have a close fit with product requirements. This finding justifies Hypothesis 3 for modestly rapid market change: single supply's disadvantage lessens with widening tolerance limits. Again, the effect of tolerance distance is not significant if market change is slow or extremely rapid (Table 1).

In the introduction we noted that for strategic reasons of avoiding pure price competition, suppliers may try to avoid offering identical skill combinations (supply differentiation). We repeated the simulation with the eureka type pattern adding a braking mechanism that keeps suppliers apart if their distance goes below a certain limit. As a result, the advantage of C_{12} over C became a few percent less, but no significant qualitative difference occurred in the outcomes (see figure 7 in the Appendix). Therefore, we neglect this condition of minimum supply differentiation in the rest of the paper.

3.2. Different User and Supplier Speed

After finishing the testing of the hypotheses, we analyzed in more detail the range of conditions under which dual supply turned out to be much better. We fix market stability (*Mstab*) at 30, where the "peak" occurs in figure 5, and add a new sensitivity analysis parameter: the agents' *relative speed*. Until now, we assumed that supplier and user have the same adaptive speed at the same distance from their respective targets. However, this equality can not be taken for granted. While suppliers elaborate on production competencies, user develops a specific skill, the ability to absorb supplier outputs. These two learning processes fundamentally differ, including possibly their speeds. How sensitive are the results discussed in the previous sections to the partners' relative speeds? We made a sensitivity analysis assigning different adaptive weights to user and supplier speeds (V_U and V_S). These weights reflect the magnitude of agents' adaptive efforts or capabilities. A new variable, *Speed ratio,* is defined as the quotient of the two weights: $\textit{Speed ratio} = V_U : V_S$. If $\textit{Speed ratio} > 1$ then user's maximum speed is the higher and *vice versa*.

Is the outstanding advantage of C_{12} at medium market stability (figure 5) sensitive to agents'relative speed? The new sensitivity analysis addressed two parameters, *Tdist* and *Speed ratio*. Now, *Mstab* was set to 30, the value at which C_{12} performed superbly earlier. Table 4 and figure 6 show the results[7].

Surprisingly, dual supply's advantage turns out to be almost the smallest at similar supplier and user speed weights, that is, in the case tested in 3.1.2 (figure 6). To learn more about the nature of the local minimum at $\textit{Speed ratio} = 1$, we repeated the sensitivity test assuming

Table 4. Profit ratios, eureka development (*Mstab* = 30).

	Speed ratio												
Tdist	0.10	0.15	0.20	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
5	1.00	1.21	2.89	3.83	7.76	3.81	2.29	2.99	2.99	3.08	3.11	3.12	3.06
10	1.36	1.37	3.38	3.56	4.71	3.04	1.73	2.15	2.19	2.16	2.32	2.24	2.16
15	1.23	1.93	3.07	3.08	3.36	1.90	1.34	1.60	1.77	1.77	1.83	1.86	1.88
20	1.16	2.01	2.67	2.42	2.74	1.72	1.13	1.36	1.51	1.48	1.56	1.63	1.58

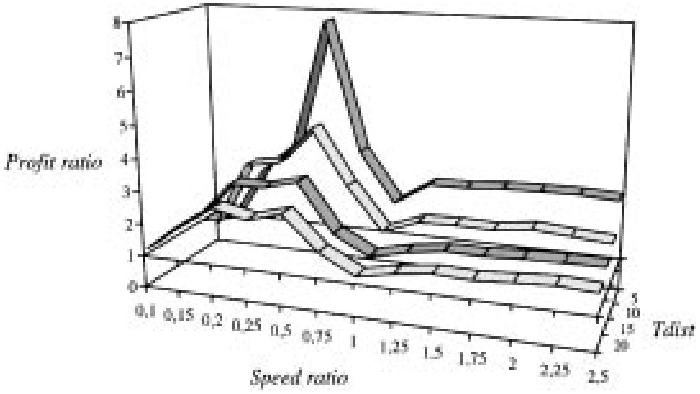


Figure 6. Different user and supplier speeds (Eureka development, *Mstab* = 30).

a bit more volatile market structure (*Mstab* = 20). Now, the results of the new sensitivity run were slightly worse for C_{12}, but again, the same qualitative outcome occurred: there is a pit in the result curves when *Speed ratio* = 1. What explanation can be given for this steady local minimum?

The answer lies in the fact that cooperations only yield high profit if quality and efficiency are combined: suppliers approach *IP* and user gets close to its suppliers. Developmental efforts have to be synchronized, and it is the presence or the lack of synchronization that accounts for the zigzags in figure 6:

If *Speed ratio* < 1 then suppliers are faster than users. This is not a problem for C_{12} (at least when *Speed ratio* is not extremely low). Since suppliers make detours in the early phase of adaptation, a bit lower user speed only means that user does not arrive “too early” to its meeting with S_1 and S_2 at *IP*. The partners get close to each other and to *IP* approximately at the same time; then, C_{12} produces high profit. Meanwhile, single supplier S and its user aim without detours at *IP*. S’s and U’s trajectories are of about the same length on average. Therefore, when S reaches the ideal point the slower U is usually still not there (quality without efficiency). This delay brings victory to C_{12}. Multiple supply’s advantage is the highest at *Speed ratio* = 0.5 (V_U is the half of V_S). The advantage vanishes gradually at lower *Speed ratio* values, because an extremely slow user is almost equally bad for both single and dual supply (figure 6). As a result, the two performances become equally poor when *Speed ratio* is about 0.1.

Speed ratio $= 1$. Now, the movements of single supplier and its user are synchronized: with equal path length, equal speed entails equal arrival time at *IP*. The relative performance of C to C_{12} improves, so *Profit ratio* decreases. This explains the dip at *Speed ratio* $= 1$ in figure 6.

If *Speed ratio* > 1 then users "run ahead". Suppliers are slow, causing efficiency problems in both forms of cooperations. But still, the advantage of C_{12} over C increases somewhat. A possible explanation is that the different supplier trajectories in C_{12} double the chance that at least one of the suppliers gets sufficiently close to the randomly moving *IP*, making the cooperation productive. Note that there is a relative speed value (2) beyond which users become so much faster than suppliers that they all reach *IP* at a very early phase of the adaptation process. From this point, an even higher supplier speed (a further increase in *Speed ratio*) does not make a difference in the outcome. Hence the explanation for the plateau on the right hand side of figure 6.

The simulation runs measured the relative performance of the two forms of cooperations with the ratio of cumulative profits. The *Profit ratio* parameter tells which cooperation is better in a certain setting, but it does not give information how successful these cooperations are in absolute terms. Maybe the winning form of cooperation is only the better of two poorly performing ones. To get more information on this, we partially repeated the relative speed analysis displayed in figure 6, collecting now information on the absolute profits produced by C and C_{12}. We focused on three representative speed ratio values (0.5, 1.0, 1.5), that is, when user's speed weight was lower, equal and higher than the respective supplier speed weight.

Table 5 reveals that the absolute cumulative profits decrease strictly monotonically with narrowing production tolerance limits (*Tdist*) in both forms of cooperation. This is just what one expects. However, it also turns out that C's production falls much more steeply with narrowing tolerance limits. That is, the outstanding advantage of dual sourcing at strict production tolerance limits is caused by the very poor performance of single sourcing.

4. Discussion

4.1. What We have Learned

The main research issue was to clarify that under which conditions dual supply is better than single supply and vice versa, when we focus on issues of learning and innovation. We described the external conditions by three variables. The first descriptor, the kind of the product development task, was dichotomic: routine and high novelty (eureka) type developments were compared. The second described the pace of market change (*Mstab*). The third variable, *Tdist*, was about the minimum level of preparation before joint production starts (in terms of distance between the agents, and between the agents and the ideal point). Later, a fourth variable was added to reflect differences in the strength of adaptive efforts, yielding difference in adaptive speed (*Speed ratio*).

We performed a series of sensitivity analyses with the first three variables (external conditions). We proposed three *ceteris paribus* hypotheses, which indicate opposing effects. Our goal was to mix conditions to see what the net outcome of opposing effects would be. We wanted to see which hypotheses dominate under which conditions. The first hypothesis

Table 5. Cumulated profits and profit ratios.

	Speed ratio		
	0.5	1.0	1.5
(a) $Tdist = 5$			
Profit C_1	47	200	166
Profit C_{12}	235	464	506
Profit ratio C_{12}/C_1	4.94	2.32	3.05
(b) $Tdist = 10$			
Profit C_1	73	351	287
Profit C_{12}	277	566	598
Profit ratio C_{12}/C_1	3.80	1.61	2.08
(c) $Tdist = 15$			
Profit C_1	99	491	388
Profit C_{12}	399	673	685
Profit ratio C_{12}/C_1	3.41	1.37	1.77
(d) $Tdist = 20$			
Profit C_1	158	680	550
Profit C_{12}	417	786	783
Profit ratio C_{12}/C_1	2.63	1.16	1.42

(H_1) claimed that single supply is better for routine tasks, and *vice versa*. The second hypothesis (H_2) stated the faster the market change, the better this is for dual supply. The third hypothesis (H_3) claimed that single supply fits better to loose product requirements and *vice versa*.

The results on routine type development tasks were the following (Table 1). The simulations indicate that these developments favor single supply (H_1 is justified). However, dual supply proved inferior to single supply under rapid market change (H_2 is not supported), and the strictness of production requirements had only a very weak effect on the outcomes (H_3 is not supported).

In case of eureka type developments, H_1 predicts that dual supply is better. But, according to H_2, single supply is favored when market change is slow (*Mstab* is high). Thus, the simulation results support H_2 and falsify H_1 for slow market change. However, because of the non-monotonicity of the resulting *Profit ratio* function (figure 5), the dichotomic distinction in H_2's wording between "slow" and "rapid" change had to be refined: the latter category has been split to "modestly rapid" and "extremely rapid". With this modifications in place, we could claim that H_1 and H_2 are justified for modestly rapid market change (dual supply is better). However, if change is extremely rapid, then single supply is preferred, falsifying both H_1 and H_2. As far as H_3 is concerned, tight production requirements clearly favor dual supply if market change is modestly rapid, but is H_3 not supported for cases of slow and extremely fast change.

The simulation results suggest that several factors have to coincide for dual supply to be more profitable. One would expect C_{12} to be superior when learning is important, that is, when conditions are unstable. However, beyond some point, increasing instability eliminates the advantage: the extra search efforts of S_1 and S_2 provide extra advantage only if market conditions leave time for it. Moreover, possessing superb skills is only a necessary, not a sufficient condition for success: still more time is needed to harvest the yields of perfection. But, if this harvesting time is too long, then finally the single supplier even as a late comer also reaches the same level of perfection. So, very slow change in market conditions deprives C_{12}'s extra knowledge from its advantage. Industrial users who intend to involve multiple suppliers have to consider if technology and consumer taste would not change significantly before they finish product development and reach reasonable returns. Furthermore, if the change in external conditions is very rare, then producers with multiple suppliers should look for other markets after a while, because their extra production knowledge will become the standard for all participants in the old market.

Users with multiple suppliers also have to estimate the minimal “state of readiness” of product development at which production may begin. In case of low quality expectations, the production tolerance limit (*Tdist*) is large, and it is to a great extent up to the producer when to begin sales. Under such conditions, one can make profit manufacturing half baked products, and again, having specialized suppliers is less important. But this strategy does not work in case of high-tech goods. For example: the first market entry of digital photo-cameras in the eighties was a total failure because of low picture quality.

The differentiation of user and supplier speeds of adaptation (V_U and V_S) reflected differences in adaptive efforts or capabilities in the model. The simulation results indicate that C_{12}'s relative advantage over C can be amplified if users' speed is about the half of suppliers' speed (at the same distance from *IP*). The absorption of supplier outputs is a non-trivial task; production lines have to be set up, routine procedures have to be reshaped, etc. Because of organizational inertia, this process may take time (Hannan and Freeman 1989): the necessary duration of users' adjustment varies over industries and possibly also over firm sizes. The simulation results show that the optimal user adaptive speeds are different in the single and in the dual supply cases. A user with one supplier has to be very keen to go on at a similar pace as its partner to avoid efficiency problems. But the same (low) user speed is not so harmful for cooperations with two suppliers that are delayed by their initial specializing efforts anyhow. Then, a bit slow user may still finish its adaptation to the ideal product requirements in time.

Note that a limitation of the given representation is that agents always follow the actual ideal point position, that is, they go for the product which is the best in market terms. In reality, there may remain some residual demand for obsolete products, and firms may go on with their production for a while. Therefore, the present simulation model mainly applies to conditions under which the viability of old products is low.

4.2. Methodological Remarks

Simulation requires artful simplification. Eliminating factors may help to concentrate on the focal questions, but eliminating too many factors radically narrows down the model's applicability (Burton and Obel 1995). Adding too many components to the model causes serious interpretation problems: if some effects support a certain outcome while others tend to suppress it, the superposition of the pros and cons may hide the underlying regularities. Therefore, we opted to start with only a handful of effects and see if the outcomes show resemblance to reality. We acted like a radio amateur that fine-tunes the switches, listening if (s)he hears some clear voice in the noise. The accidental choice of some model parameters involved in empirical testing of the model against reality was senseless prior to our investigation. But now the qualitative results obtained indicate the design of an empirical test: to check if the simulation model generates significant outcomes observable in the organizational universe (Carley 1992).

An important issue in modeling is the robustness of the results. We tested the variability of numerical findings between different runs with the same parameter configurations in several cases, and found 5–15% variance. The variance is caused by the built-in randomness of the model, and this effect can be diminished by more extended simulation times. Computational capacity still being somewhat of a scarce resource (nowadays on the side of the researcher more than on the side of the computer), we faced the old methodological dilemma: applying extra long runs on a few parameter settings *versus* testing the model with shorter runs but on a much broader parameter range. To couple search breadth with tolerably small variance range, we opted for 5000 steps as a compromise. Test runs revealed that even three-four times longer runs would not add to much to our knowledge: the curves that depict the relative performance of the two forms of cooperation get somewhat smoother, but the change in the numerical results were far from changing the qualitative outcomes.

Appendix

We list some important equations of the model. The complete code is available from the authors upon request in *Stella II* (Macintosh) format.

The ideal point's move is punctuated and random. The variable "$move_x$*" generates the random shift of IP along axis x whenever a given time period, Mstab, has been elapsed.*

1. $IP_x(t) = IP_x(t - dt) + (move_x) * dt$

$IP_i percS$ *is the ideal point's i coordinate as it is perceived by supplier S. It is calculated by adding an error component to the de facto ideal point coordinate. The perception error range is the product of the error magnitude* (*err*) *and the distance between S and IP along dimension i,* $Dist_{SiIPi}$. *Within the error range, the perceived position is chosen randomly.*

2. $IP_i percS = IP_i + random(-1, 1) * err * Dist_{SiIPi}$

Single supplier trajectory. S_i *moves towards the perceived position of* IP_i. V_{Si} *is single supplier's speed along axis i. The speed increases as* IP_i *is approached* (*with a built in smoothing mechanism to filter out oscillation around the target*). *The pattern of* V_{Si} *change reflects either routine or eureka type development tasks* (*figure* 1). *User's coordinates* (*with* *single supplier), U_i, are calculated similarly to that of the single supplier* (3, 4).

3. $S_i(t) = S_i(t - dt) + (V_{Si}) * dt$
4. $U_i(t) = U_i(t - dt) + (V_{U_i}) * dt$

Profits. The cumulated profit is stock that aggregates the profits obtained from the cooperation during the simulation period (5). *The profit component produced by the user, $Profit_U$, is multiplied with the profit component of the supplier that comes from its adjustment to IP* (6). *If one component is zero, then no profit is produced*: *the partners cannot produce alone.*

5. $Cum\_Profit(t) = Cum\_Profit(t - dt) + (Profit) * dt$
6. $Profit = Profit_U * Profit_S$

If the user-supplier distance, $Dist_{US}$, exceeds the tolerance limit, Tdist, then no profit obtains because of efficiency problems (7); *if the supplier-IP distance, $Dist_{IPS}$, exceeds Tdist, then no profit obtains because of quality problems* (8). *Within the tolerance limit, profit components are linearly decreasing functions of the agents'distance from their respective targets* (7, 8).

7. $Profit_U = \text{if } \text{Dist}_{US} > Tdist \text{ then } 0 \text{ else } (1\text{-}Dist_{US}/Tdist)$
8. $Profit_S = \text{if } \text{Dist}_{IPS} > \text{Tdist then 0 else } (1\text{-Dist}_{IPS}/Tdist)$

In case of two suppliers, the average of their profits are calculated. Moreover, one supplier can take over the inactive supplier's place partially. The ratio of production takeover (*variable "Substitution"*) *decreases linearly with the dissimilarity of their competencies* (S_1–S_2 *distance*).

9. $Substitution = \text{if } \text{Dist}_{S1S2} < 100 \text{ then } 1\text{-Dist}_{S1S2}/100 \text{ else } 0$

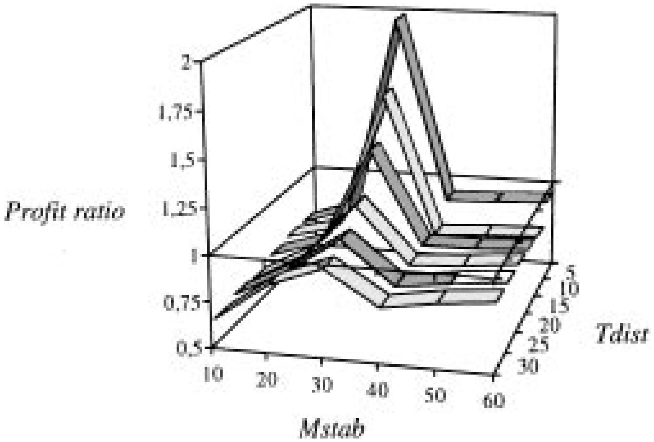


Figure 7. Eureka development with supply differentiation (*Sdist* = 3). Note: *Sdist* is the minimal distance between suppliers in a competence dimension.

Acknowledgments

This material was presented at the CMOT workshop in Washington DC, 3–4 May 1996. The authors wish to express their gratitude to Henk Gazendam, Pervez Ghauri, René Jorna, Gjalt de Jong, Tomas Klos, László Pólos, John Simons, Robert Vossen, to the three anonymous reviewers and to the journal's editor for their comments on previous versions of the paper.

Notes

1. Williamson (1985: 143–144): "... the study of economic organization in a regime of rapid innovation poses much more difficult issues than those addressed here ... New hybrid forms of organization may appear in response to such a condition... Much more study of the relations between organization and innovation is needed."
2. Factors that influence the fate and success of cooperation are too numerous to be included in the present model. The more aspects a simulation model incorporates, the bigger is the chance that the superposition of effects produces output hardly distinguishable from grey noise. In our view, the main obstacles for building and handling sophisticated models are not computational, but rather evaluational. The researchers may run into problems when interpreting the simulation, high complexity may have a negative effect on construct validity (Burton and Obel 1995).
3. Here, the meaning of market structure is that of the industrial organization literature with its traditional perspective of structure, conduct and performance. Thus, market structure includes aspects of production technology (economy of scale, scope and learning), other supply conditions (concentration, vertical integration), demand conditions (nature of the product with respect to user's ability to judge quality, price elasticity, user switching costs, differentiability of the product), and strategic conditions (entry barriers, sunkenness of costs, patentability of inventions, stage in the product life cycle).
4. This may be achieved by symmetry of dependence. A simple possibility is that both sides to the relation are equally unique to each other, have equal stakes in specific assets and equal opportunities for monitoring compliance with agreements. If there is asymmetry in one aspect, it may be compensated in another aspect of governance. For instruments and processes for achieving symmetry, see Nooteboom (1996a); for different outcomes under different market conditions, see Nooteboom (1997).
5. Unless other considerations suggest different trajectory (see in 2.3).
6. We applied the Macintosh version of the *Stella II* software (1992) for simulation. The code is available upon request from the authors. Having 5000 simulation steps, the running time was about five minutes at each parameter setting on a Macintosh Quattro computer.
7. Note that the seventh column of Table 4 is (partly) about the same parameter settings as the third column of Table 3 (where $\textit{Speed ratio} = 1$ by default). However, the numerical results show some variability. This is due the fact that agents' goal perception is random within their perception error range. Variability is the biggest, *cc*. 12%, if tolerance distance is the smallest ($\textit{Tdist} = 5$); then, utility production begins only when agents get very close to *IP*, and so the effects of randomness in perception cannot completely smoothen out in the short productive periods.

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