Allocation of resources in exploration and exploitation of technologies: Examining the complexities using an adaptive agent approach

Accompanying computer simulation

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Rosanna Garcia
Asst. Professor
Marketing
Northeastern University
202 Hayden Hall Boston, Ma 02115
617-373-7258
r.garcia@neu.edu

Anand Nair
Asst. Professor of
Department of Management
Auburn University
418, Lowder Business Building
Auburn, AL 36849-5247
nairana@auburn.edu

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Extended Abstract

1. Introduction

Balancing exploration for new technologies against the exploitation of existing knowledge is a constant theme in management and organizational science literature. Organizations must often make explicit decision-making policies for allocating resources between these two different activities. In the innovation process this balancing may be viewed as the classic tradeoff decision between R&D; research for long-run breakthrough technologies versus development of products or processes for immediate payback. Bower and Christensen (1995) provide a number of examples where well-known firms failed to keep up with technological progress in their industries because they were too narrowly focused on building products for existing key customers, or in other words, they were too focused on exploitation strategies of their existing technology instead of investing in exploratory projects. The large body of research in this area can be categorized into two groups (Dawid *et al*. 2001). The first takes an endogenous view and examines the impact of a firm's *internal* capabilities on its strategies (e.g. Cooper 2000). The second group focuses on exogenous forces, such as market structures and government policies that influence a firm's strategies (e.g. Clark & Guy 1998). However, none of these models take a systems perspective, whereby endogenous forces and their impact on the exogenous forces, and visa versa, are considered.

Extant literature alludes to this systems viewpoint, as researchers have broadly discussed the balancing of exploration and exploitation with theories of adaptive and evolutionary organizations (e.g., Brown & Eisenhardt 1997, Levinthal and March 1981, March 1991). These studies have argued that organizational ability to maximize performance levels is rooted in the organization's dynamic capabilities to adapt its exploitative and exploratory positioning in response to environmental changes. Furthermore, Lewin, *et al*. (1999) propose that a firm's strategy should co-evolve with the strategic adaptations of its competitors as well as with its partners. Co-evolution involves a feedback process whereby a firm's strategic re-alignments affect the strategic tactics of its competitors. If competitors react to strategic changes, the firm may, yet again, redirect its own strategy – and the cycle continues. These theories argue that the effects of organizational adaptations to the systemic dynamic environment are realized in the firm's performance over time. Few studies have considered jointly the impact of these forces on each other.

In this study we propose that a firm's exploration and exploitation orientation is contingent upon the firm's innovation strategy (technology orientation), its customers' demand for innovative products, and its competitors' innovation strategies. Following Lewin, *et al*. (1999), who stressed that a firm's innovation strategy co-evolves with the dynamic environment created by both customer demand and competitive pressures, it is asserted that to optimize performance the firm's dynamic capabilities must include responding to these co-evolutionary effects in determining a firm's strategic planning for innovation development. We use a complex adaptive systems approach to study these phenomena.

This paper has three goals. First, it expands on the existing theory regarding a firm's dynamic capabilities in a co-evolving system of customers and competitors using the innovation resource allocation dilemma as the framework. Second, the paper uses a game-theoretic model to gain theoretical insight regarding optimal innovation resource allocation. Third, this study introduces complex adaptive systems as a method for exploring these types of dynamic environments.

2. Exploration versus Exploitation in Innovation

Levinthal and March (1981) were one of the first researchers to investigate the exploration and exploitation dilemma. Although they present it from a technological viewpoint, when March (1991) and Levinthal and March speak of 'technology', they do not refer to technology in the sense of an input to invention and innovation. "By technology we mean any semi-stable specification of the way in which an organization deals with its environment, functions and prospers. Thus, it may be a production function, as in theories of the firm; it may be a normative structure, as in some theories of professional service organizations; it may be a constituency structure, as in some theories of political organizations." (Levinthal & March, pg 307). This study takes a much more restricted viewpoint by referring to exploration and exploitation activities as related to the innovation process, which ultimately results in new product, services or processes to meet consumer demand.

March (1991) describes exploration activities as "things captured by terms such as search, variation, risk taking, experimentation, play, flexibility, discovery, innovation" (pg. 71). From an innovation perspective, this study equates exploration to traditional research activities where a firm searches for new innovations, particularly radical and really new innovations. Implicit in this definition is the inherent riskiness of exploration activities. Exploration activities are variance inducing. Innovations can contingently disrupt and transform the organizational gestalt, often in unpredictable ways. This variance is a natural outcome of the task, and is usually recognized and accepted by innovation-centric organizations as a cost of doing business.

"The essence of exploitation is the refinement and extension of existing competencies, technologies and paradigms. Its returns are positive, proximate and predictable" (March, pg. 85). Exploitation can be likened to development activities where a firm focuses on improving existing capabilities, processes, products and/or cost efficiencies. Exploitation directly relates to the development of incremental innovations. Returns from exploitation activities are more proximate in time and are inherently less risky; they are variance minimizing.

Many studies warn of the dangers of exclusively engaging in either exploration or exploitation (March 1991, Meeus & Oerlemans 2000). Adaptive systems that myopically focus on exploration to the exclusion of exploitation are likely to find that they suffer the costs of experimentation without gaining many of its benefits. Conversely, systems that engage in exploitation to the exclusion of exploration are likely to find themselves trapped in a suboptimal stable equilibrium. Finding an appropriate balance between exploration and exploitation is a primary factor of innovation strategies, but just how does a firm allocate limited resources to the two different types of projects?

The study first examines these issues in a simplified game-theoretic setting that approximates the underlying intricacies. As the role of consumers and competitors in the innovation strategies of the firm is considered, the system becomes highly complex and non-linear where analytic solutions cannot easily be found. The benefits of each innovation strategy are dependent on the nature of the market and the competitive situation, including the degree of turbulence of the environment. By striving to take a 'systems viewpoint', a non-traditional approach to examining this type of environment must be taken. For this reason, the fundamental concepts of complex adaptive systems (CAS) are called upon in §Section 5.

3. Game-theoretic model

A strand of economics literature considers a stochastic "racing" model to determine the timing of innovation. In a recent paper Gerchak and Parlar (1999) build on this strand of research and develop conditions for optimal allocation of resources in R&D projects. We adapt the model in Gerchak and Parlar and present the key insights that will be examined in greater detail under varying contextual conditions by using a complex adaptive systems approach.

In the model formulation, the competing firms seek to optimally allocate resources to exploration of new technologies (research) or exploitation of established technologies (development). We assume that the probability of success is an increasing function of investments made in exploration or exploitation endeavors and is a decreasing function of the rival's investments. The competing firms maximize their total expected revenue by engaging in exploration and exploitation activities. The Nash equilibrium represents the optimal budget allocation of a firm as a function of the competitor's allocation.

Let (x_1, y_1) and (x_2, y_2) be the budget allocated by two competing firms (denoted by x and y) on exploration and exploitation activities respectively, such that $(x_1 + x_2)$ and $(y_1 + y_2)$ satisfies the budgetary constraints of the two firms. We consider the case of symmetric competitors such that the two firms have equal budgets to be allocated between exploration and exploitation activities. Gerchak and Parlar show that for any investment made by firm y, optimal investment in exploration made by firm x is an interior solution (i.e. $0 < x_1^*(y_1) < 1$) when $1/8 < r < 8$. Optimal investment in exploration is obtained and can be expressed as:

$$x_1^*(y_1) = \frac{(1+2r)y_1 - (1+r)y_1^2 - 2\sqrt{ry_1(1-y_1)}}{(1+r)y_1 - 1} \qquad (1)$$

Equation (1) can be used to analyze the trajectory of $x_1^*(y_1)$ for different levels of investment by firm y in exploration (i.e., changing the value of y_1 while keeping the value of r constant). Alternatively, the equation can be used to analyze the impact of changing the relative importance of exploration activities, while keeping the investments made by firm y in exploration fixed (i.e., changing the value of r while keeping the value of y_1 constant). The key results for our model as follows:

- When firm y increases the investment in exploration to a very high level (exceeding 0.9), then firm x will increase its investment in exploration.
- When firm y's investment in exploration is less than 0.9 and when firm x's relative importance of exploration activities is low, then the optimal investment in exploration made by firm x is quite low (fluctuating between 0 and 0.2).
- When firm y's investment in exploration is held constant, firm x's optimal investment in exploration is a monotone increasing function of the relative importance of exploration.

4. Theoretical Foundation/Propositions.

There have been contradictory findings regarding the roles of exploration and exploitation in organizational adaptiveness. March (1991) and others argue that a firm should not exclusively focus on one or the other, but that a balance is needed. Ghemawat and Costa (1993) concur and showed that as organizations move towards extremes, the irreversibility of an orientation tends to tip the balance toward static efficiency – a comfortable but precarious position for most firms. Ultimately this 'strange attractor'[1] leads to sub-optimal performance. By

[1] 'Strange attractors' refers to the phenomena where organisms will migrate to a certain direction because of its stableness – it is not always the optimal position for the entity.

locking oneself into a single strategy firms lock themselves out of either finding new technologies to explore in the marketplace or building core competences in which to exploit Leonard-Barton (1992). However, Lewin, *et al*. (1999) suggest that above-average returns in competitive environments can only be achieved by focusing on research activities. Innovative products are required to keep competition at bay. As competition intensifies, new opportunities as well as the potential for above-average returns decrease. Thus, it is proposed that:

P1. Organizations that focus solely on exploration activities cannot sustain positive performance levels over time, particularly in a competitive environment.

P2. Organizations that focus solely on exploitation activities cannot sustain positive performance levels over time, particularly in a competitive environment.

P3. As competition increases, firms will put a majority focus on exploration activities.

We test these propositions in the next section with an agent-based modeling methodology.

5. Agent-Based Model

An agent-based model simulation is used to extend our analysis beyond 2-players and also to easily model in various contingencies. Various contingencies directly impact the unique environment in which a firm resides. With the agent based model several external and internal contingency factors can be examined – customer demand, competitive intensity, product innovativeness, availability of slack resources, pricing advantages, network effects between consumers and risk in research outcomes. This list of contingencies is not considered as exhaustive as this is not the goal of this paper. Instead these contingencies are introduced as examples of factors that organizations might consider in determining their own innovation strategies.

There is a long tradition of using computer simulation to understand organizational decision making; (e.g. Cohen, March & Olsen 1972), organizational learning (e.g. Levinthal & March 1981, Morecroft 1985), and evolutionary organizations (e.g. Bruderer & Singh 1996). From an innovation perspective, ABMs and the related cellular automata, have been used to model the diffusion of innovations (Goldenberg, *et al*. 2002), innovation networks (Gilbert, *et al*., 2001), technological forecasting (Bhargava, *et al*, 1993) and the exploration-exploitation dilemma (Debenham & Wilkinson 2004, Dawid *et al.* 2001). This paper's model is similar to these earlier modeling approaches as we model individual firms at the micro-level with agent schemata in order to observe the dynamics of organizational co-evolution at the macro level. We model the micro-level characteristics of the system as two sets of logic rule: (i) consumer purchasing rule, and (ii) factory strategy rule; these rules are explained in greater detail in the accompanying website http://www.nuvent.com/netlogo/NL-eesim.html.

Figure 1 below shows the feedback loops that are important in this model. Figures 2A and 2B presents the flow-diagram associated with these rules. Further technical note regarding the simulation software and information regarding the model is provided in the accompanying website.

Figure 1: Causal loops of model

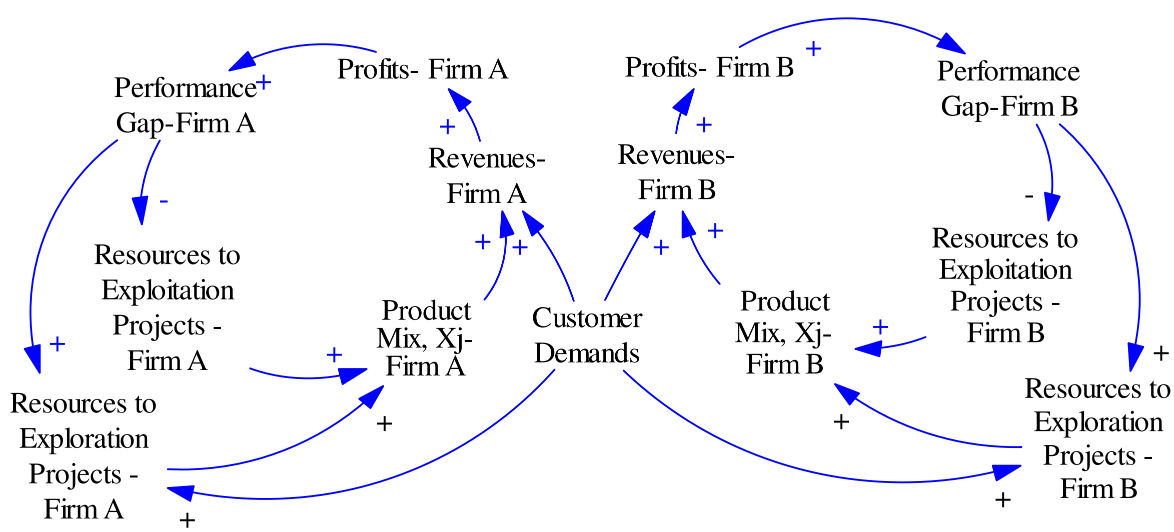


Figure 2A: Consumer purchase rules

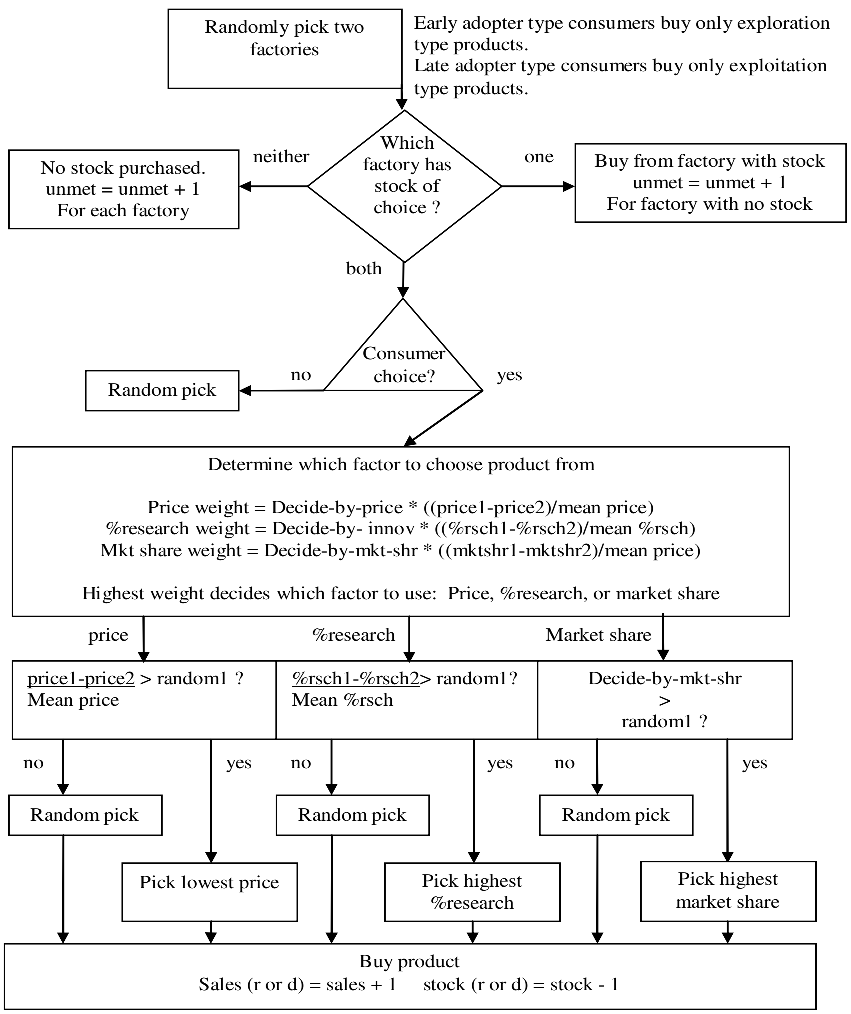
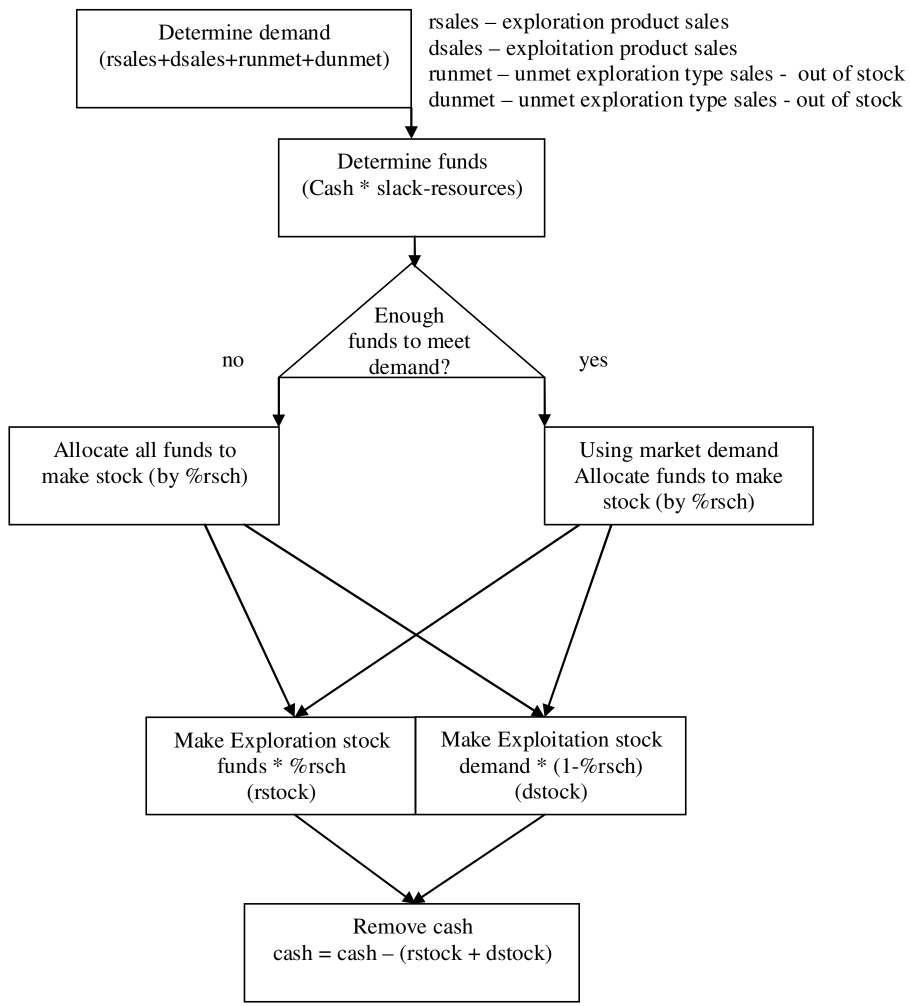


Figure 2B: Factory strategy



5.1. A Case Study of Consumer Electronics Manufacturer

For this study, four case studies of the research and development strategies of US-based, electronics manufacturing firms were considered. The senior managers involved in new product development were interviewed to ascertain the strategies they utilize in allocating resources to different project types. The model described in this study is based on one of those firms, a highly successful US consumer electronics manufacturer. This firm went public in the summer of 2003. This manufacturer introduces approximately 30 new products annually, which comprise a mix of incremental and really new products. The VP of software development explains "[these products include] some refreshes of existing products, some new for us, but similar to other competitive products in the industry, some new product ideas, [and] some new technology introductions. We always allocate new product development dollars to new products in all of these categories." Customer demand is fundamental in driving allocation decisions. The VP explains, "Customer demand in terms of sales can help focus our attention on products that are popular and, therefore, we should look at ways to keep that product line fresh and expanding. Customer feedback can help in the tweaking and this refreshing of products."

In this industry, product life cycles are short (1-5 years) as technology is continually evolving and competition is intense. Product demands are seasonal with sales peaking during the winter holiday months. Although customer demand strongly influences resource allocation decisions, it is often difficult to fully understand the needs and wants of the customer. Market demand is dynamic as variety seeking, fads, competitive offers, and demographics strongly drive consumer choice. The innovation strategy guidelines of this consumer electronics manufacturer and an organizational model of adaptive exploration and exploitation is used to examine our propositions.

The case study also serves as input for initial value determination. For example, based on the case study, the value of $\mathbf{k_1}$ for factory strategy is set at 1.5 Profitability is measured by total market share from the combined sales of innovative and incremental products each quarter that a factory maintains in the marketspace. Each manufacturer's overall market share is tracked, along with each innovation strategy, $\mathbf{p_r}$ and $\mathbf{p_d}$. Each firm's performance is also logged as revenues from sales less manufacturing costs. To determine the optimal strategy, the performance every iteration is computed:

$$\mathbf{Perf} = k_1(RSales + DSales) - (\mathbf{R} + \mathbf{D}) \qquad (2)$$

where **R** and **D** are resources to research (exploration) and resources to development (exploitation), *RSales* and *DSales* are unit sales of each type of product and $\mathbf{k_1}$ is the profit margin. Again, the reader is referred to the website to obtain greater detail about the mechanics of the model.

To test the propositions a control-factory is created and is assumed to have no organizational adaptiveness, or in other words it cannot change its innovation strategy once it has been initiated. The other factories will strive to align their innovation strategy to marketspace demand, which has been preset at 50%EA/50%LA. The goal of the non-control factories is to seek the maximum fitness level by building products to match marketspace demands, which means that resources must be allocated appropriately to achieve this goal.

6. Results

The results of two models, an oligopolistic (2 manufacturer) model and a highly competitive model (10 factories) is provided in Table 1. In these models, the question of whether a firm will have suboptimal performance in the marketspace if it allocates 100% of its resources to exploration activities (Proposition 1) or 100% of its resources to exploitation (Proposition 2) as suggested by Levinthal and March (1981) is addressed.

In the first run there are two competing firms with the control-factory taking an all-explore strategy and in the second run there are ten competing firms with the control-factory taking the all-explore strategy. Indeed, it is seen in the two-factory marketspace that Factory 1– the control-factory cannot achieve performances greater than Factory 2 (Table 1, Run 1-Outcomes). The same inability to excel in the marketspace in a ten-factory environment is observed (Table 1, Run 2-Outcomes). Yet, it should be noticed that even in the highly competitive environment of 10 factories, the control-factory does not completely die out. It is able to maintain a small market share (avg(control-factory) = 4.2 %).

Next, the control-factory was set at for an all-exploit strategy. The results are similar to those obtained when the control factory uses an all-explore strategy. However, with the all-exploit strategy the control firm *is* able to succeed with an average of a 36% market share (see Table 1, Run 3-Outcomes) in the 2-factory environment. In the more competitive environment marketspace (10 factories competing for same number of consumers), it is also able to maintain a stable market share of approximately 10% (Table 1, Run4-Outcomes). The best any of the other firms can do is about 15%, thus, the myopic strategy does not seem to lead to failure in the marketspace.

The results fail to find support for Levinthal and March's theory that firms **must** balance its resources between the two different types of activities in order to survive in the marketplace. These results does align with Hannan and Freeman's idea of structural inertia. Organizations can respond relatively slowly to the threats and opportunities in their environment and still remain profitable. In the model, it is observed that non-adaptive firms can perform on par with adaptive

Table 1: Results of Simulations

	Run 1		Run2		Run3		Run4	
Initialization								
nconsumers: consumer-population*	500		500		500		500	
(**EA/LA**): %Early-Adopters*	50/50		50/50		50/50		50/50	
nfactories: initial-factory-count*	2		10		2		10	
growth-rate*	0%		0%		0%		0%	
$\mathbf{p_{r\text{-}control}}$; %-research* (control-factory only)	100		100		0		0	
ß, resources	375		375		75		75	
$\mathbf{k_1}$; profit margin	1.50		1.50		1. 50		1.50	
$\mathbf{k_2}$; Research-risk* (research variance)	10%		10%		10%		10%	
$\mathbf{k_3}$; factory-adaptiveness *	10%		10%		10%		10%	
Outcomes								
	Control Factory	Factory2	Control Factory	Factories 2-10	Control Factory	Factory2	Control Factory	Factories 2-10
Avg Market Share	**14.8%**	**85.1%**	**4.2%**	**14.2%**	**36.2%**	**64.1%**	**9.6%**	**14.7%**
Max Market Share	**21.4**	**99.8**	**6.1**	**17.9**	**55.9**	**67.0**	**10.6**	**15.4**
Min Market Share	**0.20**	**78.6**	**1.0**	**3.2**	**32.9**	**51.3**	**7.9**	**12.5**

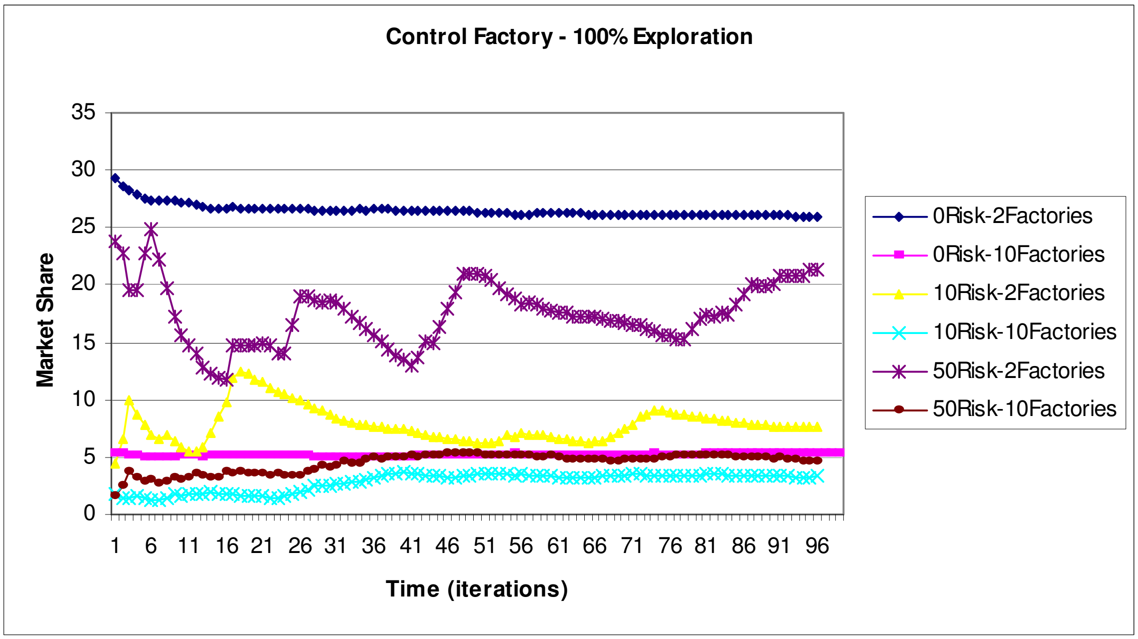
- all models were run 10 times with 100 iterations each run. The values here represent the average of these 25 runs.
*notates a 'slider' in Netlogo model

firms, especially in highly competitive environments by taking an exploration-only strategy (see Figure 3). This can also be equated to a firm serving a niche market in the types of new products that it introduces to the market place. By focusing on radical or really new products, it can claim its fair share of the marketplace. Taking an all-exploitation strategy does not benefit the firm in the long run. It is believed that this is due to the variability in exploration outcomes. The greater the variance in outcomes, the more an organization is able to survive in technologically turbulent environments. However, in the more certain environments associated with the exploitation activities, little risk results in little rewards. The variability of results from exploration activity on innovation strategy is further explored next.

Risk as a Contingency

Figure 3 shows the impact of varying research risk outcomes and competitive intensity on the outcomes. In the model, an interesting relationship exists between risk and competitive intensity. In the ten-factory environment, similar results are observed in a stable environment (no risk) as in an environment where risk is high, or about ½ of all research projects end up in failure. The average market share when risk is low is 5.2% and when it is high, average market share is 4.4%. However, when there is mid-level research-risk variance, the average market share is 3.2%. A U-shaped relationship is observed. This relationship can be better seen by observing the 2-factory situation where this relationship becomes more pronounced (see Figure 3, top three lines). These outcomes indicate that when there is no risk in exploration projects, a firm can find a niche within which it can succeed by taking only an exploration focus. This is true even in a highly risky environment since the underlying risk ultimately results in rewards. It is no worse off but it does improve its chances of reaping the rewards from risky endeavors. However, there is little benefit of focusing on exploration activities if risk is only at a mid-level. The rewards are not guaranteed.

Figure 3: Effects of Risk on Simulation



6.1. Managerial Implications

To summarize, this agent-based model simulated an environment in which firms competed for different types of consumers based on a simplistic strategy of manufacturing either incremental and/or innovative products. It was demonstrated how the contingencies affect the innovation strategy of the organization.

Since ABMs can be useful as learning tools to guide intuition, the results of this model can be generalized for other similar types of firms. The model showed that a firm can be profitable in highly competitive environments by not solely focusing on customer demands but instead finding a niche and building products for that niche. Although this is not by any means a new insight, it is further support for the effectiveness of this type of strategy in the contingent environment of high competition. It also provides additional support that theory regarding exploration and exploitation strategizing should be further developed for contingent environments. The findings do lend support to Hannan and Freeman's concept of structural inertia. Firms that slowly evolve over time can do so without significantly hurting their performance outcomes. By taking a holistic approach to the exploration-exploitation dilemma, it was seen that adaptiveness leads to performance optimization, but it is not critical that the response be immediate. Firms that find a niche within which to operate can succeed in the marketplace.

Contradictory to theory, the model provides no support for the notion that in highly competitive organizations firms should focus on innovative new products. Each firm must assess its own technological capabilities *and* those of its competition to determine how technological turbulence should determine their resource allocation decisions. This seems to be a more important factor than the numbers of competitors in the market place.

The model presents the framework for a tool for managers to use in order to explore innovation strategies within their specific environments. Previous models have been limited in their ability to provide such a tool for managerial decision-making. Many social simulations in business have not been very successful because of the emphasis on using them as predictive tools rather than learning tools. Prediction may be more successful once calibration techniques have matured for ABMs. There have been a few successful attempts at predicting human behavior in other social sciences (see Rauch (2002) for a few examples). Until that maturation is reached, it is emphasized that this paper's ABM should be used as a leaning tool to guide intuition, and not to predict behaviors or outcomes.

7. Conclusions and future research directions

To summarize, this agent-based model simulated an environment in which firms competed for different types of consumers based on a simplistic strategy of manufacturing either incremental and/or innovative products. It was demonstrated how the contingencies affect the innovation strategy of the organization.

Since ABMs can be useful as learning tools to guide intuition, the results of this model can be generalized for other similar types of firms. The model showed that a firm can be profitable in highly competitive environments by not solely focusing on customer demands but instead finding a niche and building products for that niche. Although this is not by any means a new insight, it is further support for the effectiveness of this type of strategy in the contingent environment of high competition. It also provides additional feedback in support that the Levinthal and March theory regarding exploration and exploitation should be further developed for contingent environments. The findings do lend support to Hannan and Freeman's concept of structural inertia. Firms that slowly evolve over time can do so without significantly hurting their performance outcomes. By taking a holistic approach to the exploration-exploitation dilemma, it was seen that adaptiveness leads to performance optimization, but it is not critical that the response be immediate. Firms that find a niche within which to operate can succeed in the marketplace.

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