The use of fitness landscape theory and system dynamics for the development of manufacturing strategy

Emmanuel D. Adamides

Section of Industrial Management
Department of Mechanical and Aeronautical Eng.
University of Patras, Rion 26500, Greece
E-mail: holonics@otenet.gr

1. ABSTRACT

By developing a resource-based model of manufacturing strategy, we propose an NK-simulation based framework for manufacturing strategy development. Complementarity and substitution effects among strategic actions are represented by re-enforcing and balancing loops, respectively, in a system-dynamics model. We show how our framework can be used to achieve strategic flexibility by understanding and harnessing the forces of evolution (in our approach, the rates of asset accumulation and their interdependencies) acting on the attributes of strategy, so that robust, adaptive and effective emergent manufacturing strategies can be obtained.

2. INTRODUCTION

Traditionally, manufacturing strategy has been viewed as a set of decisions on the manufacturing structure (facilities, processes, sourcing) and infrastructure (HR policies, production planning and control systems, quality systems, organisation and performance measurement) for balancing the trade-offs among the firm's performance objectives of cost, delivery speed, dependability, flexibility and quality against projected, or guessed, market requirements. This approach has two main drawbacks. First, as far as the strategy formulation process is concerned, it assumes a relatively static business environment whose attributes can easily be determined or predicted at any instance in time (Hayes 1985). Secondly, regarding the overall effectiveness of the process, it is limited by the inherent assumption, which originates from the mass production paradigm, that rigid and unbreakable relationships exist among the performance objectives which limit the range of possible strategic decisions.

The success of Japanese manufacturing management techniques, under the umbrella of what is known as lean production (Womack *et al* 1991, Womack and Jones 1998), has proven that superior market performance can be achieved not only by continuously improving operations towards higher performance objectives, but also by carefully managing the dynamic inter-relationships between them. In fact, the so-called JIT pseudo-objectives provide the strategic intent for breaking them. Furthermore, numerous successful companies have shown that emergent strategies could be much more effective than planned ones which assume predictable environmental conditions. Lately, leading strategy scholars (Hamel 1998, Mintzerg and Lampel 1999, Beinhocker 1999) have put forward the argument that by harnessing the forces of evolution acting on the attributes of strategy, emergent strategies can be more robust, more adaptive, and consequently, more effective on the long run than analytically determined singular strategies. In operations management terms, these are the pre-requisites for achieving the real goal of strategy, which is *strategic flexibility* (Hayes and Pisano 1994), and which requires the development of a set of capabilities with an evolutionary perspective in mind (how the different structural and infra-structural decisions interact in the course of time). In other words, it is not so important to achieve a strategic fit at a particular instant in time, but to be able to traverse paths of high fitness in the long run. In the same logic, the manufacturing strategy process becomes a learning process and the challenge for manufacturing strategists is to understand, create and monitor the conditions that provoke the emergence of suitable strategies for dynamically changing economies.

Computer simulation and complexity theory provide the basis for developing the necessary toolset to help manufacturing managers in accomplishing this task. By adopting a view of strategy as a play (Schrange 2000, Roos and Victor 1999) computer-based learning environments can help managers to understand and harness the forces of evolution that govern their strategies, materialised by the selection and management of the appropriate capabilities, with respect to predictable and unpredictable environmental conditions.

The contribution of this paper is towards this end. By developing a resource-based model of manufacturing strategy, we propose an NK-simulation based framework for manufacturing strategy formulation. Our framework diverts from similar considerations in the general management (Kauffman 1995, Westhoff *et al*, 1996; Beinhocker, 1999) and manufacturing management (McCarthy and Tan 2000) literature in that includes accumulation (post-action) effects due to incremental (non-discrete) decisions on the development of manufacturing assets and capabilities. In addition, complementarity and substitution effects among strategic actions (or activities) are represented in a more realist manner by re-enforcing and balancing loops, respectively, in a system-dynamics model.

3. A RESOURCE-BASED VIEW OF MANUFACTURING STRATEGY

Hayes and Wheelwright (1984) define manufacturing strategy as consisting of a sequence of decisions that, over time, enables a firm or business unit to achieve a desired manufacturing structure, infrastructure and set of specific capabilities. More generally, in a resource-based view of the firm, manufacturing strategy can be thought as a sequence of decisions on the accumulation of the *tangible* and *intangible assets* (Dierickx and Cool 1989) which are necessary for achieving the long-term fitness of its performance objectives with the environment. In the approach of environmental determinism (Aldrich 1979), the importance of a specific manufacturing performance objective is determined by the external environment. The performance objective, then, defines the resources, systems and capabilities (assets) required. In other words, the amount of assets deployed depends on the importance given to a particular strategic attribute vis-à-vis its corresponding environmental characteristics. For example, in an industry's phase where competition is driven by fast delivery, the strategic attribute of speed becomes of great importance and, consequently, the firm should concentrate its effort on installing resources, systems and capabilities that increase the speed of its operations. This means that the strategy process refers to the sequence of decisions on the rate of asset accumulation, and the firm's manufacturing competitive position is determined by the degree of fitness of its strategy attribute-specific stocks of assets, with respect to the environment. But this is not all. A firm that intends to stay competitive, in addition to developing capabilities that suit a specific state of the environment, it should develop capabilities which will allow it to respond quickly to the changes in the environment, or even to induce proactively changes in the environment.

To formalise our approach, we define *Manufacturing Strategic Attribute Asset Stock* (MSAAS) as the stock of assets whose accumulation is necessary for meeting the performance objective(s) associated with a specific strategy attribute. The value of a MSAAS over a particular time interval depends not only on the rate of its accumulation, but also on the rate of its erosion with respect to the environment (in addition to "physical" erosion due to time and use) as it is affected by competitor moves and political, social, economic and technological forces. The MSAAS of a strategy attribute, which is considered important for the current competitive environment erodes slowly or stays intact. Oppositely, the MSAAS of an attribute which is in discrepancy with the environment is devaluated fast and additional effort may be required to built the stock when the attribute comes back to fashion.

Investments in resources and systems are not purely of a reactive nature. They depend on the overall business strategy and its fitness with the production system adopted (contextuality). In addition to putting the emphasis on different performance objectives, different business strategies and different manufacturing paradigms differ in the means by which they try to achieve the best possible fitness with the environment. Depending on their choice, complementarity and substitution effects of varying intensity are observed among the accumulation processes of different MSAAS. Hence, the net outcome of the effort put towards improving the performance of a manufacturing strategy attribute, in addition to being influenced by its own stock of assets, may be amplified or decreased by the current levels of the other attributes' stocks. The firm's generic competitive strategy (cost, differentiation), as well as its more specific micro-strategy (innovator, mass-customiser, etc.), determines the importance given to the interconnections among MSAAS. Cost leadership by implementing the philosophy of mass production assumes rigid trade-offs between stocks (Table 1), whereas mass customisation is only possible by having slack or very weak relationships.

For many years, manufacturing organisations operating in the philosophy of mass production have been trying, mainly by using Operational Research techniques, to find the mix of asset levels (capacity, facility characteristics, technology, level of integration, staffing, quality management, production planning and control, organisational structure) which balances best the performance objectives and suits in an optimal, or sub-optimal, way the market's characteristics. On the opposite, lean manufacturers following mass-customisation strategies, by increasing the complementarities among operational activities, try to reduce the substitution effects (intranalities) among MSAAS (Milgrom and Roberts 1995). In order to achieve strategic flexibility, a company should be able to evaluate the pros and cons of each paradigm with respect to current competition and switch strategies accordingly.

TABLE 1

	Cost	*Speed*	*Dependability*	*Flexibility*	*Quality*
Cost		Speed can be achieved by expensive dedicated machines.	Dependability can be achieved by having costly inventories.	Dedicated equipment limit flexibility. Changes are very expensive.	Increasing quality in products and process imposes additional costs.
Speed			Fast and dependable deliveries are possible only for standard products held in inventory.	Changes in processes are very time-consuming (long set-ups).	Quality control and adjustment of defects takes time.
Dependability				High dependability can be achieved only for standard products.	Quality control and adjustment of defects may reduce dependability.
Flexibility					High quality can be achieved easily only for standard products.
Quality					

In practice, this process requires grappling with interdependent choices, while managing interdependencies among asset stocks and accumulation flows at the same time. This poses challenges for both decision-makers as well as for modellers. One response to this kind of problems has been to build on the NK-simulation approach pioneered by Kauffman (1993) to explore the emergence of order among biological organisms. In this approach, which is based on the work of Wright (1931) on fitness landscapes, the model has two basic parameters: N, the total number of policy choices and K, the number of choices that each choice depends on. Choices are assumed binary and choice-by-choice contributions to fitness levels are drawn randomly from a uniform distribution over [0,1] for each of the 2^{k+1} distinct payoff combinations a choice can be part of. The total fitness of a particular choice set is the average of the N choice-by-choice fitness levels. As far as K is concerned, when its value is 0, the fitness landscape is smooth having a single peak. Changes in the setting of one choice variable do not affect the fitness contributions of the remaining variables. Setting choices to their highest fitness contribution values leads to the highest overall fitness value. At the other end of the spectrum, when the value of K is N-1, a change in a single choice variable affects the fitness contribution of all the other choices. This results in a fitness landscape with many local peaks which cannot be improved by changing a single policy choice. In addition, conflicting constraints among choices limit the value of the highest peak which can be attained on the landscape. The same holds with respect to the value of N. As N is increased, mutual choices become increasingly constrained and the highest possible value of overall fitness is reduced.

In the above framework, manufacturing strategy can be thought as a search on a strategy fitness landscape constructed by the fitness values which correspond to all possible choice configurations. Each binary choice corresponds to a particular manufacturing strategy attribute and can be set either to 1 or 0, and optimal search paths can be determined by using dynamic programming techniques. This approach, however, cannot be used as an action learning tool and cannot account for the resource-based approach presented here, since the asset accumulation and erosion processes are non-discrete and exhibit transient behaviour. In the approach presented, manufacturing strategy becomes equivalent to the management of a network of flows of assets. To cater for this, we have developed the system dynamics based framework presented in the following section.

4. A SYSTEM DYNAMICS MODEL OF MANUFACTURING STRATEGY

System dynamics is an approach developed by Forrester (1961) for studying the behaviour of systems exhibiting high dynamic complexity as a result of complex dynamic interactions among their elements. System dynamics focuses on feedback loops which contain stocks (levels) and flows (rates). Our discussion in the previous section suggests that this approach is very suitable for developing a model for emergent manufacturing strategies. The accumulation of assets over time can be modelled by stocks, whereas the rates of accumulation and erosion as flows (Morecroft 1999).

Hence, in this approach, the value of each of the N MSAAS, $S_{n,t}$, at time t, is given by

$$S_{n,t} = S_{n,t-1} + DT(E_{n,dt} - R_{n,dt})$$

where,

$S_{n,t-1}$ is the value of the same MSAAS at time t-1,
$E_{n,dt}$ is the net effect of the effort put in accumulating assets, which corresponds to the value of assets accumulated in the time period (t.t-1) (denoted by DT), and
$R_{n,dt}$ is the value of the accumulated assets eroded in the same period

Given that intranalities among MSAAS exist, then

$$E_{n,dt} = e_{n,dt} - C(S_{1,t-1} + S_{2,t-1} + \ldots + S_{n,t-1} \ldots + S_{N,t-1})$$

where,

$e_{n,dt}$ is the gross effort put in accumulating assets for the specific strategic attribute,
C is the coupling coefficient among the attributes, which is responsible for the substitution effects (assumed to be the same for all pairs of attributes - the reinforcing effect of an asset stock on its corresponding flow is not included).

If complementary relations exist among the attributes, the negative sign in the above relationship becomes positive. Figure 1 shows, in the system dynamics diagramming language, the interconnections between two MSAAS. It soul be noted here that in our framework complements and trade-offs exist between activities (decisions) and resource stocks. This is a more realistic framework in terms of the dynamics of manufacturing strategy since resources are accumulated in a non-reversible manner and it is them who empower or restrict the future execution of activities. This is the fundamental differentiating point from the essentially static activity systems of other authors (Milgrom and Roberts 1995, Porter 1996).

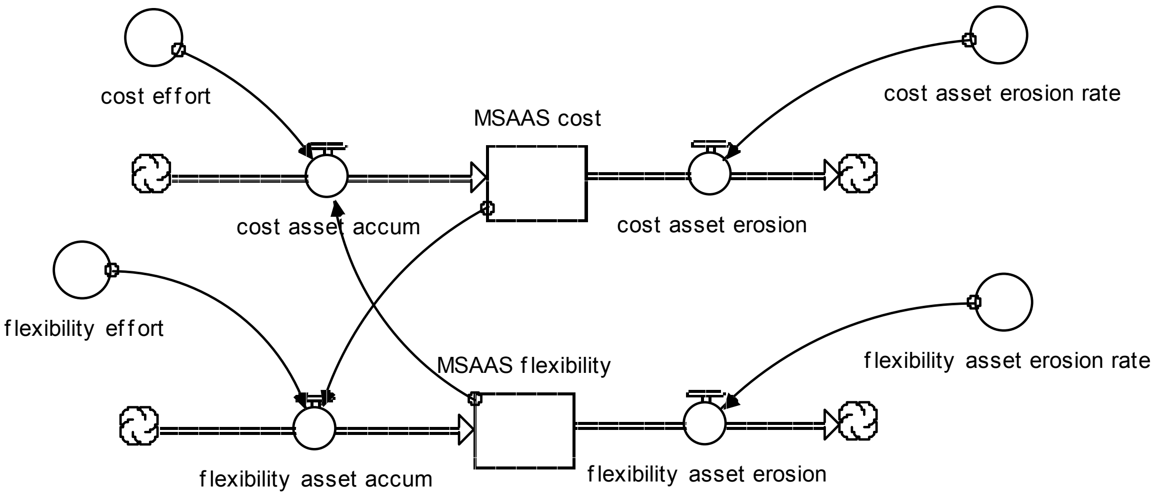

Figure 1. A system dynamics model of two interconnected asset-accumulation flows and their associated stocks.

Now, if $u_{n,t}$ is the fitness of a particular MSAAS expressed by its value at time t ($u_{n,t} = S_{n,t}$), then the total fitness of the firm's manufacturing strategy, U_t, at the same time instance can be given by the average MSASS fitness of the N attributes, or by their sum. If both $E_{n,dt}$ and $R_{n,dt}$ take random values from the same real number field, then $u_{n,t}$ varies randomly, and if the mean of the values of $R_{n,dt}$ over a time period T is larger that the mean of the corresponding values of $E_{n,dt}$, then the fitness with respect to the specific strategy attribute will exhibit an increasing trend. In other words, the fitness of an attribute increases if its corresponding assets are accumulated faster than they are depreciated. Obviously, the opposite holds if assets are eroded faster than they are accumulated.

However, asset accumulation and management of the relationships among strategy attributes are not priceless processes. They may involve large-scale investments in resources with long financial depreciation horizons and very short-term market value. The challenge for manufacturing managers is to develop the conditions for achieving superior long-term strategic fitness in an uncertain economic environment. In the following section, we show how this can be achieved by exploring the overall manufacturing strategy fitness landscape with the use of the model presented above.

5. USING THE PROPOSED FRAMEWORK

To demonstrate the use of the modelling framework presented above, we have developed a system-dynamics model that considers all five basic manufacturing strategy attributes (cost, flexibility, dependability, speed and quality). The model allows for the activation and de-activation of interconnections among asset flows through a matrix of switches. In this way, the parameter K of the NK-simulation model can be adjusted. In addition, the intensity of the couplings (the coupling coefficient, C) can be adjusted by the user through a slider-like interface. In the interactive mode, the user can specify the asset accumulation flow rate (effort towards a strategic objective), as well as the type (statistical distribution) and the rate (the statistical distribution's parameters) of asset erosion. In this way, the method of assigning fitness levels to MSAAS can be adjusted dynamically, in an indirect way, as the simulation runs. Below, we describe some experiments conducted using the modelling framework developed.

5.1 The effect of N and C in fitness evolution

To investigate the effect of the structure and intensity of intranalities among the accumulation flows, we first used a fixed accumulation rate of 1 unit per simulation time unit. The erosion rate followed a U-shaped function with maximum values of 2 at the two ends and 0 in the middle. The U-shaped function was chosen as to correspond, roughly, to the sales volume distribution over a product's life cycle. The simulations were executed for a period of 20 time units.

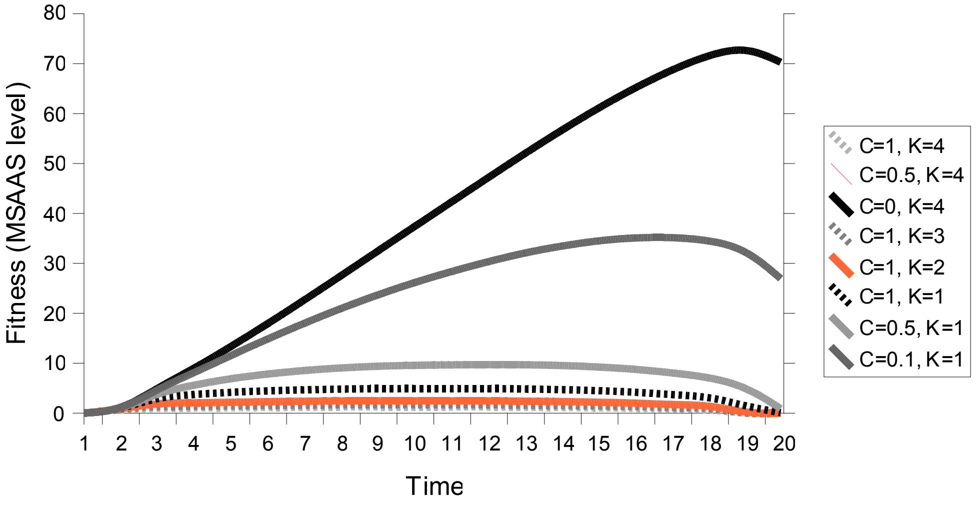

Figure 2. Evolution of total fitness for different values of K and C

Figure 2 presents the evolution of total fitness (the sum of fitnesses corresponding to individual attributes) - walk on the landscape - for different values of C (C=1 means strong coupling/trade-off between two strategic attributes) and K. One can easily see that for constant rate of asset accumulation ($e_{n,dt} = 1$) the value of fitness increases as C and K are decreased. In fact, it moves into a different scale when values of C and K become small.

Keeping the value of K constant (K = 4) and experimenting with different values of $e_{n,dt}$ and C, we observed that unless we assign very small values of C, the total fitness (the specific walk) lies within a range of small values although there is an increasing trend as $e_{n,dt}$ increases and C decreases (Figure 3).

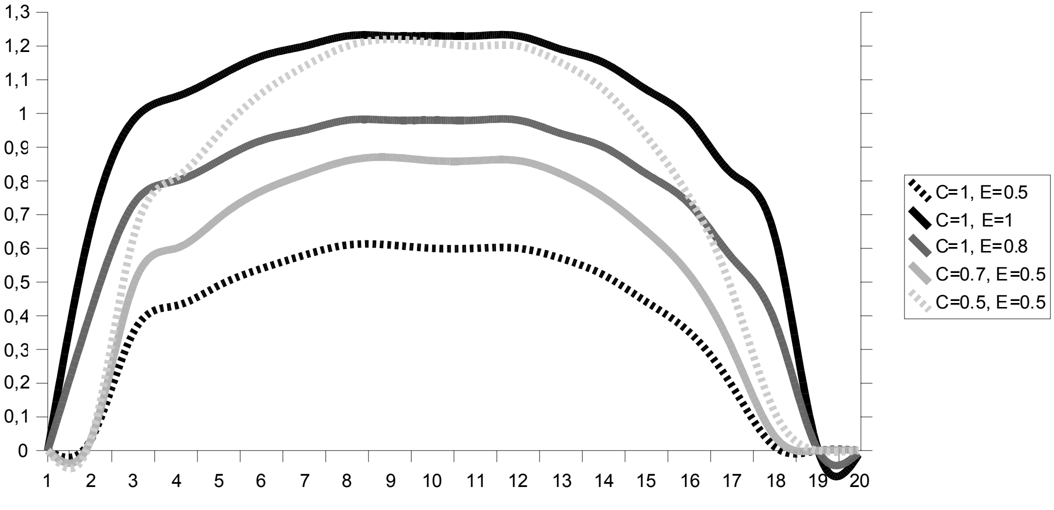

Figure 3. Evolution of total fitness for different values of $e_{n,dt}$ and C

5.2 Trying to follow the environment (strategic flexibility)

To investigate the effect of various strategies of accumulation with respect to environmental conditions, we first used a pre-defined strategy according to which the rate of accumulation of assets depends on the current value of the rate of asset erosion. This means that the firm accumulates assets at higher rates when the corresponding erosion rates are high. The accumulation rate takes values in the range 0 to 1, whereas the erosion rate takes random values in the range 0 to 1. Again, the simulations were executed for a simulation period of 20 time units. The rule used for the rate of asset accumulation (effort put towards a specific strategic objective) was that if the value of asset erosion was greater than 0.75, the value of the rate of asset accumulation was 1 unit per time unit. Else, if the value of $R_{n,dt}$ was between 0.3 and 0.75, the value of $e_{n,dt}$ was 0.5. Otherwise $e_{n,dt}$ was given the value of 0. The performance of the strategy vis-à-vis the environment was measured by the average difference between the average (random) value of rate erosion (which signifies the importance given to a strategic attribute at a particular instance in time) of all attributes and the average value of all five MSAAS. Table 2 summarises the results obtained after running 100 simulations in each CK configuration. We, again, observed that as the values of C and K decrease, the mean average difference between the average MSAAS level and the average value of erosion rate decreases, which means that the strategy has higher fitness with the environment.

TABLE 2

C	*K*	*Mean average difference between fitness and value of asset erosion rate*	*Standard deviation of the difference between fitness and value of asset erosion rate*
1.0	4	2.14	0.17
0.5	4	2.17	0.20
0.1	4	1.91	0.11
0.0	4	1.68	0.33
0.5	3	2.14	0.16
0.5	2	2.02	0.18
0.5	1	1.87	0.17

Table 3 below summarises the results obtained for the same parameters when fixed strategies (fixed values of accumulation rates) were followed. Again, reducing the trade-offs among attributes proved to be an important strategic priority. Reducing, however, the connections between attributes while keeping a constant rate of asset accumulation seems to "overflow" the asset stocks as it is signified by large values of mean average distance between the fitness (stock level) and the asset erosion rate. This means that some effort on asset accumulation is wasted. Using the model in interactive play mode, a manufacturing manager can determine when and how to adjust the model parameters so that short- and long-term discrepancies are reduced traversing a path along the peaks of the landscape.

TABLE 3

$e_{n,dt}$	*C*	*K*	*Mean average difference between fitness and value of asset erosion rate*	*Standard deviation of the difference between fitness and value of asset erosion rate*
0.5	1.0	4	1.80	0.27
0.5	0.5	4	1.73	0.28
1.0	0.5	4	1.65	0.56
1.0	1.0	4	1.92	0.52
0.5	1.0	3	1.87	0.57
0.5	1.0	2	5.19	1.19
0.5	1.0	1	5.16	1.23

Obviously, to be able to use the proposed framework, the couplings between the asset accumulation activities must be (at least roughly) determined. This is accomplished by using the Asset-Performance Objective matrix which specifies the importance of every asset/resource/capability with respect performance objectives (rated on a scale from -5 to 5) (Adamides and Stamboulis 2002). For example, capacity is an important asset for achieving low cost but once built hinders any future effort towards flexibility. The average difference between the importance of assets for every performance objective determines the degree of coupling between the asset accumulation processes for two performance objectives.

6. CONCLUSIONS

By developing a resource-based view of manufacturing strategy, we have arrived at a system dynamics-based modelling framework that can be used for understanding and exploring the dynamics of tangible and intangible asset accumulation as determinants of a firm's manufacturing strategic fit. We have shown how the model can be used, by varying the degree of strategy "intranalities" (the number of couplings/trade-offs among strategy attributes and their associate asset accumulations) and/or the intensity of their coupling, to investigate the robustness and effectiveness of various strategies under different market conditions. In addition, we showed how the relationship between the rate of asset accumulation (slow- or fast-paced) on one hand, and the extent of strategy intranalities and the intensity of coupling on the other, can be exploited so that the peaks of the fitness landscape are traversed. In summary, we have demonstrated how the management of the relationships among the asset accumulation processes can act as a hinge capability towards proactive manufacturing strategies.

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