Embedding game-theoretic concepts into system dynamics models: The case of complementary products development

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Abstract

The problem of mutual resource commitment during the development of complementary products is modeled as an evolutionary Prisoner's Dilemma game. To investigate the effect of different pure and mixed cooperation and/or defection strategies over the period of a technology cycle, a system dynamics simulation model has been built using the resource-based view of the firm. The dynamics of tangible and intangible assets, such as customer base and technological learning, were included in the model. Cooperation and defection payoffs have been assumed to be time-dependent. The model was calibrated using data from the video games industry. Simulations run for different complementors' strategies show the importance of early cooperation during technology cycles. The model can be used in an interactive mode to evaluate more complex industry-specific strategies.

Keywords system dynamics, evolutionary games, complementary products

1. Introduction

The management of complementary products and assets is one of the most important strategic activities of the firm. Complements are used to provide greater value to the customers as well as to protect innovative offerings from imitators [Teece (1990)]. In the case of systemic innovations, the complementary assets are usually integrated parts of the system offered (e.g. software-hardware, DVD-DVD player).

Firms offering complementary products and/or services are called complementors [Nalebuff and Brandenburger (1996)]. Nalebuff and Brandenburger stressed the role of complementors and defined them in a game-theoretic context as follows: "A player is your complementor if customers value your product more, when they have the other player's product than when they have your product alone". While competitors divide markets, complementors create or increase the size of a market. In a specific market segment and/or at a specific time period, otherwise competitors can be complementors.

The motivations for co-operating with a complementor include the building of a critical mass, the building of new competencies and the setting of market standards [Doz and Hamel (1998)]. However, the partnering with a complementor may hide dangers. A complementor may view the alliance opportunistically as a means to promote long-term private gains against its counterpart [Khanna, *et al*. (1998)]. For instance, a complementor may acquire the specialized skills of its partner and then decide to continue alone. Furthermore, a firm engaged in such an alliance may find out that the effort put in the alliance is too time- and cost-consuming resulting in a deterioration of its idiosyncratic skills that it would have been better to undertake the activities of the complementor itself. Finally, a firm may be too tied to a specific complementor missing opportunities offered elsewhere by others. These risks are higher at the technological innovation and product development activities where resource commitments may be decisive for the future of the firm.

It has been only over the last years that the analysis of this kind of strategic situations – to cooperate or not over the development of complements – has received considerable attention from the game-theoretic point of view. To this has contributed the shift in strategic thinking form the analysis of market specific activities and positions to the durable, firm-specific factors that underpin differences in the product-market opportunity sets of companies [Ghemawat (1997)]. Research suggests that interesting product market imperfections, which lead to different competitive positions, generally rest on factor market imperfections [Baumol *et al*., (1982)]. In this framework, resource accumulations and commitments play a central role in the analysis of competitive advantage. How strategy research met game theory is explained by the fact that resource commitment has always been a central theme in the application of game theory to the industrial economics view of strategy (e.g. [Shapiro (1989)], [Ghemawat (1997)].

Since the decision over the development of complementary products is essentially a resource commitment decision, in this paper we approach it from a game-theoretic perspective. More specifically, we investigate this long-term strategic decision "to cooperate or not to cooperate" within the framework of the evolutionary "Prisoner's Dilemma" game, which has been used extensively for the analysis of similar situations. However, we extend this simple model by embedding it in a system dynamics model to take into consideration the endogenous (e.g. learning) and exogenous (e.g. market dynamics) evolutionary mechanisms that effect decisions and outcomes through a specific technology-based product cycle. Although we use simulation to investigate the effect of pure and mixed strategies of cooperation and defection, the main objective of the paper is to show how game theory and system dynamics can be integrated for the analysis of this sort of strategic situations, rather than to explain or provide prescriptions for specific strategies through the analysis of equilibria. The model developed is structured and calibrated using the video-games industry as a reference case.

2. The evolutionary Prisoner's Dilemma game and its dynamics

The original Prisoner's Dilemma Game (PDG) is a formulation of a two-person game in which players decide simultaneously whether to cooperate or not. Mutual cooperation and defection yields the highest and lowest collective payoff, respectively, which is shared equally. However, still higher individual payoffs are achieved by defectors against cooperators, leaving the latter with the lowest possible payoff. This implies that defection is always a better decision because defectors always do better than (or at least equal to) the co-players.

This obvious result is, however, at odds with reality, not only in the business terrain, but also in the human and animal societies where cooperation emerges under certain circumstances to prevent the phenomenon known as "the tragedy of the commons" [Soden (1988)], where individual benefits result in a long-term collective disaster. In reality humans, animals and their organized forms follow mixed adaptable strategies of cooperation and competition/defection. To understand the emergence and maintenance of cooperation among selfish individuals in societies, evolutionary PDGs were introduced in which strategies are either inherited or adopted through basic imitation rules [Axelrod (1984)], [Hofbauer and Sigmund (1998)]. However, the application of evolutionary game theory into economic problems entails a great degree of additional complexity as the dynamics of the evolution (learning, mutation) must be explicitly taken into account. In addition, the mechanisms of payoff evolution should be modeled appropriately. As a consequence, richer modeling formalisms that take into account the whole system's dynamics are required.

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. It uses simulation to investigate the behaviour of feedback loops which contain stocks (levels) and flows (rates). Stocks represent the state of the system whereas flows the rate of change of this state. States evolve in time according to their relation to feedback loops. Negative feedback returns the system to a target state, whereas positive feedback leads to an ever increasing state value. As we show in the following paragraphs, system dynamics is used to model and simulate the evolutionary mechanisms within the PDG framework which represents the decision-making setting over the issue of the development of complementary products.

System dynamics models have already been used for studying the diffusion of innovations [Sterman (2000)], the innovation management process [Milling (1996)], the interface between the product and process development [Stamboulis *et al*. (2002)], the interacting resource dynamics of co-opetition (Rabbino, 1998), as well as product-line management strategies [Adamides *et al*. (2002)]. The model presented in the following section, builds on this literature and extends it further by integrating a game-theoretic framework over the issue of complement development throughout a technology cycle.

As the following case demonstrates, the marriage of system dynamics and game theory provides a platform for assessing complex strategic situations by means of simulation. Otherwise, analytic solutions would be very complicated to be derived, as the systems involved exhibit dynamic behaviour between decision points and only patterns of performance/payoffs can be observed and input to the decision logic of the next phase.

3. The reference case – Complementary products in the video games industry

The home entertainment industry, and more specifically the video games industry, provides an interesting reference case where evolutionary game theory can be employed not only to facilitate understanding of players' strategies, but also to provide a basis for strategic experimentation, given the appropriate models exist.

The two complementary players in this industry are console manufacturers and games producers. Relations between them have changed considerably since the early eighties where Nintendo monopolistically dominated the market and imposed strict rules of cooperation on developers. Today, though more fragmented, the market is structured during technology cycles which continuously shrink. Every new technology (for the consoles this refers to the technology of the main processor, e.g. 16-bit, 32/64 bit, or 128-bit or, lately, its internet accessibility, whereas for the games producers to the corresponding graphics technology) leads to turbulence and new market structures may emerge. At the beginning, as well as during, a new technology cycle complementors of both sides are faced with the dilemma of cooperating with a specific partner or not. Decisions to cooperate result in mutual commitment and resources may be exchanged (for example some console manufacturers provide software-based development toolkits to developers while the new hardware is still under development [Thomke and Robertson (1999)]). The incentives for cooperation stem form the fact that console manufacturers aim at setting an industry standard through increased sales of a wide range of high quality games, whereas games producers want to have their games in as many as platforms as possible.

The risks involved in being committed to an alliance from the very early phases of the technology development are centred around the possibility that the complementor defects during the development phase as it finds better and/or cheaper alternative partners, or when it decides to develop complements alone after gathering, through the alliance, the necessary complementary assets. Given this rationale the "best" single-step game decision for each player/complementor is to defect and leave its counterpart going alone in the development, see its outcome, and probably decide to cooperate at a later stage (in a complementor's upgrading effort) when, presumably, its cooperation will be more valuable. However, this myopic decision framework does not take into account the market evolution and technology accumulation mechanisms which may prove that in the long run more sophisticated decisions may be more effective.

4. Model structure and modelling assumptions

The system dynamics model developed explores the interactions between two firms developing and producing complementary products (consoles and video games). For each firm, the model is structured around five decisional processes: product and process development, production, cooperation strategy, market performance and dynamics, and operational performance measurement. These interact with the market adoption process as it is represented in the related sub-model (fig. 1). Following, we briefly describe each of the five sub-models of figure 1.

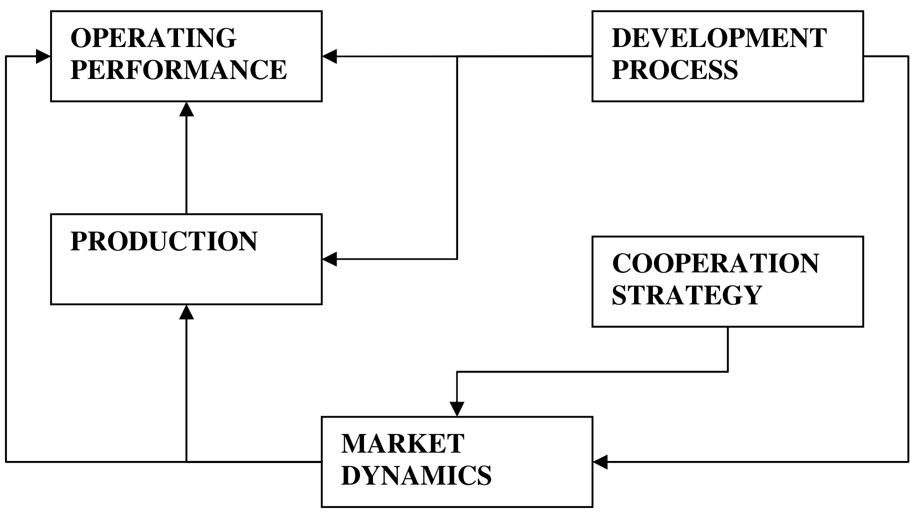

Figure 1: *The structure of the system dynamics model for a complementor*

The DEVELOPMENT PROCESS sub-model

The development and production sub-model represents the essential R&D effort that the firm needs to put in order to develop and launch a new product into the market (includes both product and production process development efforts). The effort is assumed to follow a bell-shaped (inverted U) curve. This is a valid generalized assumption for the majority of engineering projects, independent of the organization and management style employed [Maylor (1999)]. Successive projects are then modeled by an inverted (positive only) sine wave. The rate of activity is slow at the beginning of the project, increasing gradually up to a maximum, and then falls as the project reaches completion. Assuming that this effort is directly proportional to the financial resources committed (in €), the corresponding area under the curve gives its total cost. As development teams complete successive projects in a specific technology (follow-up incremental innovations or upgrades), they accumulate knowledge and experience, which in turn result in a gradual shrinkage of the duration of the projects. As a consequence, the cost of successive projects (in general, the resource commitments required) is reduced by an amount which is a function of the knowledge and experience accumulation rate. The gradual decrease of the space of possible improvements/modifications, as time passes, also contributes to the shortening of the project duration and effort put. The model deals with overlapping development projects, that is, new projects can commence before the completion of the preceding ones. The phase difference between successive projects is adjustable.

The PRODUCTION sub-model

The production sub-model deals with the dynamics of the production activity of new products. Each new product requires that the firm deploys production capacity, which embodies a leap in productivity as a result of learning before doing in process R&D. The productivity of the production function is also affected by the production activity itself. As production continues, the firm learns by doing and hence its productivity is increased. The rate of this decrease in effort and cost is adjustable to cater for very sharp drops in costs, as is the case for software. The production rate of each new product is assumed to be affected by its demand (demand leads production). Production is assumed to commence immediately after the development effort is completed and terminates with the introduction of the follow-up product.

The MARKET DYNAMICS sub-model

This sub-model represents the sales of the firm to its end customers. The sales of each new product are affected by a variety of factors. First, we assume that there is a pool of potential customers, the size of which depends on the available new products in the market. A fraction of the potential customers decides to buy the product of the first firm according to the combined prices of complementary products. This means that we assume that the decision of a customer to buy the product of the first firm (e.g. the video game console) is affected not only by the price of the product itself, but also by the price of the complementary product (e.g. the video games).Customers who decide not to buy exit the market, while customers who decide to purchase the product of the first firm, buy the product with a rate that depends on the existing customers of the firm (the word of mouth effect) as well as on the cooperation strategy that the firm decided to follow. The rate of customer acquisition of the two companies is influenced by the degree of modernity (how "new") of the product (the rate decreases as time passes), while a fraction of lost customers becomes potential customers as a new product is introduced to the market. Finally, it should be noted that for the products of the second firm, the potential customers are the customers that have already bought a product of the first firm – e.g. the video game console manufacturer. The analogy of one console to ten video games was assumed in calibrating the sales rates. The influence diagram of the factors that are involved in customer acquisition for one of the complementors is shown in figure 2.

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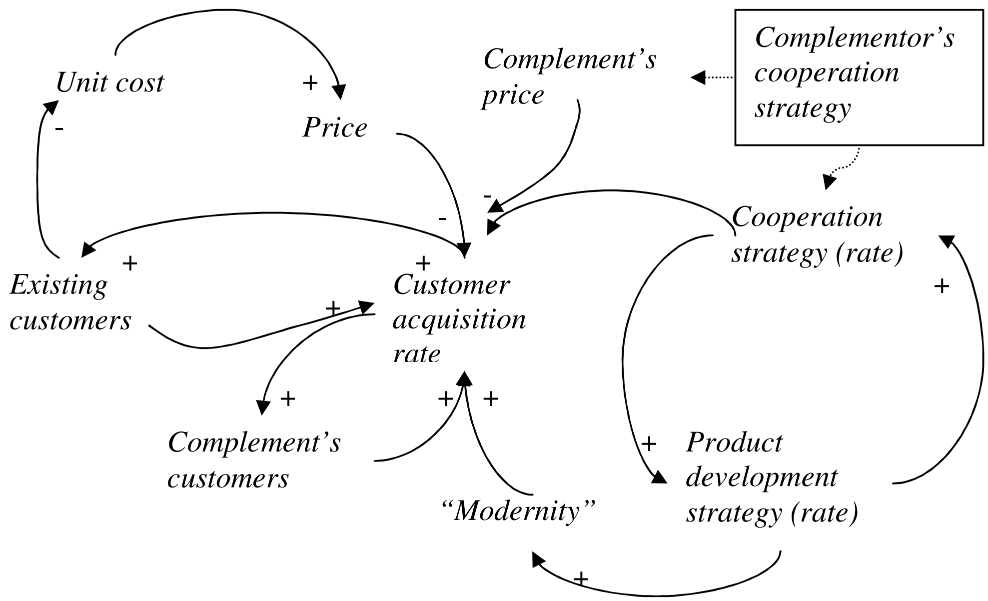

Figure 2. Influence diagram of market dynamics of a complementor

The COOPERATION STRATEGY sub-model

This sub-model implements the Prisoner's Dilemma payoff matrix. The decisions of the two potential complementors are simultaneous – i.e. both firms are faced with making decisions at the same point in time. The payoffs for each strategic decision are shown in Table 1. It is clear that for both companies the dominant strategy is not to cooperate independent of the decision of the other. After each development effort is completed, the pay-offs are materialized in the sales rate of each firm. In essence, the payoffs are the coefficients that regulate the sales rate for each firm. The values of the payoffs are diminishing as development efforts are completed (multiplied by a factor inversely proportional to the number of efforts completed). This is to model the fact that the expected gains of a firm that cooperates are greater at the beginning of the cooperation, whereas a firm that defects late has less benefits as it has already invested resources in the cooperation. Defection yields the highest outcome because the defecting firm can build on its existing market deploying more marketing resources using a different partner. Mutual defection results in other competitors valuing the cooperation of both firms less (bargaining power is diminished and the possibility of forming a highly profitable alliance is reduced).

The OPERATING PERFORMANCE sub-model

The cost and revenue (performance) sub-model deals with the evolution of the operating profitability of each firm as the production activity is undertaken and new products are introduced into the market. The firm's revenues are a function of its sales and the unit's selling price. The unit price is variable and is based on the unit cost of the product (adding a profit markup). The operating cost of a firm includes both the cost of production and the cost of R&D effort made in order to develop and launch a new product.

Firm A / Firm B	Cooperate with Firm B	Not cooperate with Firm B
Cooperate with Firm A	*B=2 A=2*	*B=0 A=3*
Not cooperate with Firm A	*B=3 A=0*	*B=1 A=1*

Table 1: *The pay-offs of each strategic (cooperation or defection) decision.*

5. The use of the model

The model was developed in the system dynamics simulation environment *ithink* v. 6.0.1. Simulations were executed for a time period of 240 months (20 years) to cater for a seven year initial technology development period and thirteen years of upgrades/modifications overlapping with the sales of the previous versions of the product. Both random and user-induced strategies were possible. The model was validated with respect to random strategies.

Figure 3 shows the effect of pure strategies on the customer rate for one of the complementors. Customer rates (sales rates) have been used as performance measures over net profitability since the real development costs of consoles and games were not available. As it can be seen in the diagram, a pure cooperation strategy yields overall higher customer rates (trace 1). This is because the firm fully utilizes the market building dynamics of its complementor at the initial stages of the cycle whereas the cannibalization effects of the late, very short development times are balanced by the early long development and sales cycles.

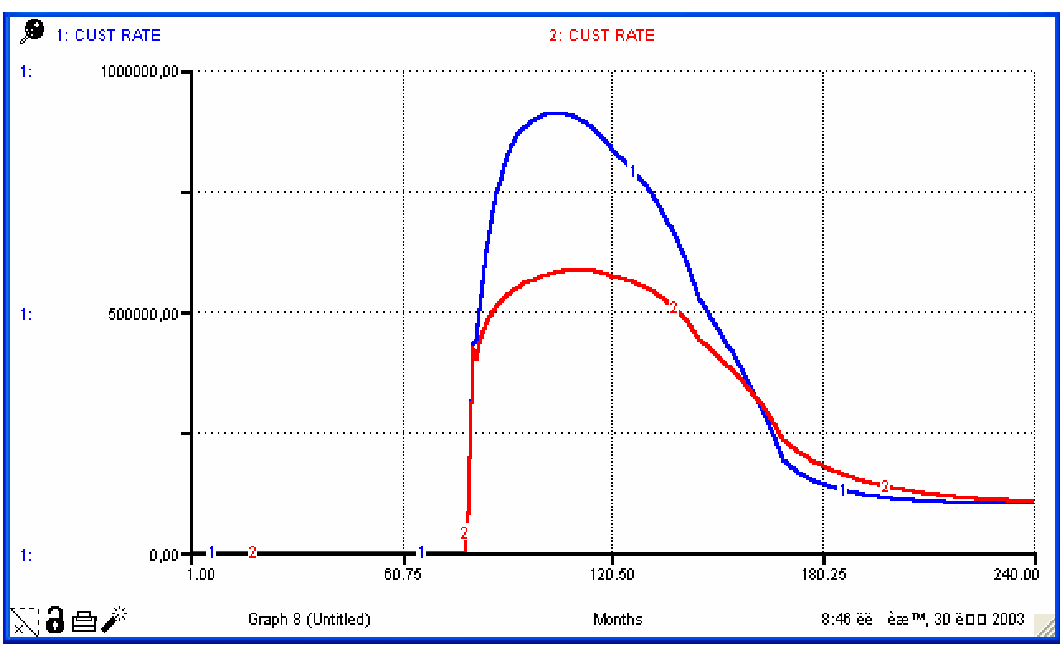

Figure 2. *Pure strategies of cooperation and defection*

In contrast to the single step game, in the repeated game as demonstrated in the figure above, the dominant strategy for each player is to cooperate.

Figure 3 shows the effect of mixed strategies on customer rates, again for one player/complementor: initial cooperation up to month 90 and then defection (trace 1) and initial defection and then cooperation (trace 2). The complementing company is assumed to be always cooperating. The net effects of both strategies on the customer rate differ significantly in the range of month 90 to month 120. In the first case, the firm exploits the market that was cooperatively built (all feedback loops involving *Customer acquisition rate* are positive), whereas in the second, the high payoffs of early defection (payoff value 3, assuming that it can benefit from a different complementor). For longer simulation runs, or for a delayed change of strategy (150th month), a clearer dominance of the initial cooperation strategy over the initial defection strategy was observed (the effect of changing strategy is minor when the market has been built).

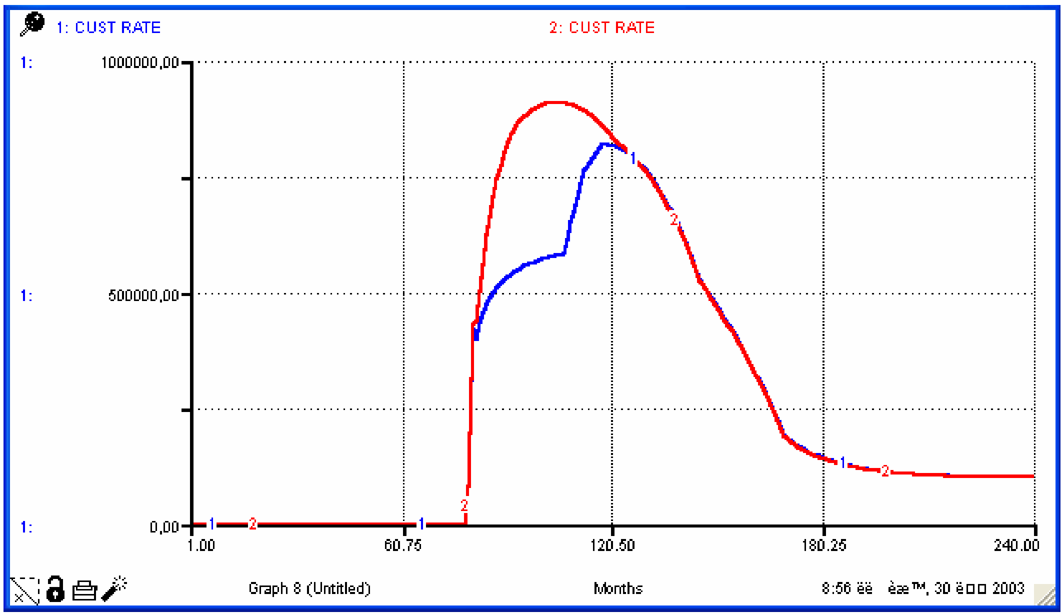

Figure 3. *Mixed strategies of cooperation and defection*

5. Conclusions

In this paper we have extended the Prisoner's Dilemma formulation by embedding it in a system dynamics model to take into consideration the endogenous (e.g. learning) and exogenous (e.g. market dynamics) evolutionary mechanisms that effect complementors' decisions and outcomes through a specific technology cycle. We have built and used a system dynamics simulation model to investigate the effect of pure and mixed strategies of cooperation and defection on the market effectiveness of complementors. Simulation experiments indicated the importance of early cooperation. However, the main objective of the paper was to show how game theory and system dynamics can be integrated for the modeling, analysis and experimentation in such a strategic situation, rather than to explain or provide prescriptions for specific strategies.

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