

Product and Process Innovation A System Dynamics-Based Analysis of the Interdependencies

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ABSTRACT

Innovation is regarded as a crucial factor for survival and competitive strength of organizations. For industrial companies innovations of the product system and particularly innovations of the processes generating these products are essential. The majority of the scientific literature focuses either on product innovation or on process innovation. In many cases the interaction between product and process innovation is not explicitly taken into consideration.

Referring to the complexity and the inherent dynamics of the industrial innovation process decision-making in innovation management is a challenging job. In addition to numerous interactions with the environment the complexity of innovation processes in industrial companies results from interactions between product and process innovation. An effective innovation management has to take these interdependencies into account coming to a congruent implementation of the different types of innovation.

In complex environments consequences of actions are often highly intransparent for decision makers. This paper provides a System Dynamics approach reflecting the interdependencies of the product-process innovation system. The System Dynamics model gives a first insight into the dynamic consequences of actions in innovation management and allows to test different innovation strategies. Finally, conclusions concerning the implementation of product and process innovations in industrial companies can be drawn.

The Management of Innovation as a Complex Problem

Innovation is regarded as the focal point of an organization's strategy and a crucial factor for its competitive strength and survival. Organizations develop innovations to adapt to their external environment and to react to perceived changes inside or outside the organization. Innovations can be implemented in the organization's outcomes, its structure, and its processes in order to maintain or to improve the level of performance or effectiveness (Damanpour, Gopalakrishnan 1999).

Various types of innovations can be differentiated: social, organizational, administrative or technical, incremental or fundamental, product or process. In any organization a large number of objects of the innovation process can be named. This paper examines product and process innovations of industrial companies.

The management of innovation is located in a highly complex and dynamic environment. There exists interaction inside the organization and interaction between the organization and its environment. The underlying interdependencies are numerous and not always transparent. Due to the complexity and the dynamic behavior of the system under investigation there is a time gap between an action/decision and the evidence of its consequences what makes the decision process even more difficult. Very often decisions which are crucial for an organization's survival have to be generated under lack of time. Due to this facts decision-making in innovation management is a very difficult and risky task. Any approach providing support and leading to more rational decision-making is welcome.

Decision-making at this level of complexity cannot be automated, but it can be substantially supported by formalized models. A Decision Support System based on the System Dynamics approach would be able to cover the complexity and inherent dynamics of the innovation process. A thorough understanding of the system and its dynamic behavior is essential to come to an effective and efficient management of the entire innovation process. A comprehensive and causal approach to model building is required to explain and to help to understand why specific behavior occurs (Milling 1996). A System Dynamics model can give an idea of the dynamic consequences of actions in innovation management and allows testing different innovation strategies. The objective is to come to coordinated and coherent policies instead of isolated operations. The congruency and the synchronous adoption of different innovation types is an important factor for organizational adoption (Damanpour, Gopalakrishnan 1999).

Product and Process Innovation in Industrial Companies

In this paper special interest is drawn to the innovation process of manufacturing companies. Innovation is regarded as a crucial factor for the survival and the competitive strength of any industrial firm. Industrial firms have to adapt to increasing global competition and dynamics. This results in a large number of innovative products, processes and services developed by the companies. The part of new products in the companies' product portfolio increased in the last years. For industrial firms the development of new products and services is the engine of growth. The firm's competitive position is determined by the ability to innovate its product portfolio and the time required to bring new products to the market. Firms have to launch new sophisticated products in increasingly fast cycles and their ability to ramp up to full scale production volume rapidly is crucial for success (Pisano 1997). With product life cycles getting shorter it becomes even more essential to expand commercial production process capacity rapidly to generate sales revenues and recoup development investments.

Innovation is the focal point in the business strategy of any industrial firm. Industrial Companies are complex and dynamic systems showing numerous interactions with their environment. The management of successful adoption of innovations in these companies is a complex and difficult venture which has to take into account a large number of internal and

external factors. Purpose of this paper is the investigation of the mutual interactions and consequences of product and process innovations in manufacturing companies.

For industrial companies innovations of the product system and particularly innovations of the related processes are essential. Due to technological facts there is a tight relationship between technical products and the processes implemented to generate these products. Developing innovation strategies management has to take into account the underlying product-process interactions. Changes in the product system have significant consequences for the firm's manufacturing system and for technical and administrative processes (Utterback, Abernathy 1975; Hayes, Wheelwright 1979 a, 1979 b; Kim et al. 1992). Before introducing new products changes in process requirements have to be considered.

The tightness of the relationship between product and process features varies with the industrial sector. In the process industries like chemicals, pharmaceuticals, and biotechnology ("Process Driven", "Process Enabling", Pisano 1997) an extraordinary close relationship between products and production process can be noticed. The investigation in this paper focuses on the innovation process in manufacturing industries. Innovation management in manufacturing companies is asked to create integrated innovation and manufacturing strategies. An improved performance of manufacturing companies can be expected from tighter linkages between product and process innovation (Kim et al. 1992). "Managing this product-process connection is one of the top challenges of the era" (Ettlie 1995, p.1224).

For a development of integrated innovation and manufacturing strategies considering the tight product-process interaction an investigation of the interdependencies of product features and the related production processes seems to be useful.

Linking Product and Process Innovation

For industrial companies innovations of the product portfolio as well as innovations of the processes generating these products are essential. In many cases the scientific literature focuses either on product innovation or on process innovation without explicitly taking into consideration the interaction between product and process innovation.

The product-process life cycle theory of Utterback and Abernathy (Utterback, Abernathy 1975) provides a useful model helping to understand the pattern of many industrial innovation processes. This model succeeds in encompassing the mutual relationships between the stages of a product's life cycle, the related production process' stages of development and competitive strategy.

By identifying, and then separating, process and product innovations the industrial innovation pattern could be related to three different stages of the innovation process: the uncoordinated, the segmental and the systemic. Utterback and Abernathy notice that the rate of product or process innovation depends on the present stage of the product's life cycle. It has to be mentioned that this concept can refer to the life cycle of a single product line and its manufacturing process as well as to a specific product generation and the growth of a whole industrial branch related to this generation of products. The process of substitution by a completely different, sophisticated kind of products is not in the focus of investigation. Figure

1 reflects the typical pattern of product and process innovation, including the three different stages.

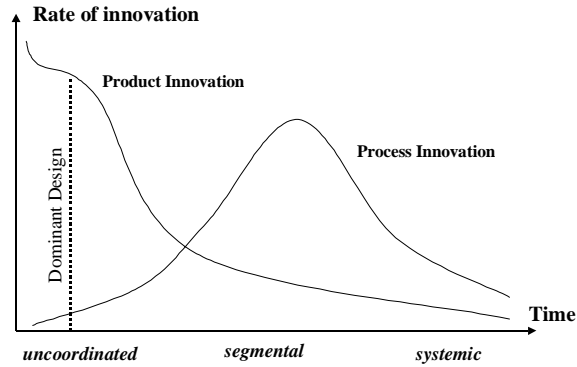


Figure 1: Utterback/Abernathy's model of industrial product and process innovation (Utterback, Abernathy 1975, p. 645; modified)

The first stage of the innovation process—the uncoordinated stage—is characterized by frequent changes in product design and low productivity of the related process. In this stage competition is merely based on product performance, a dominant product design has not evolved yet. Due to the uncoordinated and low integrated production process (technological and organizational) there are low constraints for product improvements. These frequent changes of product features inhibit process standardization efforts, which results in higher production costs.

After the emergence of a dominant product design, the firm—or the industrial branch—gradually enters the segmental stage. Specialized production equipment is introduced, the rate of innovation related to the production process increases, and the process becomes more coordinated. In this stage product innovations requiring radical changes in the production process are voided, the rising of the product innovation rate diminishes. Production costs decrease which leads to increasing sales and higher production volume.

In the systemic stage complex, highly integrated technological solutions are implemented in the firm, the production system is further standardized while cost minimization becomes an important goal. Tighter linkages between product and process features occur. Product and process changes are highly interdependent which must be taken into consideration by management. The process of standardization reduces the probability of further fundamental innovations in both the product and the process system. Due to these constraints both the product and the process innovation rate decrease.

As Utterback and Abernathy relate the three identified stages to the competitive strategies performance maximization, sales maximization, and cost minimization their approach has as well descriptive as normative attributes. The model provides explanations about systematic variations in the innovation process of industrial companies—fundamental ideas of possible

and plausible cause and effect relationships—suitable for the generation of a System Dynamics Model. Implementing the fundamental ideas of the Utterback/Abernathy approach into a System Dynamics model specific adaptations taking into consideration the recent advances in sophisticated flexible production systems and computer aided manufacturing are necessary. These technological innovations in the recent years permit a higher degree of product variation at later stages. Nevertheless the fundamental ideas of this concept can be found in current literature (e.g. Ettl 1995, Damanpour, Gopalakrishnan 1999) and the concept still appears to be valid for many industrial settings (Butler 1988).

Following the concept of Utterback/Abernathy, Hayes and Wheelwright suggest a two-dimensional product-process matrix linking product life cycle stage and process life cycle stage and reflecting a company's position in the interrelated product-process system (Hayes, Wheelwright 1979a, 1979b). The matrix represents the interaction of both the product and the process life cycle. The process life cycle-rows of the matrix represent the process structure with increasing standardization towards the systemic form. The product life cycle-columns represent the product structure going from great variety to highly standardized products. This matrix is helpful in describing industrial companies' strategic options particularly with regard to the manufacturing function. The Hayes/Wheelwright matrix concept provides substantial support in determining the direction and timing of innovation decisions in the light of a company's manufacturing capabilities.

Building on the ideas of Hayes/Wheelwright and the generic strategy typology proposed by Porter an ongoing conceptual framework is provided by Kotha/Orne. Using the dimensions "product line complexity" and "process structure complexity" this framework suggests a link between several critical elements in manufacturing competitiveness (Kotha, Orne 1989). It considers both the content of fit and the process of fit between structure, strategy, technology and performance. It recognizes that the execution of the more generic business unit strategy inherently involves manufacturing and postulates the fit of between business-level strategy and manufacturing structure.

Kotha/Orne relate high process structure complexity in manufacturing and lower product line complexity to the strategy of cost leadership while the strategy of differentiation is related to higher product line complexity and lower process structure complexity. The company's "process structure complexity" is characterized by the level of mechanization, systemization and interconnection of the production process while "product line complexity" is mainly characterized by the end product's complexity and variety and its maturity in the product life cycle.

The frameworks of Utterback/Abernathy, Hayes/Wheelwright and Kotha/Orne represent integrative approaches all succeeding in illustrating the tight interconnections between product, process and strategy in manufacturing companies. Applied to industrial innovation management these synthesized frameworks give valuable hints for the development and implementation of specific types of innovation. They provide support for decision-making concerning the specific type, the timing and the extent of innovation in relation to maturity in product life cycle, manufacturing structure as well as in relation to manufacturing strategy and competitive strategy.

Considering Product-Process Interaction in Decision-Making: A System Dynamics-Based Approach

The frameworks described in the section above provide fundamental ideas giving substantial support for the generation of a System Dynamics model focusing on the process of innovation management in manufacturing firms. The description of patterns of innovation and the analysis of interaction between the elements structure, technology, strategy, and performance identifies essential underlying cause and effect relationships. A synthesis of these ideas is a suitable foundation of a System Dynamics model covering the complexity and the inherent dynamics of the industrial innovation process.

Objective of this modeling approach is to enable insights into the specific dynamic behavior of the system and to offer a virtual environment to test different scenarios of innovation. A taxation of consequences of managerial decisions concerning investments into development, the rate, timing and implementation of certain types of innovations becomes possible in relation to specific product or process features. In it's final state the model can serve as support tool for rational decision-making and strategy generation in innovation management for manufacturing companies with a focus on product-process interdependencies. The objective is to support the development of coordinated and coherent policies instead of isolated operations.

The analysis refers to the characteristics of a process segment and a single product line's life cycle of one firm. At this level the transition to completely new product generations is not included.

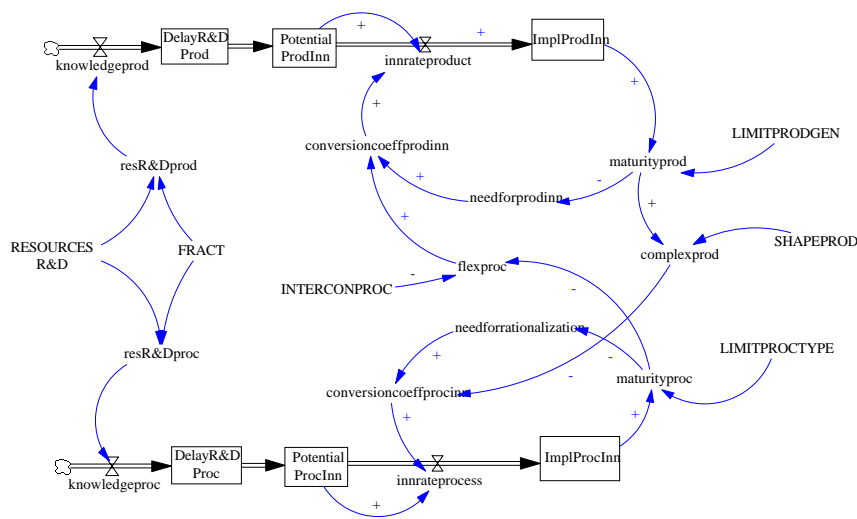


Figure 2: Simple System Dynamics model for analysis of product-process interaction

A simple System Dynamics model as depicted in figure 2 serves as a first approach integrating the concepts described above linking the basic ideas together into a feedback structure. In this first step the model only covers four sectors (R&D sector for product and process and implementation sector for product and process innovations) in a simplified manner. Dominant variable is the conversion coefficient product innovation and it's analog for process innovation which characterize the achievements in innovation implementation including promoting factors and constraints for the implementation of specific types of innovations. (For an explanation of further model variables see appendix.)

The model runs illustrate different scenarios forcing several process innovations leading to more flexible and less interconnected processes at the one hand (see figure 3) and product innovations leading to more complex products on the other hand (see figure 4). This behavior in general is confirmed by similar results indicated by the investigations of Kim et al. (Kim et al. 1992) and it is consistent with the concepts described above.

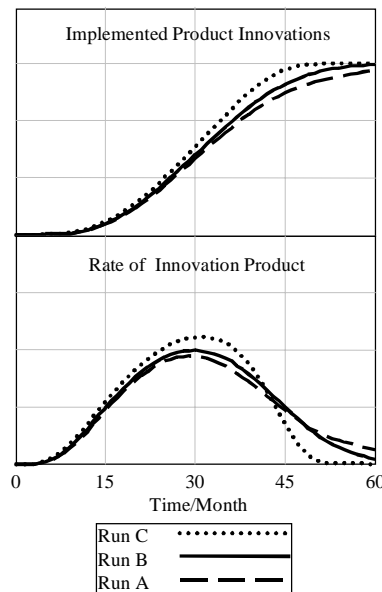


Figure 3: Number of implemented innovations in the product line and rate of product innovation over time (with process flexibility rising from Run A to Run C)

A higher rising product innovation rate (see figure 3, Run C) is related to a business strategy more dominated by the marketing function. This strategy can be boosted by the acquisition of more versatile or flexible process equipment (Kim et al. 1992, p. 56 f.) in combination with a more flexible organization and administrative processes that enable frequent changes in the product line.

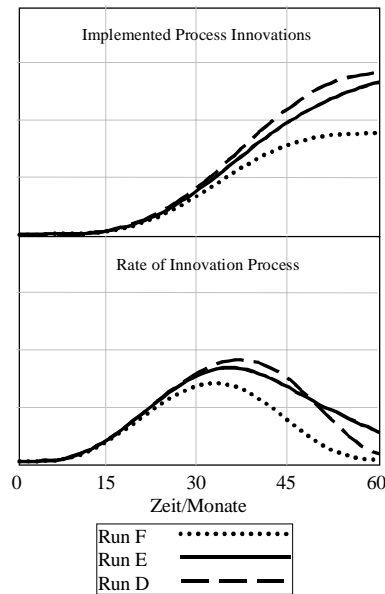


Figure 4: Number of implemented innovations rationalizing the process system and rate of process innovation over time (product line complexity rising from Run D to Run F)

Conclusions and Further Research

The System Dynamics model presented here links—in a first step—the cycle of product innovation with the innovation of the related manufacturing process. Until the model can serve as a strategy support tool it requires further steps of development. Nevertheless at this state it is able to give an impression of the dynamics of product and process innovation in manufacturing companies and illustrates their mutual constraints. These constraints are essential and to be taken into consideration in the process of strategy generation. The importance of process flexibility and flexible administrative practices and the influence of high product line complexity is illustrated.

From the feedback perspective all relevant interactions with focus on strategic implications of product-process interaction which cause the behavior of the system “industrial innovation” have to be represented. Further sets of variables reflecting for example customer’s and competitor’s behavior, learning curve effects and relevant managerial leverage points to control the industrial innovation process have to be included in following steps of model development.

The significance of technological and organizational product-process integration in the focus of manufacturing strategy and corporate strategy is recognized in recent literature (Damanpour, Gopalakrishnan 1999; Pisano 1997; Ettl 1995; Kim et al. 1992; Prahalad, Hamel 1990). In these investigations it is verified that manufacturing companies focusing on integrated product-process development with a regimen of policies, practices and structures

are more successful. In contradiction to these approaches sometimes the notion that companies' product and process development capabilities are mutually exclusive can be found in the literature. Empirical results indicate that integrated strategies—if implemented in a coordinated and coherent manner—can boost both the corporation's product development capabilities and its process development capabilities (Milling 1998; Pisano 1997). Success is significantly correlated to early and tight manufacturing involvement in product R&D taking into consideration the constraints as showed above.

Further development stages of the model are likely to provide substantial support for the generation of more effective decisions in manufacturing companies. In a next step practices for an achievement of compressed innovation implementation cycles by integrated product-process strategies will be investigated.

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Appendix

Explanation of the model variables:

<i>ImplProdInn</i>	Number of implemented innovations in the product line
<i>ImplProcInn</i>	Number of implemented innovations in the manufacturing process referring to the product line
<i>PotentialProdInn</i>	Number of potential innovations of the product line
<i>PotentialProcInn</i>	Number of potential innovations of the manufacturing process
<i>innrateproduct</i>	Rate of innovation in the product line
<i>innrateprocess</i>	Rate of innovation in the manufacturing process
<i>knowledgeprod</i>	Rate of knowledge generation suitable for product innovations
<i>knowledgeproc</i>	Rate of knowledge generation suitable for process innovations
<i>conversioncoeffprodinn</i>	Conversion coefficient for product innovations, characterizes achievements in innovation implementation in the product line
<i>conversioncoeffprocinn</i>	Conversion coefficient for process innovations, characterizes achievements in innovation implementation in the manufacturing process
<i>maturityprod</i>	Maturity in the product life cycle
<i>maturityproc</i>	Maturity in the process life cycle
<i>needforprodinn</i>	Need for innovation of the product line

<i>needforrationalization</i>	Need for rationalization of the manufacturing process
<i>complexprod</i>	Complexity and variety of the product line
<i>flexproc</i>	Flexibility of the manufacturing process
<i>resR&Dprod</i>	Resources for product R&D (capital, human capital, available technological knowledge)
<i>resR&Dproc</i>	Resources for process R&D (capital, human capital, available technological knowledge)
<i>RESOURCESR&D</i>	Resources for R&D (capital, human capital, available technological knowledge)
<i>FRACT</i>	Division factor
<i>SHAPEPROD</i>	Product features referring to it's complexity
<i>INTERCONPROC</i>	Process features referring to the level of systemization and interconnection
<i>LIMITPRODGEN</i>	Superior asymptote of the technology-S-curve
<i>LIMITPROCTYPE</i>	Superior asymptote of the technology-S-curve

Notice

Further information on the System Dynamics model (model equations) and subsequent steps of model development are available on request.