System Dynamics and Innovation: A complex problem with multiple levels of analysis

Martin Kunc
Warwick Business School
Coventry, UK
CV4 7AL

Abstract

System Dynamicists employ two principles to modeling different problems: feedback processes and stock and flows. Innovation processes can be observed and modeled at diverse level of analysis: industry, product, organization and processes. Each of these levels implies observing innovation problems with different theoretical lenses although they are strongly interrelated. The paper presents a review of the approaches followed by diverse practitioners on the use of System Dynamics in innovation. The initial evaluation of the literature suggests that system dynamicists have not followed system hierarchical principles to model innovation processes. Consequently, the results from one level, e.g. innovation processes, cannot be directly translated into the level above, e.g. industry dynamics. Future directions for research are suggested.

Introduction

Milling (2002) in his lecture delivered at the Forrester Prize ceremony during the 19th International Conference of the System Dynamics Society in Atlanta, Georgia identified the key factors that make innovation a complex problem for managers: shortened product life cycles, tight competition, and resource intensive research and development. The complexity in innovation stems to a large extent from the interrelatedness existing in organizations and from whether the elements are linked to each other in a linear or non-linear way or whether there are time delays in the system (Milling, 2002). While System Dynamics is considered suitable to model and analyze innovation processes (Milling, 2002), there is no comprehensive review of the approaches and problems tackled using System Dynamics in the area of innovation. This paper presents a review of the work in the area of innovation using System Dynamic to propose future research directions.

Innovation Analysis at the Industry Level

The concept of industry has been widely used to describe the environment where firms develop their business supplying similar products or services to a market. Basically, an industry is a feedback system comprised by firms and a market (Kunc, 2010). The two main feedback loops, which are sketched in figure 1, define the dynamics of the industry. The feedback loop “Firm Evolution” is a reinforcing feedback process. Once firms enter in the industry, they invest in operational resources that help them to attract customers. More actual customers generate more revenues, which are invested in more operational resources to attract a higher number of customers. The decision to invest in operational resources is controlled using any of two sources: the evolution of the actual number of customers or the level of saturation achieved measured by the relationship between actual and expected number of customers. The feedback loop “Market Evolution” at the center represents the process of market evolution. Not only the focal firm attracts customers reducing the pool of potential customers but also its competitors do it from the same pool, which is represented by the loop at the right in figure 1. They engage in a competition for capturing most of the potential customers that finish when there are no more potential customers. So sales from initial customers declines until stabilizes at the replacement level (Bass, 1969). The total number of potential customers is unknown for the participants in the industry; however, the number of potential customers at any time is a function of the technological attractiveness driven by innovation processes. The attractiveness of the technology is a function of the firm technology level with respect to the technology requirements of the potential customers. Thus, firms may be able to increase the pool of potential customers modifying their technology to satisfy their requirements, which are unknown to the participants in the industry. It is the interaction between firms that generates the aggregate behavior of the industry known as industry life cycle.

The approach employed in models of innovation at industry level should start with an explanation of the micro behavior to interpret the macro aggregate patterns (Kunc, 2010). The micro behavior explanation is based on the concept of feedback view of management. There are two main behavioral modes, which were extracted from experimental research on the management of firms in industries (Kunc, 2010), reflecting the preferences as well as biases in the management team with respect to the use of the information flows and its influence on the decisions. These behavioral modes, also called strategy types, are Reactive and Proactive (Kunc, 2010). Both modes are sketched in figure 1 as R for reactive and P for Proactive. The R mode uses mainly past information of the market evolution or feedback. The P mode is based on expectations about the market size and the information from the market serves to confirm or update upwards these expectations.

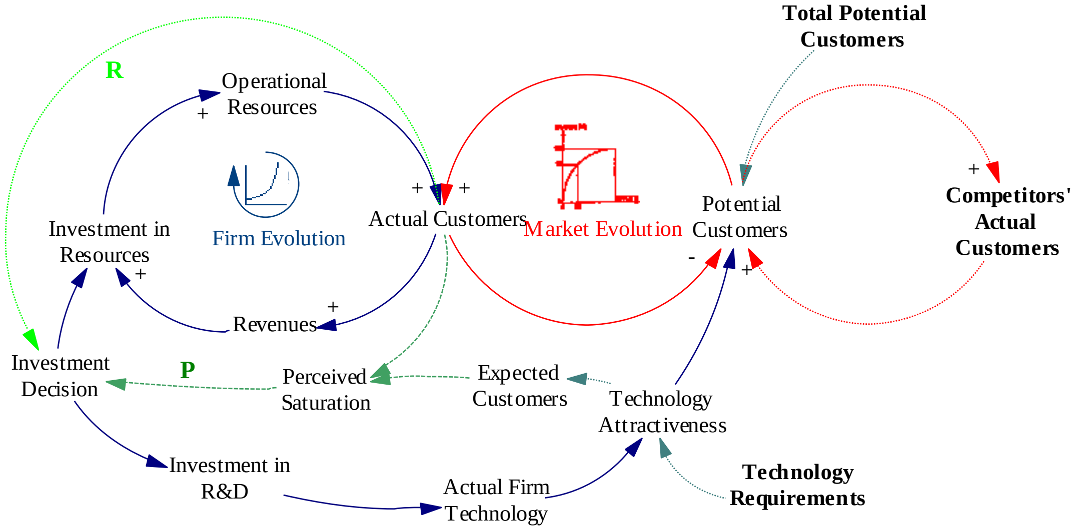

FIGURE 1: INDUSTRY EVOLUTION: A DYNAMIC BEHAVIOURAL MODEL

In an interpretation of the previous model, Kunc (2010) modeled the process of innovation at industry level as the competition between firms following Porter's strategies (cost leadership or differentiation). The model represented innovation as a resource that can be accumulated over time given certain policies. In more detail, Kunc (2010) suggests that technology resources comprise two resources[1]: Product Technology and Operational Efficiency. Product technology describes the technological level of the product portfolio and it is a key resource for firms following a differentiation strategy. Operational efficiency, which indicates the level of productivity of the operational resources, is a key resource for firms following a cost

[1] Resources are conceptualized as stock in system dynamics practice (Kunc and Morecroft, 2009).

leadership strategy. Product Technology represents an index of the level of the product characteristics. In the model, the characteristics of the product can be directly associated to the level of potential customers' requirements; for example, a product technology level of 100 is fairly close to cover all the possible customers' requirements, and, consequently, the firm may be able to attract a huge number of customers from the total available market. Moreover, a higher product technology level relative to competitors' level will attract not only potential customers but also customers from existing competitors. Therefore, innovation is directly driven by the competitive interactions of firms rather than exogenous scientific shocks.

Proposition 1. System Dynamics employed at industry level implies the conceptualization of firms as resource systems where innovation is only one of the many functions characterizing the competing firms in the industry. Therefore, the analysis of innovations is performed at macro level without detail of the innovation processes that occur within firms. The focus is on industry dynamic behavior.

Innovation Analysis at the Product Level

The simplest model of the evolution of markets over time is the Bass Diffusion Model (Bass, 1969). The Bass Diffusion Model has been extensively used to describe the diffusion of innovations in System Dynamics (Sterman, 2000). The model describes a process similar to the behavior generated by the "Market Evolution" feedback loop (see figure 1) – new markets usually describe an S-shape growth curve. However, there is a difference between the "Market Evolution" feedback loop and Bass Diffusion Model, in their basic version Bass Diffusion Model considers the diffusion process independently from the effects of firms' strategies or customer preferences distribution. Even though this model has these limitations, it is a solid starting point for modeling innovation at product level.

Figure 2 shows the stock and flow diagram of the Bass Diffusion Model. The Bass Model is a two-feedback process whose behavior over time is an s-shaped growth. Similarly to the "market evolution" feedback loop, the model has two main stocks: potential adopters and adopters. Even though the reinforcing feedback loop "Word of Mouth" dominates after an early growth phase, the first adopters are induced through advertisement. The "conversion" from potential adopter into adopter is generated through the number of contacts between adopters and potential adopters and the probability that a contact is successful in attracting a new adopter. The number of adopters compared to the Total Population, where the innovation takes place, dilutes this effect. As the number of adopter increases, the number of potential adopter decreases and the balancing feedback loop "Market Saturation" takes control. "Market Saturation" feedback loop reduces gradually the growth rate until there are no more potential adopters.

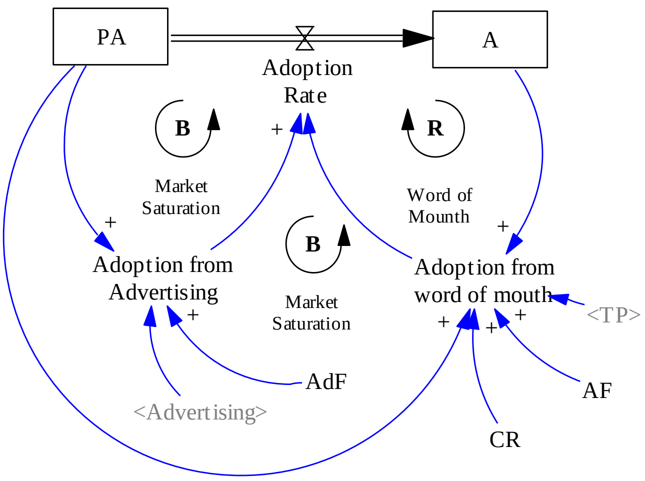

FIGURE 2. BASS DIFFUSION MODEL - STOCK AND FLOW DIAGRAM

The formulation traditionally of the Bass Diffusion Model generates some interesting questions on the dynamic of new markets generated by innovations that they have not been extensively addressed before. First, how firms obtain the values for the variables like contact rate, adoption fraction or advertising effectiveness; why are these variables considered fixed, why population is considered homogeneous. Second, what kind of strategic influence firms has on the diffusion of innovations, for example what is the capacity expansion strategy? Third, how firms calculate the size of potential adopters; what they use to create their expectations about this number; firms can change over time the number of potential adopters or they face inevitably a sales slowdown. Consequently, innovation generates more innovation, an endogenous reinforcing feedback process. The model is very robust to present aggregate data, but it does not address uncertainties, which are faced by management. For example, the number of adopters represents the customer base and futures sales in non-durable goods, but in the case of durable goods such as VCR, TV, cars or PC, sales are represented by adoption rate. Initially, adoption rate is the main source of income for producers of durable goods, but then a lower proportion of sales are obtained from replacement sales.

Differences in terms of the conceptualization of market evolution strongly affect the evolution of industries imposing different types of strategies and behavior to managers. For example, in a durable goods industry, sales are very intensive in a short period, so the pool of potential adopters is quickly depleted. High short-term penetration strategies will generate pressure to expand operational resources; as a result of this expansion most of the capacity will be idle in the medium term once sales drop to replacement level. Excess in capacity will deteriorate firm performance, and without additional markets to deplete, which can be obtained from product innovation, they have to leave the industry. To conclude, innovations are important sources of uncertainties not only during the development of the technology but also when they are implemented in the market. Bass Diffusion Model is an interesting starting point but it is limited in the behavioral assumptions that drive diffusion. Consequently, the market sector has to be enhanced with consumers' aspects such as heterogeneity to represent more closely the life cycle of an industry rather than a specific product; and it has to include the effect of firms on its evolution.

Kunc and Morecroft (2007) explain the use of System Dynamics to help a company in the Fast Moving Consumer Goods industry to understand the dynamics of its new products in the market. The authors represented the adoption of the new product as a competition between three firms: Carex, Lever and Supermarkets where each of the firms try to achieve objectives such as market share, volume or sales by performing promotions and advertising. The model also includes the behavior of consumers to firms' actions creating a feedback process similar to the feedback loop "Market Evolution" in figure 1. In this type of analysis, the product is already defined, liquid soap, and the main area of interest is the distribution of potential customers across the options existing in the market. Consequently, stocks and flows represent customers across different product options existing in the market and feedback processes are used to make firms' responses endogenous in the model. This type of analysis reflects mainly the operational aspects of innovation: how many customers will buy the product? How fast? When? How much will it cost? But not the development process of innovations or the impact of innovation on adopters.

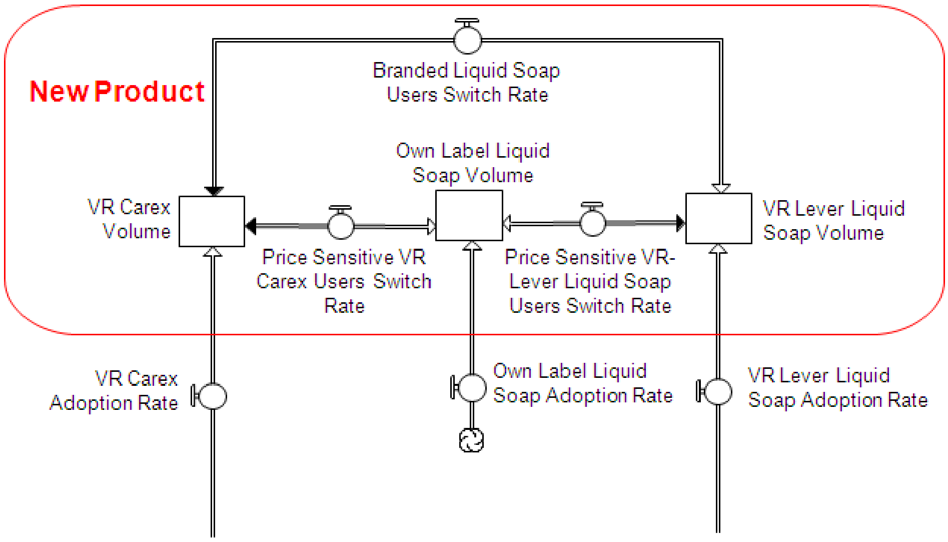

FIGURE 3. STOCK AND FLOW MARKET MODEL FOR A COMPETITIVE ENVIRONMENT (Kunc and Morecroft, 2007)

Proposition 2. System Dynamics employed at product level implies conceptualizing people as following different stages in the adoption of a new product. Each of these stages represents diverse options in the market as well as diverse stages in product adoptions. Stocks reflect the accumulation of people in each stage and feedback processes reflect the endogenous behavior existing in the market. This level of analysis considers the innovation as given and concentrates on its adoption.

Innovation Analysis at the Organizational Level

In this level of analysis, the focus is on the implementation of new technologies by an organization and the feedback processes driving this process. System Dynamicists adopt a subjective view of technology adoption (Black, Carlile, and Repenning, 2004) rather than the objective view found in economic literature. This view focuses on the feedback processes generated by the use of technology in the course of daily activities since the introduction of new technology may not produce the expected changes in behavior. One of the seminal works on this view is Black et al (2004) paper on the adoption of CT scanning (Barley, 1986). The authors integrated three ideas from organizational theory: focus on the activity that technology is influencing; the accumulation of knowledge in the main actors adopting the new technology; and the interactions between the activity and the relative accumulation of knowledge of the actors involved. Figure 4 displays the extended model employed in Black et al (2004). The model contains the two main actors in the adoption of the CT scanner: doctors and technologists. Both actors are represented by their relevant knowledge stocks: operating knowledge and diagnostic knowledge. A strong interrelationship between both actors occur at the activity level represented in the variable “Fraction of New Operating Decisions by Doctors” and the causes of changes in this variable can be observed in the different level of knowledge accumulation between doctors and technologists (variable “Doctors’ Knowledge Relative to Technologists”). Embedded in the model are reinforcing feedback processes that highlight virtuous cycle generated by increasing use of a technology for one actor but increasing marginalization of another actor. Only certain behavioral issues like “Threat of Role Reversal” can stop this process. The consequences of the interactions existing in this social system have to be addressed using simulation. System Dynamicists also incorporate issues like delays (variable “Time to Accumulate Knowledge”) and implicit limitations in the level of knowledge accumulated (variable “Maximum Knowledge”). While some of these variables are difficult to quantify, the use of model calibration and validation processes (Sterman, 2000) eliminates the potential issues with the values of soft variables.

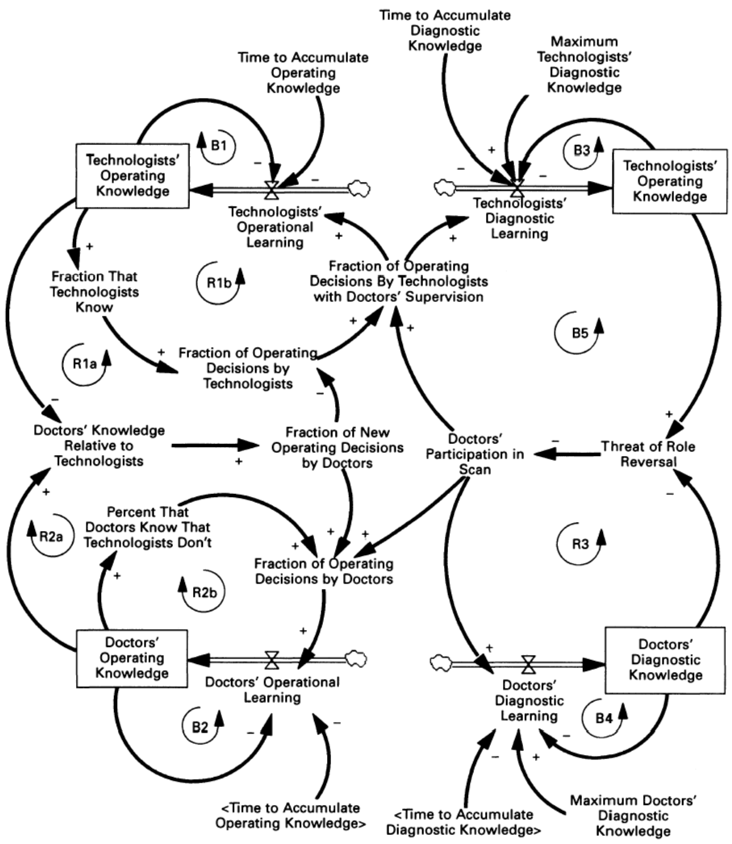

FIGURE 4. MODEL ON THE DYNAMICS OF ORGANIZATIONAL ADOPTION OF NEW TECHNOLOGY (SOURCE: FIGURE 3 – Black et al (2004))

The use of SD models in this context open the door to understand more qualitative, in-depth, social processes. Black et al (2004) suggest that "formal models can be used as representational tools to bridge the gap between the "thick description" found in ethnographic accounts and the complex recursive conceptualizations. By operationalizing accounts that use both rich data and recursive approaches, our effort has been to leverage the ethnographer's insights in a way that allows for more general application. Most models, however, represent relatively general inquiries, often based on stylized axioms about the phenomenon studies." (Black et al (2004), pp. 604)

Proposition 3. System Dynamics employed at organizational level implies conceptualizing the impact of technologies on activities under a given context. The use of technology is represented through the activities that technology affects and the actors that perform them. Stocks reflect the accumulation of knowledge related to the use of new technology. Feedback processes capture the social interactions between the actors and the potential displacement of certain actors given the adoption of a new innovation. Consequently, SD models are employed to understand social aspects of innovation.

Innovation Analysis at the Process Level

In this level of analysis, the focus is on the development of new products. To understand this problem, System Dynamicists represent new product development projects as a sequence of tasks and the effects of the interactions between resources (people, machinery), project scope and targets (Ford and Sterman, 1998). Project management is usually affected by the relative difficulty of managing parallel tasks, concurrence among activities, unbalances between activities due to delays and iterations within and between phases (Ford and Sterman, 1998). The amount and productivity of resources limit the rate at which tasks are performed affecting the flow of tasks between different stages. Project scope defines the amount of work to be performed in number of stages. Targets define the levels of performance and priorities. A sector map of the interaction of these aspects is presented in figure 5. The interaction between these factors is complex enough to require the use of modeling and simulation. In the OR field, other tools have also been employed in this field.

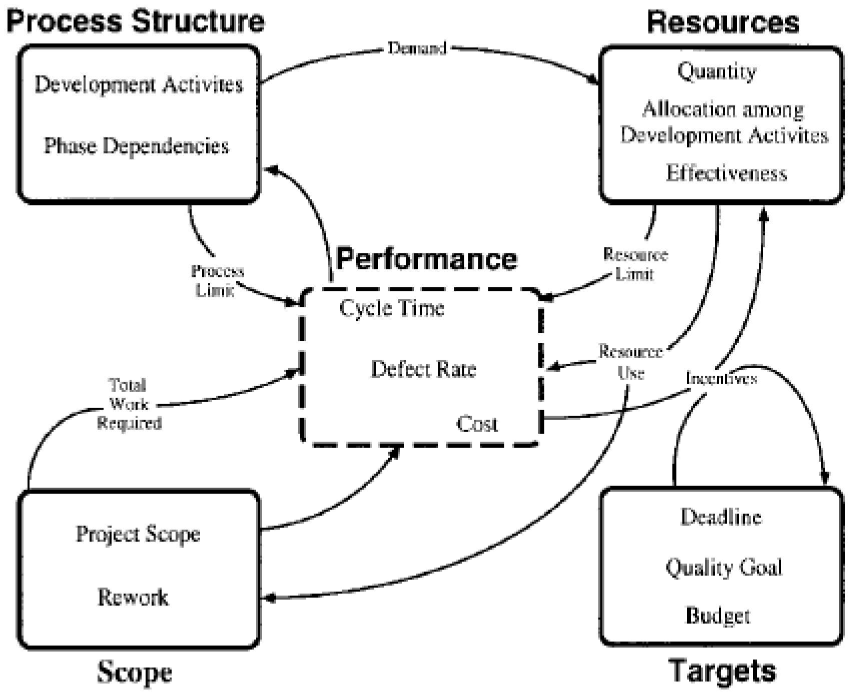

FIGURE 5. PRODUCT DEVELOPMENT SUBSYSTEMS (SOURCE: FIGURE 1 - (Ford and Sterman, 1998)

System dynamicists will represent product development processes as networks of stocks and flows similar to figure 6. Figure 6 shows a development process based on a single phase where each stock represent the stage of the process and flows indicate the direction of the tasks. For example, "Task completed not checked" represent the number of tasks that have finished but they have not been approved. "Task completed not checked" is accumulated by new tasks finished (flow "Change task rate") and it depletes by the rate at which tasks are approved (flow "Approve task rate") or rejected due to problems (flow "Discover change rate"). All flows depend on the amount of resources that can be assigned to each task. While it may not be a problem to have specific resources to each task, one of the main issues with managing projects is to control costs. Consequently, projects usually share resources that have to be assigned to achieve the defined targets generating feedback processes difficult to manage.

System dynamics models have been employed to uncover resource allocation policies that affect the achievement of targets in the area of quality, deadline and budget due to its dynamic complexity (Ford and Sterman, 1998) under diverse scenarios.

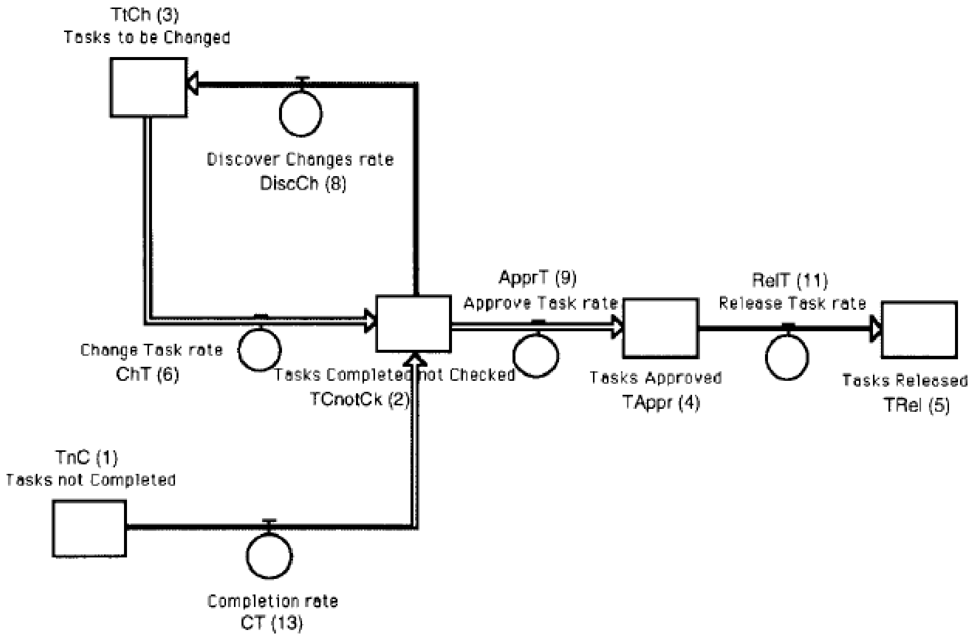

FIGURE 6. PRODUCT DEVELOPMENT STOCK AND FLOW NETWORK (SOURCE: FIGURE 3 - (Ford and Sterman, 1998))

Proposition 4. System Dynamics employed at process level implies conceptualizing innovation during its development. Stocks reflect the stages, which are defined by the project scope, that are needed to develop a new technology including rework, tests, approval and final release. The flow between each stock reflects the speed at which tasks are performed and their movement between stages. Feedback processes capture the interactions between resource allocation and tasks rates and the necessary tradeoffs to achieve the targets in terms of deadline, budget and quality.

Conclusion

Simon (1996) suggests that systems are composed of interrelated subsystems that are hierarchical in structure. However, systems' hierarchies are arbitrary and, in many cases, there is no relation of subordination among systems (Simon, 1996). Innovation is a complex system composed by multiple levels: industry, product, organization and process whose hierarchy is not clear. System dynamicists analyzed innovation issues applying similar principles: stocks, flows and feedback processes but identifying different premises for each level. For example, technology is a resource (stock) accumulated by investments at industry level but technology is a set of stages (stocks) driven by the allocation of resources at process level. Therefore, models are providing different lessons for a unique system composed by multiple levels. Consequently, system dynamicists should consider the implications of their models to reflect the hierarchical structure existing in real world.

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