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Decision Support

Multi-period models for analyzing the dynamics of process improvement activities

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ABSTRACT

Managing knowledge based resource capabilities has become very important in recent years and during a finite horizon it seems to be reasonable to develop the capabilities intensively at the beginning as one can utilize those over a longer period of time. With the help of multi-period models we check the validity of this idea and characterize the dynamics of development activities. The paper identifies the factors that shape these dynamics and from the behavior of these factors we conclude when the dynamics can be increasing or decreasing. We point out that in stable environment there is tendency for decreasing dynamics but future expectations can significantly modify this outcome. Relationships between the successful or less successful implementation of a business strategy and the dynamics of improvement activities are highlighted as well. For specific model structures explicit solutions are derived.

1. Introduction

The implementation of continuous process improvement seems to be a crucial point in modern business life. Not long ago, when Mr. Watanabe, the chairman of Toyota Motor Corporation, was asked about the essence of Toyota Way, he mentioned continuous improvement as one of the two most important pillars of managing a company (Watanabe, 2007). The successful implementation of the principles of the Toyota Production System has revolutionized many industries, and the principles of TPS are used by many other manufacturers like Porsche or VW (Fear and Knoop, 2007).

The inclusion of process improvement into models is popular, especially since the appearance of seminal papers like (Fine (1986)), or Dorroh et al. (1994), who presented a model to determine the amount of resources to be devoted to knowledge acquisition. Chand et al. (1996) developed a dynamic model and analyzed the effect of continuous process improvement on capacity allocation to maximize profit over time. They introduce the concept of productivity knowledge that can be increased by improvement activities. Li and Rajagopalan's (1998) study models quality assurance efforts, level of productivity and quality knowledge improvement efforts as decision variables. All these studies advocate early significant investments with declining rate in knowledge discovery programs. Besides this extensive theoretical development of dynamic quality-based learning models Ittner et al. (2001) carried out a direct empirical test of these models. Carillo and Gaimon (2000) identify conditions whereby investment into process change occurs at an increasing rate over time, but in their model process change may cause immediate losses. In one of their later studies, Carillo and Gaimon (2004) define two models to gain insights on how plant performance is impacted by training and process change. Vörös (2006) builds a model whereby demand directly depends on the performance quality of the product. The inclusion of quality improvement process into the dynamic approaches has been recently analyzed by Chenavaz (2012) and it was found that under multiplicative separable demand function process innovation is the main determinant of a firm's pricing policy over time and product innovation has no impact. In the paper of Li and Lee (2010) the driving dynamics of quality is considered in case of peer-production. Among others, they found that a monopolistic platform provider has no incentive to offer multiple quality classes of services. The operations-marketing interface is further analyzed by De Giovanni (2011) where both advertising and quality improvement contribute to the build up of goodwill, and the co-operation of manufacturer and retailer leads to a better market position.

Considering simultaneous quality and process improvement activities Vörös (2006) pointed out also that the dynamics of quality and process improvement activities can be increasing as well, however he missed to fully characterize the dynamics of improvement activities. Thus, according to the wide variety of research reports, already alone the dynamic behavior of improvement activities is a challenging question.

This study attempts to identify all the factors that shape the dynamic nature of improvement activities and provides a complete analysis of when are the dynamics of improvement activities increasing or decreasing. The paper determines a key expression

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and finds that the dynamic behavior of the components of this key expression explains mainly the dynamics of improvement activities.

Interestingly, in all the theoretical models mentioned above, time is a continuous variable, and the tools of optimal control theory are used. Models many times tend to assume continuous differentiability and time independent model parameters, and we rarely see multi period models in this field. Recently, one of the latest contributions is made by Berstein and Kök (2009), who develop a multi-period model and consider a decentralized assembly system with process improvement activities. Among others, they point out that under cost contingent contracts, there always exists an equilibrium (in Stackelberg competition) where in each period either all suppliers invest in process improvement or no supplier does. They provide a procedure to calculate the optimal investments into productivity knowledge.

This paper develops multi period versions of optimal control models to analyze the dynamic nature of price and improvement activities. In this model the time horizon is divided into periods and in each period we have to make decision on the intensity of improvement activities. In turn, improvement activities, if they are at positive level, increase the productivity knowledge. The level of productivity knowledge at each period determines unit production costs. In each period we make decision on price level as well, which determines the volume of demand at the period. At the end of the planning horizon the accumulated knowledge can be sold at a given price. A strong characteristic of the model is that the input parameters of demand function may vary from period to period.

Although the Berstein and Kök (2009) single firm model is a multi period one, their model is also analyzed for the special case when the parameters of the linear demand function are time independent in order to ease the understanding the nature of more general structures. This analysis helps us to reveal relationships between model structures and the dynamics of improvement activities. Besides the insights provided by the multi period technique, we give the explicit description of the optimal solution for this special parameter setting.

Altogether, our study intends to extend our knowledge in four points: for rather general models, among the most interesting findings there is the identification of the factors that shape the dynamics of improvement activities. Moreover, finding relationship between model structure and the dynamics of improvement activities, the paper classifies models from which the dynamics of improvement activities simply must follow. This result allows us to position the well known models mentioned above in a table which classifies the model structures (see Table 2 later). The study reveals relationship between the successful or less successful implementation of a business strategy and the dynamics of improvement activities (see Table 1 later), and gives the explicit solution of models with linear demand and investment cost functions.

The next section develops a rather general multi period model, and Section 3 analyzes this model with linear demand and investment cost functions. Based on this, in Section 4 the analysis turns back to the basic model and Section 5 explains why the dynamics must sometimes follows from model structures. Section 6 presents the conclusions.

2. Developing multi period models

In this section we formulate a general model and the final aim is to analyze it. To ease the discussion, first we specify the functions of the general model in the next step, and later we turn back to the base case. We suppose that our firm's product has unique characteristics others cannot copy, substitute, or imitate easily, thus our firm can behave like a monopoly with certain extent. This way demand can be described by the function $D^t(p_t)$ at period t, where p_t is the selling price of the product at period t, and we divide the planning horizon into T periods ($t = 1, \ldots, T$). The unit production variable cost is $c(q_t)$ at period t, where q_t measures the accumulated productivity knowledge at period t. This productivity knowledge can be increased by improvement activities at each period, and the extent of the improvement activities at period t is measured by the variable y_t. The cost of this productivity improvement effort is $f(y_t)$ at period t. We suppose that at the end of the planning horizon the accumulated productivity knowledge can be sold at the unit price of P. As the lowest possible value of this parameter can be zero, the inclusion of the selling price of productivity knowledge extends the scope of the study, more importantly, positions our model closer to real life. Managers frequently introduce new product generations on the basis of knowledge accumulated during the life of previous generations, purchase knowledge, or sell it when they quit the business. Thus the accumulated productivity knowledge may have value. Let us note that Li and Rajagopalan (1998) already have used the concept.

The basic model we consider can be written in the following form then:

$$\max_{p_t, y_t} \sum_{t=1}^{T} [(p_t - c(q_t))D^t(p_t) - f(y_t)]\delta^t + [Pq_T]\delta^T \tag{1a}$$

subjected to, for all t, that,

$$q_t = q_{t-1} + a_t y_t \tag{1b}$$

$$p_t, y_t \geqslant 0. \tag{1c}$$

where T is the number of periods, t is the index of a period, $t \in [1, T]$, p_t is the selling price at period t, decision variable, q_t is the accumulated productivity knowledge at period t, with the initial value of q_0, dependent variable, y_t is the level of process improvement efforts at period t, a decision variable, $f(y_t)$ is the cost of productivity improvement effort at period t, $c(q_t)$ is the unit variable cost function at period t, $D^t(p)$ is the volume of demand at period t, when the price is p P is the selling price of one unit productivity knowledge at the end of the planning horizon, and δ is the $1/(1 + r)$, where r is the discount rate, and a_t are positive parameters.

In Model (1) the discounted gross profit, plus the terminal value of the accumulated productivity knowledge are maximized under the rule of how productivity knowledge is accumulating. We suppose that productivity knowledge accumulates as a linear function of improvement efforts.

3. Multi-period models with time independent linear demand and investment cost functions

To ease the exploration of the nature of the model varified in (1), first we define simplified versions. Berstein and Kök (2009) point out interesting characteristics of the model in (1) when the unit variable cost function $c(q_t) = c_0(q_t)^{-\beta}$ (where c_0 and β are positive parameters), the productivity improvement (investment) cost function $f(y_t) = ky_t$, $k > 0$, where k is constant parameter, moreover $P = 0$, and $a_t = 1$ for all t. We further simplify their model with assuming time independent parameters at the demand function. We are going to point out some properties of the dynamics of variable y (the level of improvement efforts) with linear demand functions. Let us assume the parameters of the demand function do not depend on time, i.e. $D^t(p_t) = \alpha - \gamma p_t$, where α and γ are positive parameters.