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A dynamic model for the optimization of decoupling point and production planning in a supply chain

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A R T I C L E I N F O

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A B S T R A C T

In this paper, we propose a dynamic model to simultaneously determine the optimal position of the decoupling point and production–inventory plan in a supply chain such that the total cost of the deviation from the target production rate and the target inventory level is minimized. Using the optimal control theory, we derive the closed form of the optimal solution when the production smoothing policy and the zero-inventory policy are applied. The result indicates that under the production smoothing policy, the overestimation of demand rate during the pre-decoupling stage guarantees the existence of the optimal decoupling point; meanwhile the optimal decoupling point exists under zero-inventory policy when the demand rate is underestimated. Also we perform mathematical analysis on the behavior of the optimal production rate and the inventory level and the effect of problem parameters such as the length of the product life cycle and the forecast error on the performance.

1. Introduction

A decoupling point is a push–pull boundary in the supply chain. From the upstream of the supply chain (i.e., the raw material supplier) to the decoupling point, the supply chain plan is scheduled based on the demand forecast which is a push strategy; meanwhile, from the decoupling point to the downstream of the supply chain (i.e., the end customer), the supply chain operations are driven by the customer orders rather than forecasts which is a pull strategy. In terms of the product delivery strategy, it is also known as a make-to-stock (MTS) (a make-to-order (MTO)) strategy in the push (pull) range of the supply chain. The appropriate positioning of the decoupling point is an important design issue in the realm of the supply chain management. As shown in Fig. 1, the candidate positions of the decoupling point exist on any stage of the supply chain.

As Olhager (2003) mentioned, there are many reasons and effects of shifting the decoupling point forward or backward to the end customers. For example, if the decoupling point moves backward to the customers, the response time to customer is increased and the manufacturing efficiency improves; meanwhile the forward shifting will cause the increase of WIP and the reduction in the product customization. The advantages of the forward shifting are the disadvantages of the backward shifting of the decoupling point and vice versa.

There exist two different approaches in determining the position of the decoupling point, strategic approaches and analytic approaches. The strategic approaches intend to provide guidelines using knowledge-based systems or conceptual models for selecting decoupling point. The analytic approaches use mathematical models or simulation models to find an optimal position of the decoupling point. Most of the mathematical model-based approaches tried to minimize the manufacturing related costs subject to satisfy the certain level of customer response time.

Most of the previous mathematical models assume that the decoupling point is the unique decision variable. However the production planning, inventory policy and operational decisions such as scheduling and sequencing also affect to the performance of the supply chain. It is obvious that the supply chain can be optimized if all these issues can be handled simultaneously if the problem complexity is not considered. In addition, previous models analyze either a static or steady state equilibrium of supply chains considering the minimization of average cost with the infinite planning horizon. However, the nature of the problem is dynamic and the planning horizon is finite. The considering problem is dynamic since the true demand is realized in the post-decoupling point, thus the operations (e.g., production rate or inventory level) may be adjusted using the available demand information. Today it is widely accepted that the product market undergo a life cycle of introduction, growth, maturity and eventual decline not entering toward a stationary state. Therefore the assumption of the finite planning horizon is more realistic in real world scenario.

In this paper, we consider a problem of determining the position of the decoupling point and the production planning

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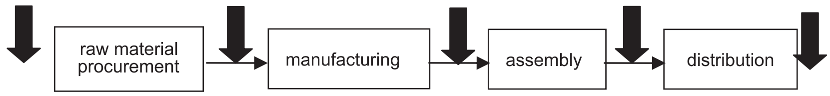

Fig. 1. Candidate positions of a decoupling point.

and inventory strategy simultaneously under different planning policies. The proposed model is a continuous and dynamic model such that the objective function is the minimization of the total cost of the deviation from the target production rate and the target inventory level. The optimal position of the decoupling point, the optimal path of the production rate and the inventory level are the decision variables. The problem is solved using optimal control theory. Also we will examine the effect of the accuracy of the forecasting error in pre-decoupling point, the effect of the assumption of the finite planning horizon and the sensitivity analysis of the problem parameters.

The paper is organized as follows: Section 2 reviews the relevant literature. In Section 3, we describe the considering problem and propose dynamic models. The closed form of optimal solutions are presented when target parameters are given in Section 4. We present some theoretical results for the production smoothing policy in Section 5. Section 6 represents results for the zero-inventory policy. Finally some concluding remarks are given in Section 7.

2. Literature survey

For strategic positioning of a decoupling point, Olhager (2003) proposed a P/D (production lead time/delivery lead time) ratio and the relative demand volatility. MTO corresponds to a P/D ratio that is less than one and MTS is a viable option for low relative demand volatility. For low relative demand volatility, we may employ an MTS policy for the economies of scale even in the range of $P/D<1$. Naylor et al. (1999) combined the lean thinking and agile manufacturing paradigms with the positioning of the decoupling point. Authors insisted that the lean paradigm (agile paradigm) can be applied to the pre-decoupling point (post-decoupling point). Kundu et al. (2008) proposed a knowledge-based approach in determining the position of the decoupling point. They considered the tradeoff between the physical efficiency of the supply chain and the market responsiveness. The research suggested that as the order volume and the product life cycle increase and the unit transportation cost decreases, the decoupling point must be shifted backward to the upstream. Van Donk (2001) proposed a guideline for choosing the position of the decoupling point for food processing industries.

Yanez et al. (2009) proposed a simulation platform built on an agent-based planning system in order to determine an appropriate position of the decoupling point in the timber industry. The performances of the different decoupling points are measured using the daily average inventory WIP and the weighted fill rate of demands. Jammernegg and Reiner (2007) considered the tradeoff between the inventory reduction and the increase in order fulfillment cycle time. They studied a three-stage supplier network using a stochastic simulation. Another type of simulation is based on generalized stochastic Petri nets by Viswanadham and Raghavan (2000). The objective of the Petri nets model is the minimization of the sum of inventory carrying cost and the delayed delivery cost.

For the mathematical model-based approaches, Gupta and Benjaafar (2004) considered a model such that the objective function is the minimization of the sum of inventory holding cost and the product/process redesign cost subject to a service-level constraint. The problem is solved by the queuing theory. Sun et al. (2008) considered the problem of positioning multiple decoupling points based on the bill of material of a product in a supply network. They proposed a mathematical model with the minimization of supply chain cost which is the sum of the setup, inventory, stock-out and asset specificity cost subject to the delivery time constraint required by the customer. The model is 0–1 integer programming which can be solved by a commercial software package.

Soman et al. (2004) pointed out that the decoupling point decision is closely related to the production planning, inventory policy and operational decisions. In a hybrid MTO–MTS system, important questions are as follows: the capacity allocation among MTO and MTS products, the determination of the safety stock for MTS products, the order acceptance/rejection decision for MTO products and the scheduling and sequencing of products. However the handling of the whole issues along with the problem of the positioning the decoupling point is very complex. Thus Soman et al. (2004) proposed a hierarchical planning framework for food production system.

In this paper, we attack the problem of the determining the position of the decoupling point, the production planning and inventory strategy simultaneously. It is also seen that the proposed solution is based on the mathematical model that can be optimally solved using the optimal control theory. In addition, we address the issue of the effect of the forecasting error and the length of product life cycle on the performance measure.

3. Problem description

Notations:

T	decoupling point in a supply chain
P_0	estimated demand rate (i.e., production rate) during the pre-decoupling point
$P(t)$	production rate at time t during the post-decoupling point
T_0	length of product life cycle
$F(t)$	cumulative customer demands at time t where $F(T_0)=N$
$D(t)=F'(t)$	demand rate at time t
Ω	constant target production rate during post-decoupling point
$I(t)$	inventory level at time t during post-decoupling point
θ	constant target inventory level during post-decoupling point
K	constant cost per unit deviation from target production rate
h	constant cost per unit deviation from target inventory level

Consider time t over a finite product life cycle of a single product. At $t=0$, the production planner estimates the demand rate of the product, P_0. The production starts with the production rate $P(t)=P_0$ from the raw material procurement at $t=0$ to the decoupling point at $t=T$. At the decoupling point, the true demand rate $D(t)$ is realized during the product life cycle from time $t=T$ to $T+T_0$. When the production during the pre-decoupling point is finished, the inventory level would be $I(L)=P_0T$ where L is the throughput time of the supply chain.