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Development of Optimization Models for Addressing Various Decision and Information Related Issues in Supply Chain Planning

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Abstract

We consider a model of a two-stage serial supply chain that processes a single part type. Each stage has an infinite-capacity raw-parts (RP) buffer, a finite-capacity production facility (PF) with deterministic production lead time (PLT), and an infinite-capacity finished-parts (FP) buffer. Stage 2 receives orders from end customers and places orders to stage 1. Stage 1 receives orders from stage 2 and places orders to an initial supplier with inexhaustible supply of initial raw parts. Upon receipt of an order, a stage immediately ships the order quantity from its FP buffer to its customer. The order arrives after a deterministic order lead time (OLT). If there are not enough parts in the FP buffer to meet the order, an expensive external inexhaustible-supply subcontractor (S) immediately complements the missing parts of the order. Each stage has revenue from the parts it sells and incurs inventory holding costs in its RP and FP buffers, as well as fixed and variable production and order costs. In case it cannot meet all the demand, it either pays the cost of complementing the order to the subcontractor, or it passes this cost to its customer. For this model, we formulate several variants of a finite-horizon production-and-order planning problem. The variants differ with respect to the level of collaboration and information

sharing between the two stages. First, we distinguish between the cases where the decisions are made in a centralized/decentralized way. In the letter case, we further distinguish between the cases where the decisions are made sequentially/simultaneously and use local/global information. In a follow up work, we plan to numerically experiment with these variants in order to quantify the effect of the problem parameters, the type of collaboration, and the level of information sharing on order and production variability and supply chain profitability.

Keywords: supply chain planning; centralized vs. decentralized decision making; local vs. global information.

Nomenclature

Facilities

R_i : stage-i raw-parts (RP) buffer, $i = 1,2$; R_3: customer demand source;

P_i : stage-i production facility (PF), $i = 1,2$;

F_i : stage-i finished-parts (FP) buffer, $i = 1,2$; F_0: (inexhaustible-supply) initial raw-parts buffer;

S_i : (inexhaustible-supply) stage-i subcontractor, $i = 1,2$;

Indices

i : stage index, $i = 1,2$;

t : period index, $t = 1,\ldots,T$;

Decision variables ($i = 1,2$, $t = 1,\ldots,T$);

$P_{i,t}$: quantity produced by P_i in period t;

$X_{i,t}$: indicator (binary) variable of $P_{i,t}$ equal to 0 if $P_{i,t} = 0$, and 1 if $P_{i,t} > 0$;

$R_{i,t}$: inventory in R_i at the end of period t;

$F_{i,t}$: inventory in F_i at the end of period t;

$D_{i,t}$: quantity of order placed by R_i to F_{i-1} at the end of period t;

$Y_{i,t}$: indicator (binary) variable of $D_{i,t}$ equal to 0 if $D_{i,t} = 0$, and 1 if $D_{i,t} > 0$;

$S_{i,t}$: quantity of order placed by F_i to S_i at the end of period t;

Parameters ($i = 1, 2$, $t = 1, \ldots, T$);

$P_{i,t}^{\max}$: production capacity of PF P_i in period t ;

L_i^p : production lead time (number of periods) of PF P_i ;

L_i^d : order lead time (number of periods) from F_{i-1} to R_i ;

$D_{3,t}$: (external) final customer orders placed by R_3 to F_2 at the end of period t ;

I_i : interest rate used by stage i to compute inventory holding cost rates;

M : a very large number;

Costs ($i = 1, 2$)

p_i : (variable) unit production cost at P_i ;

x_i : fixed setup cost at P_i ;

r_i : unit inventory holding cost per period in R_i ;

f_i : unit inventory holding cost per period in F_i ;

I_i : interest rate used by stage i to compute inventory holding cost rates;

d_i : (variable) unit order cost from R_i to F_{i-1} , $i = 1, 2, 3$;

s_i : (variable) unit order cost from F_i to S_i ;

y_i : fixed order cost from R_i to F_{i-1} ;

1. Introduction

The work presented in this paper is part of a project supported by grant MIS 379526 “ODYSSEUS: A holistic approach for managing variability in contemporary global supply chain networks,” which is co-financed by the EU-ESF and Greek national funds through NSRF – Operational Program “Education and Lifelong Learning” – “THALES: Reinforcement of the Interdisciplinary and/or Inter-Institutional Research and Innovation”. The main goal of ODYSSEUS is to study the phenomenon of supply chain demand variability, identify the physical points of its creation, analyze its causes, and evaluate its negative impact on supply chain performance. One of the requirements of ODYSSEUS is to develop quantitative models to support decisions related to demand variability and in particular the “bullwhip effect” (the phenomenon that demand variability increases as one moves upstream in the supply chain). The literature on the bullwhip effect is vast. Much of it involves the development and analysis of stochastic dynamic models of supply chains. Representative examples are Chen et al. (2000a,b), Cachon and Lariviere (2001), Lee et al. (1997a,b), Alwan et al. (2003), and Zhang (2004).

In this paper, we formulate a deterministic dynamic capacitated lot-sizing planning problem (Buschkühl, et al. 2010) and variants of it for a simple two-stage serial supply chain model, in order to study the bullwhip effect. Such problems are simple and fit the practical MRP-framework (Tempelmeier, 1997). They are also solvable with readily available mathematical programming software and heuristic approaches (Tempelmeier and Destroff, 1996). In a follow up work, we plan to use these variants to quantify the effect of the problem parameters, the type of collaboration, and the level of information sharing on order and production variability and supply chain profitability. In this respect, our models are related to Saharidis et al. (2006, 2009).

2. Basic Supply Chain Model

Diagram 1 shows a graphical representation of the basic model described in the Abstract. Triangles represent buffers, and circles represent production facilities. Solid black arrows indicate the material flow and dashed grey arrows indicate the order flow. The decision variables of the model are shown in blue color, while its parameters are shown in red color.

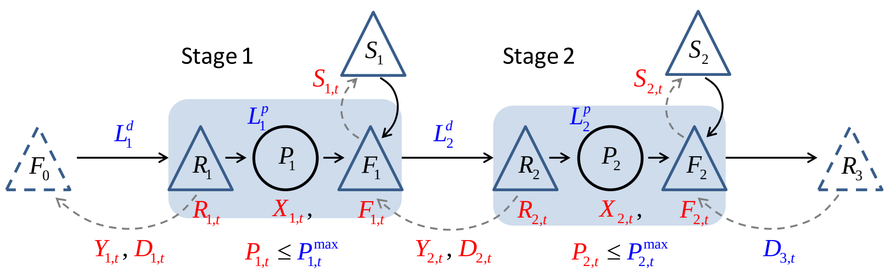

Diagram 1. Basic supply chain model.

We make the following assumptions regarding the variable cost rates:

$$d_{i+1} > d_i + p_i\,,\ i = 1,2 \tag{29}$$

$$r_i = I_i \cdot d_i\,,\ i = 1,2 \tag{30}$$

$$f_i = I_i \cdot (d_i + p_i)\,,\ i = 1,2 \tag{31}$$

$$s_i > d_{i+1}\,,\ i = 2,3 \tag{32}$$

Inequalities (29) and (32) are necessary for ensuring the profitability and competitiveness of stage i, respectively. Expressions (30) and (31) are the usual inventory holding cost assumptions.

We consider a finite-horizon planning problem for the basic model. The horizon is divided into T discrete time periods, and decisions are made at the end of each period. The final customer orders of each period are known in advance. The PLTs and OLTs are constant.

In each period, the order of events and decisions is as follows. For $i = 1, 2$: 1) R_i receives $D_{i,t-1-L_i^d}$ parts from F_{i-1}; 2) P_i starts processing $P_{i,t}$ parts which it takes from R_i. 3) F_i receives $P_{i,t-L_i^p}$ parts from P_i. 4) F_i also receives $S_{i,t}$ parts from S_i. 5) R_i orders $D_{i,t}$ parts from F_{i-1}, and F_{i-1} immediately sends these parts to R_i.

Next, we formulate several variants of the finite-horizon planning problem. The variants differ in terms of the level of collaboration and information sharing between the two stages.

3. Variants of the Planning Problem

A) Centralized Decision Making: The two stages maximize their total profits jointly and simultaneously subject to customer order requirements and other constraints. This problem can be formulated as the following MILP problem:

$$\max \sum_{t=1}^{T} \sum_{i=1}^{2} \left[d_{i+1} D_{i+1,t} - \left(y_i Y_{i,t} + d_i D_{i,t} + x_i X_{i,t} + p_i P_{i,t} + s_i S_{i,t} + r_i R_{i,t} + f_i F_{i,t} \right) \right] \tag{33}$$

Subject to

$$R_{i,t} = R_{i,t-1} + D_{i,t-1-L_i^d} - P_{i,t}, \quad i = 1, 2, \quad t = 1, \ldots, T \tag{34}$$

$$F_{i,t} = F_{i,t-1} + P_{i,t-L_i^p} + S_{i,t} - D_{i+1,t}, \quad i = 1, 2, \quad t = 1, \ldots, T \tag{35}$$

$$P_{i,t} \le P_{i,t}^{\max} \cdot X_{i,t}, \quad i = 1, 2, \quad t = 1, \ldots, T \tag{36}$$

$$D_{i,t} \le M \cdot Y_{i,t}, \quad i = 1, 2, \quad t = 1, \ldots, T \tag{37}$$

$$R_{i,t}, F_{i,t}, P_{i,t}, S_{i,t}, D_{i,t} \ge 0, \quad i = 1, 2, \quad t = 1, \ldots, T \tag{38}$$

$$X_{i,t}, Y_{i,t} \in \{0,1\}, \quad i = 1, 2, \quad t = 1, \ldots, T \tag{39}$$

B) Decentralized Sequential Decision Making: Stage 2: Leader; Stage 1: Follower. The stages maximize their individual profits separately and sequentially, starting with stage 2.

B.1) Local Information: Stage 1 pays the cost of S_1. Stage 2 solves a local-information self-profit maximization problem and decides, among others, the values of $D_{2,t}$. Stage 1 takes these values as given and solves its own local-information self-profit maximization problem.

Stage-2 problem:

$$\max \sum_{t=1}^{T} d_3 D_{3,t} - \left(y_2 Y_{2,t} + d_2 D_{2,t} + x_2 X_{2,t} + p_2 P_{2,t} + s_2 S_{2,t} + r_2 R_{2,t} + f_2 F_{2,t} \right) \tag{40}$$

Subject to (34)-(39) for $i = 2$ only.

Stage 1 problem:

$$\max \sum_{t=1}^{T} d_2 D_{2,t} - \left(y_1 Y_{1,t} + d_1 D_{1,t} + x_1 X_{1,t} + p_1 P_{1,t} + s_1 S_{1,t} + r_1 R_{1,t} + f_1 F_{1,t} \right) \tag{41}$$

Subject to (34)-(39) for $i = 1$ only.

B1.2) Global information: Stage 2 pays the cost of S_1. It solves a global-information self-profit maximization problem and decides, among others, the values of $D_{2,t}$ and $S_{1,t}$. Stage 1 takes these values as given and solves its own local-information self-profit maximization problem.

Stage-2 problem:

$$\max \sum_{t=1}^{T} d_3 D_{3,t} - \left(y_2 Y_{2,t} + d_2 D_{2,t} + (s_1 - d_2) S_{1,t} + x_2 X_{2,t} + p_2 P_{2,t} + s_2 S_{2,t} + r_2 R_{2,t} + f_2 F_{2,t} \right) \tag{42}$$

Subject to (34)-(39).

Stage-1 problem:

$$\max \sum_{t=1}^{T} d_2 (D_{2,t} - S_{1,t}) - \left(y_1 Y_{1,t} + d_1 D_{1,t} + x_1 X_{1,t} + p_1 P_{1,t} + r_1 R_{1,t} + f_1 F_{1,t} \right) \tag{43}$$

Subject to (34)-(39) for $i = 1$ only.

C) Decentralized Sequential Decision Making: Stage 1: Leader; Stage 2: Follower. The stages maximize their individual profits separately and sequentially, starting with stage 1. Stage 1 decides $Y_{2,t}$, $D_{2,t}$, and $\Sigma S_{2,t}$ and pays $y_{2,t} Y_{2,t}$. Stage 2 plans only its production and detailed supply from S_2, given that $\Sigma S_{2,t}$ has been decided by stage 1.

Stage-1 problem:

$$\max \sum_{t=1}^{T} d_2 D_{2,t} - \left(y_1 Y_{1,t} + d_1 D_{1,t} + y_2 Y_{2,t} + x_1 X_{1,t} + p_1 P_{1,t} + s_1 S_{1,t} + r_1 R_{1,t} + f_1 F_{1,t} \right) \tag{44}$$

Subject to (34)-(39) and

$$\sum_{t=1}^{T} D_{2,t} \leq \sum_{t=1}^{T} D_{3,t} - S_{2,t} \tag{45}$$

Stage-2 problem:

$$\max \sum_{t=1}^{T} d_3 D_{3,t} - \left(d_2 D_{2,t} + x_2 X_{2,t} + p_2 P_{2,t} + s_2 S_{2,t} + r_2 R_{2,t} + f_2 F_{2,t} \right) \quad (46)$$

Subject to (34)-(36) and (38)-(39)

D) Decentralized simultaneous Decision Making: The stages maximize their individual profits separately and simultaneously. Stage 2 solves the same problem as in variant B.1 and decides, among others, the values of $D_{2,t}$. Stage 1 solves a local-information self-profit maximization problem and decides the selling price d_2 that allows it to achieve a desired profit margin β. The two problems comprise the components of an equilibrium problem.

Stage-2 problem:

$$\max \sum_{t=1}^{T} d_3 D_{3,t} - \left(y_2 Y_{2,t} + d_2 D_{2,t} + x_2 X_{2,t} + p_2 P_{2,t} + s_2 S_{2,t} + r_2 R_{2,t} + f_2 F_{2,t} \right) \quad (47)$$

Subject to (34)-(39) for $i = 2$ only

Stage-1 problem:

$$\min d_2 \quad (48)$$

Subject to (34)-(39) for $i = 1$ only, and

$$\sum_{t=1}^{T} d_2 D_{2,t} \geq (1+\beta)\left(y_1 Y_{1,t} + d_1 D_{1,t} + x_1 X_{1,t} + p_1 P_{1,t} + s_1 S_{1,t} + r_1 R_{1,t} + f_1 F_{1,t} \right) \quad (49)$$

$$d_2 \geq 0 \quad (50)$$

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