Coordination in Production Networks

PhD Thesis Booklet

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Budapest, Hungary, 2008

1 Introduction

In the past decades the circumstances of industrial production have dramatically changed. The increasing customer expectations require ever shorter delivery times, customised products and extremely high service levels. Besides the traditional problem of the uncertain demand, recent paradigms—such as mass customisation, decreasing product life-cycles, delayed differentiation, outsourcing—, and the increasing incidence of networked production systems necessitate novel models and solutions for achieving more efficient production and logistic processes.

One of the most important issues of production is still the proper management of inventories [Chik07]. Although several lot-sizing models address the different variants of the problem that are classic nowadays, they have some assumptions that usually do not hold any more. Two of such models are directly related to my dissertation: the one-period *newsvendor* and the multi-period *Wagner – Whitin* (see e.g., [HS96]). The former one is the most often applied model for determining the optimal production and storage quantity of deteriorating and short life-cycle products, while the latter offers an effective dynamic programming algorithm for solving the deterministic multi-period problems.

However, in order to improve the operational efficiency, it is not sufficient to focus on an individual enterprise, but the whole production process involving several companies should be taken into consideration. In this case, the decentralisation of the decisions leads to suboptimal overall system performance due to the phenomenon of *double marginalisation* [Tiro88], which can be interpreted as the symptom of the *prisoners' dilemma* in supply chains. Currently, the most promising approach taken to this problem involves tighter *cooperation* along the supply chains.

The practically widespread business model of the *vendor managed inventory* (VMI) is based on this idea and aims at concentrating the decision—and the responsibility, too—to one partner in a supply relation [SKS00]. However, these types of contracts are nowadays forced by the customer representing more market power, and the suppliers must act upon the customer's will. The theoretical analysis of these so-called *channel coordination* problems followed the practice only in the recent years [Cach03, LW07, SAG06].

The goal of my research was to develop models, algorithms and protocols for improving the efficiency in supply chains, with a special focus on practical problems. I intended to develop precise mathematical models and information technology infrastructure considering conditions in real production networks, together with such efficient algorithms that support decision making and help estimating the possible consequences of the decisions. I considered the criteria of realisability and applicability all along my work, but at the same time I did not give up the exact and solid mathematical principles.

During my research, I studied the international scientific literature, discussed with industrial experts and analysed large volume of industrial data in order to become familiar with the existing problems and solutions. After this phase, I formalised the models and tried several approaches to find acceptable trade-offs between the accurate representation of the reality and solution efficiency. During the development, I used professional tools both for software design and implementation.

A few times, I had to step back in this sequential process and review the previous decisions based on the feedbacks and the obtained results. Since every model is just an abstraction of the reality, furthermore, the necessary parameters are usually only estimations, I performed sensitivity analysis of the models in order to study their behaviour in uncertain environments. The main, analytically proven properties of the models have also been demonstrated through large-scale simulation experiments run both on artificial and industrial datasets.

2 Main Contributions

My studies centred around two interconnected research fields of centralised and decentralised coordination. I formulated my results in four theses that I present in Chapters 3 and 4 in my PhD dissertation.

Thesis 1: Newsvendor Model with Emergency Production

I have formulated a novel variant of the single period newsvendor model assuming that shortage must be avoided even with an additional production. In this case the expected total cost is:

$$c_s + c_p\mathbb{E}[\xi] + c_p\mathbb{E}[\max(q-\xi,0)] + c_s\mathbb{E}[\delta(\xi-q)], \tag{1}$$

where c_s denotes the setup cost, c_p is the production cost per unit, ξ is the realised demand (a stochastic variable), q is the production quantity (decision variable) and δ is an indicator function: it assumes 1 if its argument is positive and 0 otherwise.

Minimising this function is not as easy as in the standard model, therefore I suggested using a special demand distribution, the *logistic distribution*, and for this case I proved that if an optimal q^* exists, it is uniquely given by the following formula:

$$q^* = m - b \ln \left(\frac{bc_p}{c_s - bc_p} \right), \tag{2}$$

where m and b are parameters of the logistic distribution: the expected value and a constant times the standard deviation, respectively.

I proposed this model for the end of the product life-cycle in order to guarantee high service level towards the customer. This thesis is presented in Section 3.1 of my PhD dissertation and the related results were published in [5, 6, 8].

Thesis 2: Dynamic Lot-Sizing in Case of Uncertain Product Life-Cycle

I modified the standard model of the uncapacitated single item lot-sizing problem by considering uncertain length of the product life-cycle, which may cause remaining unsold, obsolete inventories. The resulting stochastic program is the following:

$$\sum_{i=1}^{n} \left(\Pr(\eta > i) \left(c_s \delta(x_i) + h \left(I_{i-1} - \frac{F_i}{2} \right) \right) + \Pr(\eta = i) c_p I_{i-1} \right) \to \min \tag{3}$$

s. t.

$$I_0 = x_0 \tag{4}$$

$$I_i = I_{i-1} - F_i + x_i \quad (i \in \{1, \ldots, n\}) \tag{5}$$

$$I_{i-1} \geq F_i \quad (i \in \{1, \ldots, n\}) \tag{6}$$

$$x_i \geq 0 \quad (i \in \{0, \ldots, n\}), \tag{7}$$

where c_s denotes the setup cost, c_p is the cost of obsolete inventory per unit, h is the inventory holding cost per unit, F_i is the forecasted demand for period i, I_i is the inventory level at the end of period i, x_i is the production quantity in period i, η is the remaining product life, n is the length of the horizon and δ is an indicator function: it assumes 1 if its argument is positive and 0 otherwise.

I have modified the original dynamic programming solution given by Wagner and Whitin for this problem, which resulted in an $\mathcal{O}(n^3)$ running time algorithm. I suggested using the model in practical situations on a rolling horizon basis.

This thesis is presented in Section 3.2 of my PhD dissertation and the related results were published in [1, 2, 6, 7].

Thesis 3: Coordinating the Newsvendor Model

I have modelled the one-period lot-sizing task as a decentralised newsvendor problem, where the supplier has no information about the parameters of the demand distribution. I have developed a supply protocol for the VMI case, where the customer should share the knowledge about the parameters and compensate the supplier for the imprecise forecast subsequently.

I proposed the following payment function:

$$c_0\xi + \frac{c_1}{b'}(m' - \xi)^2 + c_1\frac{\pi^2}{3}b', \tag{8}$$

where c_0 and c_1 are fixed price parameters, m' and b' are the parameters of the logistic distribution shared by the customer and ξ is the realised demand. I proved that the expected payment is at minimum if and only if the customer shares as accurate demand forecast as possible. Accordingly, the presented protocol guarantees the optimal lot-sizing decision in the decentralised newsvendor model.

This thesis is presented in Section 4.1 of my PhD dissertation and it was published in [3, 9].

Thesis 4: Coordinating the Multi-Period Model

In case of the multi-period problem, I considered the practically widespread *rolling horizon* planning approach and proposed also a compensation-based protocol for enforcing truthful information sharing. Besides the standard measurement of the forecast imprecision, I developed a novel performance index and suggested a rule for choosing the right measurement depending on the production characteristics. For both cases, I have developed compensation schemes that make the customer interested in truthful information sharing, furthermore, I extended the solution also to the uncertain life-cycle case studied in Thesis 2. All in all, I proved that given rational partners, the proposed compensation schemes result in optimal lot-sizing decisions in the decentralised case.

This thesis is presented in Section 4.2 of my PhD dissertation and it was published in [4, 10].

Other Results

My dissertation contains some further results not formulated into theses, either because they provide only minor contributions to my research or they are not yet published.

In Section 3.3.1, I propose a simple decision rule for selecting the appropriate model from the two approaches presented in Theses 1 and 2 as well as the standard Wagner – Whitin model. This approach has been taken in a pilot lot-sizing application and a simulation environment, in addition, it was published in [6, 8].

In Section 4.3, I introduce a game theoretic generalisation of the models presented in Theses 3 and 4. This approach is also based on the fundamental idea that the VMI is a *service*, and it creates a framework for studying and determining its price.

Finally, in Section 5.2.2, I study the forecast generation in simulation systems, namely the *martingale model of forecast evolution*. I conclude that some aspects of the forecast evolution—such as the short product life-cycles—cannot be expressed in the standard model and I present a possible extension that I used in my simulation system.

3 Application of the Results

Each problem addressed in my dissertation is directly relevant at the industrial partners of the VITAL project (NKFP grant No. 2/010/2004) aimed at realising *real-time, cooperative enterprises* [18, 20]. The studied factories formed a complete *focal* network: a central assembly plant producing low-tech consumer goods served by several external and internal material suppliers. My results presented in the dissertation have been applied in a pilot lot-sizing application, in the development of an information sharing system and in several technical reports supporting business process re-engineering.

In Chapter 5 of my dissertation I briefly overview two implemented systems related to my research. The first one is a complex information sharing and monitoring platform deployed at the focal manufacturer participating in the research project [15, 16, 17]. The system contains different performance measurements including the forecast quality measurements of Thesis 4. The other application is a pilot simulation environment for analysing the behaviour of a VMI supply channel. The system applies a combination of the two lot-sizing models presented in Theses 1 and 2, and evaluates the performance and the payment considering the rolling horizon coordination contract of Thesis 4.

As it turned out, the experiences and the concepts of my work can be used in other industrial sectors, too. My research is continuing with a network situated in the European automotive industry (AC/DC: Automotive Chassis Development for 5-Days-Cars – EU FP6 IST 031520) which aims at shifting toward a *customise-to-order* approach. Although it basically differs from the consumer goods industry, the fundamental goals and problems are surprisingly similar [17]. Furthermore, such circumstances are being reported also from other industrial fields—like pharmaceutical and high-tech—including increased variety of products, strict standards, high quality requirements and short product life-cycles.

Publications

Publications Related to the Four Theses

Journal Papers in Foreign Language

[1] Egri P., Váncza J.: Cooperative Planning by Coordinating the Supply Channel. *Production Systems and Information Engineering*, 4, pp. 3–19, 2006.

[2] Váncza J., Egri P.: Coordinating Supply Networks in Customized Mass Production – A Contract-Based Approach. *CIRP Annals – Manufacturing Technology*, 55(1), pp. 489–492, 2006. (IF **0.989**)

[3] Egri P., Váncza J.: Cooperative Production Networks – Multiagent Modeling and Planning. *Acta Cybernetica*, 18(2), pp. 223–238, 2007.

[4] Váncza J., Egri P., Monostori L.: A Coordination Mechanism for Rolling Horizon Planning in Supply Networks. *CIRP Annals – Manufacturing Technology*, 57(1), pp. 455–458, 2008. (IF **0.779**)

[5] Egri P., Váncza J.: Channel Coordination with the Newsvendor Model Using Asymmetric Information. *International Journal of Production Economics*, submitted, 2007.

[6] Egri P., Váncza J.: An Inventory Planning Portfolio for Products with Uncertain Life-Cycle. *International Journal of Production Economics*, submitted, 2008.

Conference Papers in Foreign Language

[7] Egri P., Váncza J.: A Logistics Framework for Coordinating Supply Chains on Unstable Markets. *Proc. of* 3^{rd} *Conference on Digital Enterprise Technology*, Springer, pp. 59–66, 2006.

[8] Egri P., Váncza J.: Incentives for Cooperative Planning in Focal Supply Networks. *The* 6^{th} *International Workshop on Emergent Synthesis*, pp. 17–24, 2006.

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[10] Egri P., Csáji B. Cs., Kemény Zs., Monostori L., Váncza J.: Komplexität der Bedarfsprognosen und ihrer Wirkungen in kooperativen Logistiknetzwerken. *Proc. of 10. Paderborner Frühjahrstagung*, pp. 455–469, 2008.

Other Publications

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[11] Egri P., Kovács A., Márkus A., Váncza J.: Project-Oriented Approach to Production Planning and Scheduling in Make-To-Order Manufacturing. *Production Systems and Information Engineering*, 2, pp. 23–36, 2004.

Conference Papers in Foreign Language

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Summary

Articles	18	Impact factor	2.472
With SCI	4	Independent citations	9

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