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Coordinating decentralized linear programs by exchange of primal information

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ABSTRACT

We present a scheme for coordinating decentralized parties that share central resources but hold private information about their decision problems modeled as linear programs. This setting is of particular importance for supply chains, in which the plans of independent, often legally separated, parties have to be synchronized. The scheme is based on an iterative generation and exchange of proposals regarding the parties' input to or withdrawal from the central resources (i.e. primal information). We prove that the system-wide optimum can be identified in a finite number of steps. A simple numerical example illustrates the information exchange and the models involved when coordinating a two-stage supply chain.

1. Introduction

Coordination of decentralized systems involves a series of challenges. One is that decentralized parties may either *prefer* to keep some data private because it constitutes a strategic advantage for bargaining or may even be *obliged* to keep their data private due to antitrust law. The latter especially applies in a horizontal collaboration of companies. In these cases the identification of a system-wide optimal solution may be a very hard task.

An important example of a decentralized system is a supply chain with legally separated parties. One would expect that today's commercial information and planning systems will address the above-mentioned challenge. However, Enterprise Resource Planning (ERP) systems can create an overall transparency of shared data but do not provide functionalities for planning when some data have to be kept private. Even Advanced Planning Systems (APS), which have been created especially for decision support in supply chain planning, assume a central planner at the top of a planning hierarchy and thus access to the data of all supply chain partners involved – at least in aggregated form. The reason is that APS are based on the concept of hierarchical planning. Hence, a collaborative synchronization of plans over organizational boundaries in light of information asymmetries is currently neither covered by ERP systems nor by APS.

Another approach is to make use of a trusted third party, called mediator, which is supplied with all the data necessary for generating a system-wide optimum by solving a central model. What remains is a fair split of the gains of the central solution among all parties involved (e.g., Frisk, Göthe-Lundgren, Jörnsten, & Rönnqvist, 2010).

In case no central planning entity is accepted or available, a decentralized coordination scheme like the Dantzig–Wolfe decomposition (Dantzig & Wolfe, 1960) has to be looked for. Note that the master model of the Dantzig–Wolfe decomposition may be combined with one party's local planning domain (see Sweeney & Murphy, 1979). Then no third party is needed. However, the exchange of dual prices for linking central resources in Dantzig–Wolfe decomposition may turn out to be an obstacle: First, not all managers may have an understanding of what dual prices signify and might be reluctant to reveal these data. Second, the exchange of dual prices may be undesirable because they allow the inference of capacity utilizations which are often regarded as being sensitive. A reason is that once underutilized capacities become known to the buyer she might exploit this information in future price negotiations with the supplier. Consequently, this information should be kept confidential. Third, in the context of operational supply chain planning prices for input materials, which represent a "central" resource here, are often fixed beforehand and are not subject to negotiations at this planning level.

Thus, we have developed a new *coordination scheme* which supports the identification of a system-wide optimal solution in such decentralized settings, where parties' decentralized decision problems can be modeled as linear programs (LP). LP are frequently applied for modeling supply chain decisions — both in theory and practice. As an example we refer to aggregate planning, where LP are used to trade off different cost factors such as inventory holding and backorder costs (see, e.g., Munhoz & Morabito, 2014).

The methodology of our coordination scheme is novel. We assume that parties play a specific role, namely that of the informed party

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(IP) or one of the reporting parties (RP). In the course of the scheme all parties exchange proposals as candidates for a coordinated solution and the RP communicate the corresponding profit changes compared to a given default solution to the IP. The proposals and profit changes are the primal output of mathematical programming (MP) models. The scheme is able to identify the optimum in a finite number of steps. Subsequently, the IP determines for each RP whether to keep the default central resource allocation or to implement the best proposal generated in the course of the scheme.

To illustrate the coordination by primal information we will outline how the scheme can be used in inter-organizational supply chains. Consider a two-tier supply chain. Let the upstream party (supplier) produce some products on a potential bottleneck resource and sell them to the downstream party (buyer). Let the availability of these products be a limiting factor in the sales and operations planning (S&OP) of the buyer. Thus, the buyer cannot fulfill customer demand without purchasing raw materials from the suppliers. This often occurs when the costs for capacity expansion are prohibitively high such as in process industries. To establish a coordinated solution in this scenario, the following research question has to be answered: How can we generate an optimal plan for this supply chain in a decentralized manner? Or taking the buyer's perspective: how can she determine her supply chain wide optimal sales and purchase quantities without solving the centralized problem?

The most natural approach is that both parties exchange different proposals for the purchase quantities and jointly choose the best. This is a rather common approach, and underlies industry best practices like CPFR (Collaborative Planning, Forecasting, and Replenishment, see VICS, 2004), too. Especially in step 6 of the CPFR concept, named "Create order forecast", parties are expected to balance the sales forecast with available capacities. However, instead of finding a balance for each party locally, our scheme could be employed advantageously to find a system-wide optimal balance iteratively. Moreover, our approach is related to APS software tools that often provide interfaces where a buyer and a supplier can exchange their preferred purchase plans iteratively (see, e.g., Knolmayer, Mertens, Zeier, & Dickersbach, 2009), stating the timing and quantities of a specific item. The iterative exchange of purchase plans (or more generally: proposals) is also the base of our scheme. However, our scheme also *generates* those proposals which finally will lead to an optimal system-wide solution. In our opinion it is a central asset that our mechanism is so closely aligned to common business practice. To emphasize the factor that makes the difference here, we refer to our information exchange as "primal" — i.e., direct solutions of the optimization problems like quantities — opposed to "dual" information like shadow prices.

Potential applications for our approach are given in many industries. An impressive example is the case study of Frisk et al. (2010) regarding collaboration of transport planning of logging trucks for eight large forest companies in Sweden. They report that cost savings of 8.3 percent can be obtained when solving a central linear transportation model compared to the sum of the optimal solutions of each company. Furthermore, comparing potential savings of the coordinated solution over the cost of the actual transportation yields a saving of 14.2 percent. Note that transportation costs account for about one third of the total raw material cost in the forest industry in Sweden. Further cases of collaborative planning can be found for instance in the semiconductor industry (e.g., Shirodkar & Kempf, 2006) and process industries (e.g., Berning, Brandenburg, Gürsoy, Mehta, & Tölle, 2002).

The remainder of this paper is organized as follows: Section 2 briefly reviews the related literature. Section 3 describes the setting including a small numerical example from S&OP. In Section 4, we outline the scheme, show the solution of the numerical example, and propose a solution procedure for one of the models which has a bilinear objective function. Section 5 concludes the paper. All proofs are given in Appendix B.

2. Literature review

Coordination mechanisms in the form of contracts have been dealt with extensively in the literature (see Cachon (2003) and Tsay, Nahmias, and Agrawal (1998) for detailed reviews). In the majority of papers reviewed symmetric information is assumed while in Burnetas, Gilbert, and Smith (2007), Cachon and Lariviere (2001), Cachon and Zhang (2006), Corbett and de Groote (2000), Corbett, Zhou, and Tang (2004), Lutze and Özer (2008), Özer and Wei (2006), Schenk-Mathes (1995), Shang, Song, and Zipkin (2009), and Schmidt, Gaur, Lai, and Raman (2015) asymmetric information is addressed. An exception is the paper of Shang et al. (2009), who assume the existence of a third party with complete information about the decentralized problems. These papers rely on the adverse selection framework. This framework is characterized by a principal, who cannot identify his profit-maximizing solution due to private information such as hidden characteristics of the agent(s). In contrast, we consider a more symmetric setting here: All parties have some private data and decision authority preventing the others from implementing their individual profit-maximizing solutions. Furthermore, the focus of the underlying decision problems differs from ours: While the models of the above papers address uncertainties, they do not include general linear constraints like those used in deterministic MP.

On the other hand, most papers dealing with the coordination via MP models apply classical decomposition techniques (see Dantzig & Wolfe, 1960 and Benders, 1962) or their modifications. This has a long tradition, beginning with Dantzig and Wolfe when they interpreted their decomposition procedure as decentralized decision-making. There is a large number of papers which rely on the original algorithm of Dantzig and Wolfe or subgradient optimization and adapt it to specific application settings (see, e.g., Kutanoglu & Wu, 1999 and Walther, Schmid, & Spengler, 2008). Arikapuram and Veeramani (2004) used the L-shaped method as an alternative approach.

In general, the exchange of dual information, which is essential for classical decomposition, has several disadvantages compared to primal information. This has already been discussed in the introduction. Hence, we believe that the exchange of primal information has a better chance of acceptance in practice because decision makers clearly understand which piece of information they disclose.

The coordination of MP problems without the exchange of dual information has been addressed by only a few authors (e.g., Schneeweiss & Zimmer 2004; Fink 2006; Dudek & Stadtler 2005, 2007 and Kovács, Egri, Kis, & Váncza 2013). Like our approach, the papers of Dudek and Stadtler propose coordination schemes that rely on an iterative exchange of (supply) proposals. However, these schemes, as well as that of Kovács et al. (2013), are limited to the coordination of lot-sizing models. In contrast, our scheme is more general and can be applied to many different settings where the decision problems can be modeled as LP.

3. Coordination of S&OP in supply chains

3.1. Model

In this section we will describe the coordination of Sales and Operations Planning (S&OP) in supply chains of legally separated parties. It is widely recognized that S&OP is highly relevant in practice (e.g., Chopra & Meindl, 2007). However, it is usually stated as a centralized decision problem. Subsequently, we will introduce the S&OP for a decentralized setting where existing information asymmetry among parties is kept as far as possible.

A main task of S&OP is the identification of the profit-maximizing sales, production and inventory quantities in a mid-term planning level usually divided into monthly time buckets. Synchronizing these mid-term plans has a series of benefits. First of all, this is the