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Coordination of perishable crop production using auction mechanisms

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ABSTRACT

We present a tactical level planning tool to address the issue of coordinating production of perishable specialty crops under decentralized control and incomplete information. The objective of this research is to address an emerging problem seen in the business model of agricultural cooperatives. These vertically expanded farmer associations market their products jointly. However, within the cooperatives farmers remain competitors seeking their own best interest, simultaneously seeking contracts for the most profitable crops in the most desirable part of the season; this behavior can work to the detriment of the group. The model developed considers the problem of asymmetric information and internal competition within the cooperative, as well as traditional factors relevant to agricultural planning. Thereafter, an auction based coordination mechanism is formulated, which leads production decisions toward a coordinated outcome despite each individual acting independently and on his/her best interest. The mechanism is shown to approximate optimal production targets through focused information discovery and a well-structured contract allocation methodology. The results presented show the viability of implementing such planning scheme in practice as well as the optimality gap under a variety of settings.

1. Introduction

Supply chains of fresh fruits and vegetables have been under rapid transformations in the last two decades, leaving a highly consolidated industry with few retailers of strong bargaining power. This has placed a significant downward pressure in market prices paid to producers whose level of consolidation remains low (Cook, 2001). These new conditions translate into high risk and thin margins for farmers (Cook, 2001; Jang and Klein, 2011; Smalley, 2013; Welsh, 1997). As a result, farmers are responding by expanding their operations vertically, either individually or as part of growers associations/cooperatives to capture more attractive profit margins (Perosio et al., 2001).

For the case of agricultural cooperatives and growers associations, the integration usually takes form through increased horizontal collaboration accompanied with vertical expansion of the distribution scope (Matson et al., 2010). This type of supply chain integration offers multiple benefits to associated farmers, including added services, economies of scale and particularly higher bargaining power (Barham and Tropp, 2012). However, these associations need to embark in two aspects of production planning: **External**, in which they make projections for the production required by markets (demand); and **Internal**, in which they allocate the contracted demand to individual members (the supply). Unfortunately, these associations very often lack the necessary tools to internally allocate production contracts to their members in a fair and transparent manner (Karina et al., 2012). Compounding the production allocation problem is that, in practice, farmers seek to optimize their own position, very often not completely revealing internal information such as their cost structures and expected yields (Cook, 2011), which works to the detriment of system-wide profits. As a result, coordination problems are a real difficulty found by these emerging cooperative business models. In particular, one relevant coordination problem is that of determining a tactical plan and a production/marketing schedule for the upcoming season, which must be finalized before planting takes place. This is done to ensure that the aggregate harvest of all farmers is aligned with the objectives of the cooperative.

In this research paper we address the planning difficulties that arise in the context of horizontal coordination for a cooperative that has expanded vertically and seeks to develop a tactical plan for the upcoming season. We bring forward the use of multi-stage auctions that rely on price changes for crops to indirectly influence the actions of member farmers. This auction is shown to be implementable through a mathematical model and decision support tool relevant to the production planning problem and leads to coordinated outcomes for the cooperative as a whole.

In the remainder of the document we will provide some background on supply chain coordination mechanisms and supply

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chain problems in agriculture (Section 2). Thereafter, in Section 3 we provide a brief overview of the relevant production and consolidation decisions, and of the structure and assumptions for the envisioned coordination mechanism. Section 4 formulates the coordination problem in its centralized form, assuming a single entity has control over all decisions and information; thereafter the problem is formulated as a decentralized problem solved through an auction mechanism. Section 5 shows some computational results formulated as a case study. Section 6 provides some concluding remarks and a discussion of the results.

2. Literature review

Supply chain management and coordination are complex issues which have prompted a great amount or research in recent years. Through supply chain management we are able to better understand and manage the flow of physical goods and information throughout an enterprise. This is also the case in the management of agricultural supply chains (ASCs); however, the complexity of planning production and distribution in this industry is further compounded by factors such as limited shelf life of products, their variable yields, volatile market prices (Makeham and Malcolm, 1993) and the very long lead times from planting to harvest time (Lowe and Preckel, 2004). Furthermore, due to the inherent perishability of fresh fruits and vegetables, factors such as food quality, safety and weather related variability further compound the complexity of the planning problem (Salin, 1998).

In the context of managing an ASC, we find that optimizing the efficiency of an entire enterprise is fundamentally different from optimizing each individual component (Higgins et al., 2009). Yet, we find that current formulations for agricultural supply chains fail to capture the added complexity of integrated models including the objectives, strategic behaviors and the information available to each component of the chain (Higgins et al., 2009; Lucas and Chhajed, 2004). In particular, we find that little research is done in the context of coordination mechanisms for agricultural supply chains.

In this section we will take an extended focus on supply chain management and its application to agriculture. Moreover, we will analyze the implementation of specialized coordination mechanisms used in other contexts to show their viability and potential when applied to agricultural planning.

2.1. Supply chain coordination literature

Collaboration between supply chains has been shown to provide competitive advantages to all involved parties both empirically and theoretically. However, despite the intent to collaborate, coordination can sometimes prove to be elusive and specific measures must be taken in order to ensure that efforts to collaborate lead to mutually beneficial outcomes.

We say that a supply chain is coordinated if a set rules, when implemented, result in a tangible positive change as compared to a baseline measure. To do this, intuitive solutions such as information sharing can be used (Lee et al., 1997). Unfortunately, although information sharing may increase transparency, it may not necessarily align the objectives of the supply chain nor guarantee that the information shared is accurate (Cachon and Netessine, 2004). In this situation, more sophisticated approaches to coordinate supply chains such as revenue sharing, advanced commitments and buyback contracts may be needed (Simchi-Levi et al., 2003).

In order to align the incentives and actions of the supply chain we resort to specialized coordination mechanisms, which we will refer to as follows:

> *A coordination mechanism is a [set of rules] for which the implementation of optimal strategies by decentralized, self-interested parties may lead to an improved outcome and neither violates individual rationality nor budget balance for the participating parties* (Albrecht, 2010).

In the context of the previous definition, we find two concepts*: Individual rationality (IR),* defined as allowing agents to act freely and without obligation to participate; *budget balance (BB),* meaning that the mechanism requires no external subsidies to be implemented; to this, we add *incentive compatibility (IC)* which is the property of eliciting truthful information from participants and *ex-post efficiency,* or ensuring that the mechanism culminates on all goods being allocated to the party which values them most (Myerson, 1981). In this paper we will refer to optimal or efficient allocations interchangeably to refer to an outcome in which all contracts are allocated in a way such that no agent can be made better off without reducing the wellbeing of the rest and where system-wide profits are maximized subject to the restrictions of the enterprise.

Unfortunately, implementing a mechanism is not always straightforward. Many times, the properties of IR, BB, IC and ex-post efficiency are at odds with each other and may not all be attained simultaneously. For instance, it has been shown that for bilateral trade, no mechanism can guarantee ex-post efficiency without external subsidies (Myerson and Satterthwaite, 1983). Most mechanisms involve complex multi-agent systems which require extensive game-theoretical analysis and may not be amenable to exact solutions nor guarantee a solution which cannot be improved (Tesauro and Bredin, 2002).

2.1.1. Mechanisms used in supply chain management

Despite the challenges that exist for implementing mechanisms for coordination in a supply chain, researchers have not shied away from formulating models that address the coordination problem through mechanism design. Moreover, in many industrial applications a family of mechanisms which have grown in popularity due to their simplicity and theoretical backing in support of optimality are auctions. These mechanisms work well in a context where private information must be extracted from agents, pricing for goods must be performed and an optimal allocation is desired.

Research on auctions in supply chain coordination can be found on a variety of contexts, ranging from auctioning a single item (Chen, 2007; Chen et al., 2005), to auctioning multiple products when suppliers have a limited capacity creating a high interdependence between production/allocation decisions (Gallien and Wein, 2005; Mishra and Veeramani, 2007). Moreover, even when coordination problems exist on complex settings where decisions are highly multidimensional, auctions can be implemented successfully; such problems include situations where the simultaneous allocation of goods must be done across multiple periods, for multiple products, and may be subject to capacity restrictions by suppliers. For these problems of a large scope, we find a useful relationship between distributed-decision-making, mathematical modeling and decomposition methods. Specifically, an auction can be implemented by formulating an optimization problem which is subsequently solved through dual decomposition. Here, the structure of dual decomposition lends itself to interpretation as an auction for which prices are announced by a centralized party and where bidders respond with quantities (Albrecht, 2010; Vohra, 2011). Examples of research which use this decomposition approach are numerous and include Arikapuram and Veeramani (2004), Ertogral and Wu (2000) and Kutanoglu and Wu (1999).

Clearly, auctions are mechanisms of great practical importance in the context of supply chain coordination, and dual decomposition