



Real-time optimization and control mechanisms for collaborative demand and capacity sharing

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ABSTRACT

This work presents a new mechanism for real-time resource allocation, order administration, and process monitoring in Collaborative Networked Enterprises (CNE). The motivation is to mitigate the uncertainties and risks caused by arbitrary nature of customer orders, dynamic changes in demand patterns, and unforeseen supply disruptions. Enterprise collaboration is enabled by Demand and Capacity Sharing (DCS) among enterprises considering four decision criteria: (a) Total cost; (b) Demand fulfillment; (c) Resource utilization; and (d) CNE stability. A Task Administration Protocol (TAP) is designed for priority-based allocation/re-allocation of resources and real-time monitoring of DCS processes. The TAP is enhanced with a Predictive Best Matching Protocol (PBMP), which optimizes allocation decisions in real-time while taking into account potential future events. The new Real-Time Optimization (RTO) mechanism is proven in experiments to be an advantageous solution for mitigating undesirable impacts of uncertainty and dynamicity on the CNE performance with respect to the four undertaken decision criteria.

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1. Introduction

Globalized economies, dynamic, competitive, volatile, and complex business environments are the main drivers of the transformation from traditional *individual* and *self-reliant* enterprises to *Collaborative Networked Enterprises* (CNE). A CNE refers to a collaborative network of distributed, interconnected, and self-organizing small-to-medium-sized enterprises, which collaborate through sharing *information*, *resources*, and *responsibilities* to create value and achieve individual and common benefits (Nof, 2003). The performance effectiveness of CNE depends on the design of collaborative control mechanisms supported by the principles of CCT, the Collaborative Control Theory (Nof, 2007; Nof et al., 2015). The transition from traditional *chains* to emerging *networks* of enterprises, *i.e.*, multiple “same-echelon” enterprises, has enabled *lateral collaboration* strategies to minimize total costs and enhance service level, resource utilization, and stability of CNE. Lateral collaboration allows enterprises with extra capacity, known as Capacity-Sharing Enterprises (CSE), to help enterprises with capacity shortage, known as Demand-Sharing Enterprises (DSE), fulfill higher portions of their demand. The notion of enterprise collaboration is applicable to any CNE where enterprises process

certain *resources* supplied from upstream in order to provide certain *products/services* to downstream, *i.e.*, any class of production, manufacturing, supply, and service enterprises.

Enterprise collaboration has been investigated from various perspectives (Table 1). The focus has been on the improvement of service level (Kutanoglu and Mahajan, 2009; Olsson, 2009; Yoon and Nof, 2010, 2011; Paterson et al., 2011, 2012; Axsäter et al., 2013), and stock (Kutanoglu and Mahajan, 2009; Torabi and Moghaddam, 2012) and service (Olsson, 2009; Axsäter et al., 2013) costs, safety stock level and stockout probability/costs (Paterson et al., 2011, 2012). Besides, lateral collaboration enhances overall stability of CNE and guarantees stability of DSEs, in case the entire CNE is stable (Moghaddam and Nof, 2014). Lateral collaboration strategies, however, may impose significant costs to CNE, associated with negotiations and transactions, along with lateral transshipment of stocks (Burton and Banerjee, 2005). It is proven that this phenomenon is intensified by random or *blind* matching of enterprises in subsequent echelons (*e.g.*, retailer-customer), and can be resolved by *dynamic best matching* of enterprises considering *capacity-demand gaps* (Moghaddam and Nof, 2013, 2014). Real-time execution and control aspects of lateral collaboration decisions, however, have not received enough attention in literature (see Table 1). In addition, the existing control studies lack the aforementioned dynamic best matching functionalities (*e.g.*, Yoon and Nof, 2010, 2011; Seok and Nof, 2014).

The main goal of this study is to develop mechanisms to (a) bridge the existing gap between planning and detailed process

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Table 1
Recent studies on enterprise collaboration.

Study	Criteria	Enterprise matching	Solution scope
Burton and Banerjee (2005)	Lateral transshipment cost	Fixed	Planning
Lee et al. (2007)	Response time to demand variations; Penalty costs	Fixed	Planning
Kutanoglu and Mahajan (2009)	Overall service level; Stock costs	Fixed	Planning
Olsson (2009)	Service level; System cost	Fixed	Planning
Yoon and Nof (2010)	Global benefit of CNE; Demand fulfillment rate	Fixed	Control
Yoon and Nof (2011)	Total profit; Demand fulfillment rate; Impacts of low-performance parties	Fixed	Control
Tiacci and Saetta (2011)	Mean supply delay	Fixed	Planning
Paterson et al. (2011, 2012)	Stockout probability; Safety stock; Service level	Fixed	Planning
Torabi and Moghaddam (2012)	Total profit; Lead-time; Inventories and backorders/stockouts	Random	Planning
Axsäter et al. (2013)	System cost; Service level	Fixed	Planning
Seok and Nof (2014)	Lost sales; Capacity utilization; Long-term balance of benefits to all parties	Fixed	Control
Moghaddam and Nof (2013, 2014)	Total cost; Demand fulfillment; Resource utilization; Stability	Dynamic best matching	Planning

execution, and (b) optimize collaboration decisions through dynamic best matching among collaborative enterprises. Planning determines the sequences of operations for a finite horizon, based on the current knowledge on the future system's status, where uncertainties can be incorporated in the decisions via probability distributions (e.g., Lee et al., 2007; Paterson et al., 2012) or fuzzy sets (e.g., Torabi and Moghaddam, 2012). Major challenges of such approaches, however, are low flexibility, precision, and viability of decisions facing abrupt changes/disruptions and dynamic complexity of interactions among CNE participants. Examples include conflicts among collaborating enterprises (Chen and Nof, 2010), willingness or incentives to collaborate, e.g., full/partial (Yoon and Nof, 2010), association/dissociation decisions (Yoon and Nof, 2011), and dynamic enterprise coalition formations (Seok and Nof, 2014). In addition, collaboration without considering dynamic variations in capacity-demand gaps is likely to diminish the overall CNE profit and service level (Moghaddam and Nof, 2014).

In this work, a new control mechanism is developed to (a) rationalize, coordinate, and harmonize distributed operations, and (b) optimize collaboration decisions in real-time. The first objective is addressed by developing a Task Administration Protocol (TAP) for effective control of Demand and Capacity Sharing (DCS) operations. The TAP (Ko and Nof, 2012) is composed of three sub-protocols for priority-based task initialization, resource-aware task allocation, and task monitoring re-allocation. In this context, a task refers to an order. A Predictive Best Matching Protocol (PBMP) is also developed to tackle the second objective, i.e., Real-Time Optimization (RTO) of DCS decisions. The PBMP is responsible for dynamic matching of orders to resources in real-time. Inspired by the notion of Model Predictive Control (MPC), the PBMP matches entities (e.g., proposals, enterprises) in the current timeslot, while taking into account system characteristics in the *near future* timeslots. The RTO is then concerned with the total costs of collaboration, i.e., fixed costs of negotiation, information sharing, etc., along with variable costs of transshipment, and service level, i.e., demand fulfillment rate.

The proposed mechanism requires cyber-supported collaboration infrastructures for effective information sharing and enhanced connectivity among distributed participants. Advances in collaborative e-Work over the last two decades have provided effective computer-supported and communication-enabled solutions for design, engineering, and control of CNE (Nof et al., 2015). Development of the TAP and PBMP then relies highly on agent-based technologies in order to proactively identify resources, provide real-time value-added information, and reduce potential conflicts and errors (Klusck, 2001), as well as workflow technologies to enable scalability, availability, and reliability of processes. It is shown that deployment of agents, coordination protocols, and workflows—as the first theoretical foundation of collaborative e-Work (Nof, 2007)—coupled with planning models provide a

powerful *design-control loop* that enhances the quality of enterprise collaboration decisions. The PBMP is indeed an agent-based optimization technique based on *mediator architecture* where a mediator agent monitors, synchronizes, and optimizes the activities of other distributed agents (Barbati et al., 2012).

The remainder of this work is organized as follows. Section 2 presents the developed RTO mechanism in detail, including the planning and real-time control functionalities. Section 3 presents numerical experiments on the developed framework and comparison with current related approaches. Conclusions are drawn in Section 4.

2. The RTO mechanism

Consider a two-echelon CNE with I customers and J collaborative enterprises. A customer may refer to a business enterprise in a lower echelon or a final consumer. Each enterprise has finite capacity and is responsible for a certain demand region, i.e., no partial fulfillment is considered. The reason is to avoid conflicts in delivery, e.g., shipments timing and duplication of facilities, and protect reputation. In line with the dynamic variations in capacity-demand gaps, an enterprise may turn into a CSE or DSE over time. DCS is the primary strategy in abridging such gaps. In addition, enterprise-customer matching is updated *periodically* to minimize the capacity-demand gap, and thus the total collaboration cost and unfulfilled demand (Moghaddam and Nof, 2014). The idea is to minimize the need for collaboration by optimally adjusting the customers' demand to the available capacity of enterprises.

The RTO mechanism is designed as follows. The collaboration plan is updated at the beginning of each period. The length of periods may vary (e.g., day; week; month; quarter) depending on the requirements and nature of the system as well as possibility of modifying the plan. The plan includes information about (a) the amounts of products/services produced by and supplied from each enterprise; (b) the anticipated inventories/backorders at each enterprise; (c) the matching between enterprises and customers; and (d) the DCS decisions. A Mixed Integer Programming (MIP) model is developed for generating the plan. Upon generation and execution of the plan at the beginning of each period, the TAP and PBMP are triggered to execute, monitor, and modify the collaboration tasks and processes, and provide feedback for generating the next period's plan. The control protocols deal with real-time order acceptance, evaluation and allocation/reallocation of resources, and dynamic best matching of orders to enterprises, and DCS proposals. Details of the planning and control mechanisms are presented in the following subsections. The nomenclature of notation and acronyms is provided in Appendix A.

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