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Innovative Applications of O.R.

Multi-criteria robust design of a JIT-based cross-docking distribution center for an auto parts supply chain

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ABSTRACT

We present a solution framework based on discrete-event simulation and enhanced robust design technique to address a multi-response optimization problem inherent in logistics management. The objective is to design a robust configuration for a cross-docking distribution center so that the system is insensitive to the disturbances of supply uncertainty, and provides steady parts supply to downstream assembly plants. In the proposed approach, we first construct a simulation model using factorial design and central composite design (CCD), and then identify the models that best describe the relationship between the simulation responses and system factors. We employ the response surface methodology (RSM) to identify factor levels that would maximize system potential.

To make the system immune to factors that could adversely affect performance, we propose a robust design approach by incorporating Latin hypercube sampling and take the noise factors (disturbances) into account. Due to the need of accommodating multiple performance measures and to ensure all responses stay within the desired targets, we adapt Derringer–Suich's desirability function to determine the optimal operating conditions. Finally, we use bootstrapping to compare the results obtained by the classic RSM and the proposed robust design. The proposed model helps the studied auto parts supply chain to develop insights into the system dynamics, and to identify the operating setting that minimize the impact of supply uncertainty on the performance of the cross-docking facility.

1. Introduction

1.1. Background

This research was motivated by the need of a third-party logistics provider (3PL) to improve its "Just-In-Time" (JIT) operations. The 3PL is a member of an automobile joint venture between a Chinese and a Japanese car manufacturer with 2500 employees and annual output of 240,000 cars. The supply chain of the joint venture stretches for more than 1000 kilometer between parts suppliers (PSs) and the car assembly plant (AP1) located in Wuhan, central China. A cross-docking distribution center (CDDC), operated by the 3PL, is located near the PSs in Guangzhou, south China. Past success and booming prospect suggest that the Chinese car market will continue to grow at a rate of 10–15% over the next decade (Feng et al., 2010). The joint venture is in anticipation of opening another assembly plant (AP2) to meet the demand. The current capacity at the CDDC is deemed insufficient to fulfill the logistics needs should the new AP2 become operational. However, a new CDDC commercial site in a desired location is hard to come by. Management at the 3PL decides to expand the existing CDDC so as to keep pace with the growth and minimize the coordination and real estate costs. The leading CDDC concern is how to optimize its internal configuration. Management mandates the revamped distribution center operates optimally and robustly so as to reduce supply chain vulnerability while achieving efficiency.

To successfully reconfigure CDDC, the current and future operations must be understood thoroughly. After repeated communication with the executives, the redesign team narrows the performance measurements down to three categories. Specifically, the multi-criteria design goals are: (1) to minimize parts Dwelling Time in the storage area (DT), (2) to minimize the Number of parts staying Exceeding the threshold time (NE), and (3) to maximize the Number of Throughput (NT). Due to the need to convey our recommendation in animation, we adopt simulation as part of our modeling approach. The comprehensive simulation model serves as a test bed for experimenting alternative configurations and allows us to provide visual insights beyond other design techniques. In short, this research proposes a unified framework that designs a robust CDDC to meet the requirements of the JIT supply chain. It optimizes the operating conditions for the CDDC so that the performance metrics: DT, NE and NT, reach desired targets and are immune to the adverse effects of supply risks.

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1.2. Literature review

1.2.1. Cross-docking

Cross docking (CD) is increasingly gaining ground as a logistics technique that rapidly consolidates shipments from suppliers to realize the scale economy of outbound delivery. Conventional distribution center consists of five basic functions: receiving, sorting, storing, retrieving and shipping. By eliminating the need of storing and retrieving, the most expensive logistics functions (Lee and Ho, 2002), cross-docking essentially reduces inventory holding cost and enhances system efficiency.

Forger (1995), Witt (1998), and Gue (1999) discussed the implementation issues of CD in practice. In the planning level, Jayaraman and Ross (2003) and Ross and Jayaraman (2008) tackle the production, inventory, outbound transportation, and single layer CD problem in a supply chain. Sung and Song (2003) address an integrated service network design to determine the location of CDs and to allocate inbound and outbound trucks. Ma et al. (2011) study a cross-docking distribution network to find the trade-offs between transportation cost, inventory and scheduling requirements. In the operational level, most research is concerned with vehicle routing and scheduling. Yu and Egbelu (2008), Boysen et al. (2008), Chen and Lee (2009), and Chen and Song (2009) regard cross-docking as a two-machine flow shop problem which emphasizes continuous flow with minimum cycle time in CD. Boysen and Bock (2011) propose a new method for scheduling CD's part supply from a central storage center. Vahdani and Zandieh (2010) and Konur and Golias (2013) apply meta-heuristic algorithms to schedule trucks in CD. Although CD is commonly employed in auto industry (Kaneko and Nojiri, 2008), none have addressed its operations with robust design to meet the JIT production needs, and none have considered multi-metric performance optimization (see Table 1a). In today's highly competitive environment, performance measures are often of multiple dimensions (Shang and Tadikamalla, 1998; Shang et al., 2004). Management of the 3PL expects the reconfigured CDDC to maximize its potential, balance the DT, NE and NT objectives, and handle disruptive events in supply with minimal loss.

1.2.2. Simulation optimization

Response surface methodology (RSM) is a sequential method which collects statistical and mathematical techniques to improve and optimize responses of interest (Myers et al., 2008). RSM has many real-world applications in a variety of fields. Table 1b surveyed its integration with simulated systems in which RSM serves as a practical optimization tool to seek the optimal factor setting that maximizes the response variable. Among the researchers who employed RSM for simulation optimization, none have examined the CD design (see Table 1b). Unlike Shang et al. (2004) who use the Taguchi method to deal with Environmental Factors (EFs) in supply chain design, we apply a relative new design of experiment method, i.e. Latin Hypercube Sampling (LHS) technique (Dellino et al., 2010, 2012), to obtain the factor combinations for EFs. Although Taguchi method has been widely used in *real-world (physical) experiments* (Sahoo and Sahoo, 2011), LHS is better suited for risk and uncertainty analysis in *simulation experiments* (Kleijnen, 2008; Dellino et al., 2010, 2012). The comparisons between real-world and simulation experiments can be found in (Kleijnen et al., 2005; Wan et al., 2006; Shen and Wan, 2009). Our study is the first in literature to combine the large scale discrete-event simulation model with RSM and LHS methods to address the robust optimization issue. We consider both the decision factors and the environmental factors in the auto supply chain and demonstrate the superiority of our design. We show that the proposed method offers an effective approach to develop a robust system for real-life application.

Overall, the contributions of our manuscript are fourfold: (i) we formulate a novel cross-docking optimization problem that addresses the *practical* need of a real-life 3PL company. The project meets the practical needs of the 3PL company; (ii) we propose a very useful solution procedure, that includes discrete-event simulation and metamodel-based optimization; (iii) we adapt novel techniques – Latin Hypercube Sampling (LHS) and Bootstrapping, to develop an efficient procedure to search for robust solutions. The proposed approach is relatively new in theory (Dellino et al., 2010, 2012), and we are the first to put these methods to business use, in particular to the supply chain setting. In addition, and (iv) we compare the robust solution approach with the classical RSM solution. The robust approach is frequently neglected by practitioners, but it has *gained increasing attention* given today's volatile, complex and competitive business environments.

The remainder of this paper is organized as follows. In Section 2, we propose an integrated multi-criteria robust design optimization framework. Section 3 develops a comprehensive CDDC simulation model, while Section 4 rationalizes the chosen factors and response measures. The classic design and the proposed robust design are contrasted in Section 5. Section 6 concludes this research and provides future research directions.

2. A multi-criteria robust design for cross docking distribution center

2.1. The proposed framework

We propose a hybrid model that aims to build an agile and resilient system (see outlines in columns 2–3 in Fig. 1), which differs from the classic response surface methodology (see column 1 in Fig. 1). A simulation model is first developed to emulate the supply chain and to estimate the impact of diverse operating conditions on the performance of DT, NE and NT. As simulation itself does not prescribe optimal solutions, an optimization technique is needed to attain the best performance (Nelson, 2004). Metamodels are capable of describing the underlying relations (Kleijnen, 2005; Barton and Meckesheimer, 2006) by establishing the relationship between the independent variables and the simulation outputs. They are subsequently explored by optimization techniques to derive the best system outcome.

Factors that influence the performance of a system can be divided into two types: decision factors (DFs) and environmental factors (EFs). DFs are controllable variables, denoted as d_i, whereas EFs are uncontrollable variables (noises), denoted as e_i. Although EFs are uncontrollable in the real-world, they are estimated and approximately controlled for experimental purpose. The objective is to apply the robust design concept to identify the optimal setting of DFs that maximize the system performance while minimizing the variability transmitted from EFs (the disturbing factors). The robust design concept was pioneered by Taguchi (1987), who believe the 'robustness' can be achieved by reducing variation in design. He divided robust design process into three stages. (1) System design: applying the engineering principles to create a prototype; (2) parameter design: uncovering the settings for the product/process parameters to minimize variation and tolerances; and (3) set tolerances on the control parameters to minimize the loss. Borrowing the structure of Taguchi (1987), our robust design for CDDC incorporates simulation for system design, and employs both DFs and EFs in a model for parameter design. This differs from the classic RSM, which only focuses on DFs.

Montgomery (2007) showed that Taguchi method is inefficient and in many cases ineffective. To avoid the weakness of the Tagu-