Computers and Chemical Engineering 87 (2016) 164–179

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

A computationally efficient simulation-based optimization method with region-wise surrogate modeling for stochastic inventory management of supply chains with general network structures

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ARTICLE INFO

Article history:
Received 7 May 2015
Received in revised form 22 January 2016
Accepted 22 January 2016
Available online 1 February 2016

Keywords:
Simulation-based optimization
Inventory management
Trust-region algorithm
Surrogate modeling
Kriging

ABSTRACT

Simulation-based optimization is widely used to improve the performance of an inventory system under uncertainty. However, the black-box function between the input and output, along with the expensive simulation to reproduce a real inventory system, introduces a huge challenge in optimizing these performances. We propose an efficient framework for reducing the total operation cost while satisfying the service level constraints. The performances of each inventory in the system are estimated by kriging models in a region-wise manner which greatly reduces the computational time during both sampling and optimization. The aggregated surrogate models are optimized by a trust-region framework where a model recalibration process is used to ensure the solution's validity. The proposed framework is able to solve general supply chain problems with the multi-sourcing capability, asynchronous ordering, uncertain demand and stochastic lead time. This framework is demonstrated by two case studies with up to 18 nodes with inventory holding capability in the network.

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1. Introduction

A supply chain is a complicated system containing networks of information flows and material flows (Chopra, 2010; Garcia and You, 2015; Simchi-Levi, 2008). A typical supply chain usually contains different but interdependent facility nodes for different purposes, ranging from the procurement of raw materials, product processing, delivery of finished products, etc. The efficiency of a supply chain can be evaluated from different aspects, including the economics, rapidness of service, environmental sustainability, etc. Therefore, the supply chain management is focused on improving the above metrics and it has become more and more important for manufacturing companies to achieve growth in profits (Grossmann, 2005; Relvas et al., 2006; Varma et al., 2007; Wassick et al., 2012). Among the supply chain system, the inventory plays a critical role for connecting different functional units into a highly integrated system (Zipkin, 2000). The inventory management concerns demand forecasting, physical inventory carrying and quality control. It is dedicated to coordinating the logistics with production planning, and it can also help the supply chain system to respond to various kinds of uncertainties (Michalski, 2009).

The objective of inventory management optimization under demand uncertainty is to maximize the performance of the inventory system in a stochastic environment by determining an optimal set of inventory control parameters with regard to a certain inventory control policy. This is a challenging problem since there are two key performance measures: maintaining a low operation cost and not violating the service level constraints. Combined with its stochastic nature, the problems are usually intractable (Cheng et al., 2003; Jung et al., 2004). Also, the idealized assumptions necessary for mathematical models make the solutions inapplicable for real world cases (Kochel and Nielander, 2005). In order to reproduce details such as the multi-stage nature of the network, fluctuation of demands, uncertain lead times, and the integration of versatile "intelligent" control strategies, the simulation method has become mainstream for the modeling of a real-world supply chain and has been adopted by an increasing number of companies to evaluate their performance (Shah, 2005).

However, there are still a few research challenges in simulation-based optimization approaches for stochastic inventory management. The simulation is usually computationally expensive since multiple replications are required to overcome the noise in the returned result. Also, in contrast with mathematical models, simulation provides a "what-if" response to the system inputs in which there is no accessible gradient information. Though there are general approaches for solving simulation-based optimization

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http://dx.doi.org/10.1016/j.compchemeng.2016.01.015
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Nomenclature

Experiment design

N_d	number of days in a planning horizon
N_{inv}	number of inventory stocking nodes in the network
N_{rep}	number of simulation replications
N_s	number of sampling points

Index

i,	j inventory node
q	design point
t	planning period

Sets

I	inventories in the entire inventory network
D_i	customer nodes immediately linked to node i

Simulation parameters

c_i^b	unit backorder cost for node i
c_i^h	unit inventory holding cost for node i
$sl_i^{\min}$	service level lower bound for node i

Simulation variables

ABO_i	average backorder of node i
AOC_i	average daily operation cost of node i
AOH_i	average on-hand inventory of node i
BO_i	real time backorder of node i
BS_i	base-stock level at node i
FOD_{it}	sum of orders filled by node i without delay on day t
$IMFO_{ijt}$	immediately fulfilled order from node j to node i on day t
$INVB_{it}$	backorder amount of node i at the beginning of day t
$INVH_{it}$	on-hand inventory of node i at the beginning of day t
$INVO_{it}$	on-order inventory of node i at the beginning of day t
$INVP_{it}$	inventory position of node i at the beginning of day t
OD_i	order amount of node i at the beginning of day t
OH_i	real time on-hand inventory of node i
ROD_{ijt}	order received by node i from node j on day t
SL_i	service level of node i
SOD_{it}	sum of orders received by node i on day t
TLC	total daily operation cost of the supply chain
$TLOD_i$	total amount of orders received by node i over the entire horizon
$TLSO_i$	total amount of orders satisfied by node i without delay over the entire horizon

Parameters in optimization algorithm

Δ_k	trust-region size at iteration k
α	positive multiplier for model recalibration
δ	modified trust-region size
λ_i	error bound for the region-wise surrogate at node i
ε_i	error term for the region-wise surrogate at node i
υ_m	component m in vector υ
ρ	indicator of the similarity in the trust-region algorithm
η	indicator of the step-size in the trust-region algorithm

Vector/matrix

$\mathbf{X}_s$	design matrix for sampling
$\mathbf{X}_{s,q}$	the q^{th} design point in the design matrix
$\mathbf{x}$	vector of the base-stock levels
$\mathbf{x}_k$	vector $\mathbf{x}$ at the kth iteration
$\mathbf{y}$	result vector for the sample input vector

problems such as genetic algorithm (GA) and simulated annealing (SA), they are all metaheuristic approaches which cannot guarantee the solution's quality (Mansouri, 2006; Mele et al., 2006). An important branch of simulation-based optimization resorts to the use of surrogate models, where the black-box functions are sampled and predicted by analytical approximations ranging from linear regression to adaptive nonlinear models (Cozad et al., 2014; Wang and Shan, 2007). However, inventory control optimization has unique and unfavorable features. First, a supply chain network is usually composed of a number of facility nodes and the problem's dimension can be high if there are many control parameters to be determined. Second, both the objective and the constraints for the inventory control problem are black-boxes; hence, it is a significant burden to construct the surrogate function for each equation. In addition, many existing surrogate-based methods lack generality and are based on some premises such as normally distributed demand, divergent networks, convexity assumptions, etc. Thus, an efficient algorithm for solving more general inventory control optimization problems under uncertainty is the next step for research (Chu et al., 2015b; Jung et al., 2008).

Instead of delving into supply chains with idealized presumptions, we focus our solutions to inventory system simulators featured with more realistic considerations. The definition of "general" allows the inventory system to adopt more flexible inventory control policies and principles including multi-sourcing and asynchronous decision making. The change of inventory control parameters will not only affect the performance of each node in the system but also the expected material flow rates within the entire network. A concomitant challenge is that the simulation becomes a more unpredictable black-box response, losing benign characteristics such as convexity and the possibility to be simplified as multiple single-stage models. In this work, we propose a novel region-wise surrogate modeling method for solving the inventory management optimization problem for a general supply chain network under uncertainty. By integrating the design of a simulation experiment, simulation by objective-oriented programing, and kriging metamodeling, a trust-region framework with iterative model recalibration algorithm is introduced to tackle the general inventory control problem with multi-sourcing options and asynchronous reordering. We reduce the entire supply chain network into region-wise approximations and further extend the surrogate-based optimization framework's capability to solve a large inventory system under both demand uncertainty and lead time uncertainty.

The novelties of this work are summarized as follows:

- A novel region-wise surrogate modeling of an inventory system with complex network structure
- Trust-region based algorithm with iterative model recalibration for surrogate-based optimization
- Application of simulation-based optimization to general supply chain networks with multi-sourcing capability

The remainder of the paper is organized as follows. In Section 2, a literature review for recent studies on simulation-based optimization for inventory systems is presented. Our assumptions for

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