不確実かつ複雑な市場において適正な材料調達ポートフォリオを実現する  
マルチ期間ロバスト最適化技術

Risk-Aware Multiperiod Optimization for Procurement Portfolio Amid Extreme Complexity and Uncertainty

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**要　旨**

グローバルサプライチェーンにおける複雑性および不確実性の増加により、工場の材料調達は在庫日数、購入コストなどのキャッシュフロー関連KPIの最適化において大きな課題に直面している。我々は、これらの課題に対処するマルチ期間ロバスト最適化技術を開発した。これにより、材料購入先の選択、発注のタイミング、および注文量に関する最適化された調達計画を実現し、過剰在庫および欠品リスクを抑えることが可能となる。本アプローチをシミュレーションデータおよび実際の工場データを用いて評価を行った。従来の手法に比べて大幅な改善を示し、在庫コストと購買コストの合計で 43.3% 以上の削減を達成した。

**Abstract**

Due to the increasing complexity and uncertainties within global supply chains, factory procurement faces challenges in effectively optimizing KPIs such as inventory days, cash flow, and purchase costs. Cash flow optimization in terms of inventory management to strike a balance between risk of demand miss and having extra inventory is incrementally challenging because of uncertain demand, price, lead time etc. This paper introduces an innovative Robust Optimization technology to address these challenges, providing optimized recommendations on order timing, supplier selection, and order quantities with cost modelling of inventory and demand backlog risk considering multiple time periods, dynamically. Utilizing synthetic and real factory data our approach demonstrates significant improvements over traditional methods. Our method achieves 43.3% reduction in combined inventory and purchase cost, thereby enhancing overall procurement decision-making and improving cost efficiency in the face of market uncertainties. We propose a metric to measure the risk and demonstrate that implementing the proposed strategy results in a dramatic reduction in risk, in terms of missing demand (backlog). This proves the significant potential of the proposed technology to reduce operational costs while providing measured control over demand backlog risk. Through a case study with a PID device solutions BD we found the cost reduction is 24.8% in a simplistic setting with a single supplier.

1 Introduction

Procurement of raw materials for production involves key performance indicators such as inventory days, cash flow, and purchase costs. This issue of procurement management is a key to improve the cashflow. The optimization of procurement, encompassing two key decisions: a) determining optimal quantities and suppliers, and b) scheduling procurement periods effectively to minimize the operational cost including the ordering cost, storage cost and risk of demand backlog. A major issue faced by the production planning is the demand is unknown in advance.

Even a small inaccuracy in forecasts can lead to very high inefficiencies in cash flow if inventory levels are too high or exposes to significant risks and financial losses if inventory levels are too low [2].

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Fig:1: Overview of supply chain process

Fig:1 presents the process flow of the supply chain. Even when all the parameters associated with the inventory management is known the planning is challenging. The uncertainties associated with various parameters such as demand makes procurement optimization inherently complex, even though it is critical for financial performance. Additionally, at times the uncertainties can even be very dramatic which further aggravates the issue [2]. In this paper we address the issue of this complexity of the supply chain. In this paper we propose a mathematical framework to optimize the procurement when the factory is experiencing uncertain demand in a multiperiod setting. The framework considers multiple suppliers and outputs the optimal quantity to be procured across the planning horizon that minimizes the operational cost. In that sense we are optimizing the supplier portfolio. As per current practices the procurement managers tend to maintain inventory levels through manual gut feel that often leads to inefficient cashflow management and unquantified risk of backlog or demand miss.

We make three major contributions in this research. Firstly, we formulate a mathematical framework to optimize the procurement management in a multi supplier, multi period scenario to minimize the operational cost considering demand uncertainty. Secondly, we consider the appropriate notion of risk to provide the optimal recommendation on *how much* to procure *when* (per month) *from which* supplier to strike an optimal tradeoff between overstocking (inefficient cashflow management) and understocking (demand backlog (risk)). Thirdly, to highlight the business value we perform extensive evaluation to quantify the performance of the proposed strategy in terms of cost reduction for a product that uses silver paste as the most expensive component. To have a representative performance we compare the proposed strategy with the existing benchmark with distribution of real demand, silver price from the commodity market etc.

2 Optimization for procurement management

2.1 Optimization with known demand (deterministic case)

Although mathematical optimization is a matured area in terms of academic research but due to the uncertainty in the real world for high impact decisions like procurement management the real implementation is not among the state of the art practices [1]. We start from the ideal case with hypothetical assumptions and eventually move on to the more realistic. The inputs to the problem are the demand for each period *t* in the planning horizon of length , set of suppliers *S*, where each supplier s can be characterized by a fixed ordering cost denoted by, variable ordering cost per unit in time *t* denoted by , capacity in time *t* denoted by and procurement lead time denoted by The problem is to decide the quantity to order from supplier *s* at time *t* that arrive at time *t′*, which consider the lead time *Ls* satisfying *t′* =*t* +*Ls*. The objective of this model is to minimize the total costs, which include fixed and variable ordering costs, as well as inventory and backlog costs, while subject to capacity and quality constraints. The unit inventory and backlog cost are denoted by *h* and *b*, respectively.

A mixed integer linear programming (MILP) is developed for the deterministic model presented below. In addition to the key decision variables , other decision variables are also included as auxiliary variables. Specifically, we introduce a set of binary variables which is equal to 1 if an order is made from supplier s at time *t* and arrives at time *t′* and 0 otherwise. We use to denote the arrive quantity from supplier *s* at time *t*. Finally, are introduced to denote the inventory and backlog quantity at the end of each time *t*.

(1)

where : planning horizon, *S*: set of all suppliers. The constraints are

(2)

(3)

(4)

(5)

(6)

(7)

(8)

(9)

(10)

(11)

The objective function (1) minimizes the total cost, including fixed and variable order cost, inventory holding and backlog cost. The constraint (2) describes the inventory balance for different planning period. Constraint (3), (4), (5) together defines the relationship between ordering time, lead time and the arrival time. Constraint (6) ensure order quantity equals to the arrival quantity. Constraint (7) links the decision of whether make order with the decision of order quantity. Constraint (8) and (9) limits the quality requirement and supplier capacity. (10) and (11) are the integer and non-negativity constraints. The optimization problem presented from (1) to (11) serves as a framework for optimal multiperiod procurement management when all the parameters such as demand, silver price etc. are perfectly known in advance. This gives an upper bound of the performance of the optimization framework in this context. In the following section we translate this deterministic optimization problem to a stochastic optimization problem where the demand is not perfectly known in advance. In this paper we do not discuss about the complexity of the above optimization problem, the complexity appearing in the title corresponds to the supply chain with uncertain parameters.

2.2 Optimization with unknown demand (stochastic case)

Under this setting observing an instance of historical demand we make some distributional assumptions to address the uncertainty to consider the practical scenario of stochasticity. In our case, demand is the most critical parameter and often exhibits high fluctuation over time [2]. To address the realistic scenario of uncertain nature of demand we leverage sample average approximation (SAA) that translate the deterministic optimization problem presented in (1) to (11) to its stochastic equivalent.

SAA is a method used in stochastic optimization to convert problems involving randomness into deterministic ones. In stochastic optimization, the objective function and constraints often contain random variables, making them complex to solve. SAA addresses this by drawing a set of independent and identically distributed (i.i.d.) samples from the random variables’ distribution. These samples are then used to approximate the expectation in the objective function and constraints with their sample averages. For details on SAA we direct the reader to [3].

By substituting the expectation with the sample average, the original stochastic problem is transformed into a deterministic optimization problem. The solution obtained from this deterministic problem approximates the solution of the original stochastic problem. To address the stochastic case the there are two modifications over optimization problem proposed in (1) to (11). Firstly, the objective function in (1) gets transformed into:

(13)

(14)

Under the SAA framework equation (2) and (7) get transformed into equation (13) and (14), respectively. As the sample size increases, the approximated objective function and constraints become more accurate representations of their expected values. Consequently, the solution derived from the SAA method converges to the true optimal solution of the stochastic problem with high probability. We call the above formulation as SAA based procurement portfolio optimization (SAA-PPO).

2.3 Baseline strategy

We compare the two strategies namely, i) optimization with known demand in (1) to (11), and ii) SAA-PPO in (3) to (13) with a greedy heuristic considered as the baseline strategy for comparison. Under this baseline strategy firstly, select a primary supplier: choose the supplier with the lowest price and establish a long-term contract for regular orders set at 70% of the average historical demand, unchanged throughout the planning period. Next, engage a secondary supplier: for residual demand in each period, order from the next cheapest supplier, up to a limit as per capacity constraint. One week’s safety inventory is considered equivalent to the average demand during the average lead time.

3 Performance evaluation: Experiments and results

In this section we describe the setting under which the performance evaluation is conducted and discuss the results.

3.1 Experimental setup and results

We conduct the performance evaluation in a realistic setting with real demand experienced in the factory of an industrial electronic product. Each timeslot corresponds to a month.

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Fig.2: Total cost incurred by Baseline method (existing)

We consider three suppliers with cost varying as per the silver price in the commodity price of silver that is known in advance. We consider lead time corresponding to each suppliers that is inversely proportional to the ratio of the mean price charged by the respective suppliers. In the experiement we generate 100 instances of demand from 2020 to 2023 following the same mean and variance of the actual historical demand experienced by the factory. There are two important performance attributes, namely, i) average performance and, ii) risk. Average performance corresponds to the notion of cost incurred under the respective strategy in a nominal case where risk is associated with the worst case performance and closely related to the robustness of the objective function with respect to the decision variables. We evaluate the strategies with, i) in-sample and ii) out-sample inputs to effectiveness on similar inputs and test the model's generalizability to new data. In-sample evaluation measures the model's performance on the same dataset used to solve the optimization problem, i.e, measures the objective function in the same instance. More specifically in this, the optimization problem is solved given the inputs, optimal order is computed and the objective function in (12) is evaluated. This value becomes the in-sample performance.

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Fig. 3: Total cost incurred by SAA-PPO

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Fig. 4: Total cost incurred by Detrministic optimization

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Fig. 5: Box plot of distribution of cost for all strategies

On the other hand, out-sample evaluation measures the model's performance on a separate, unseen dataset not used where the optimization problem is solved. This measures the objective function on a set of input parameter where the solution comes from another set of input parameters. We perform this for 100 such instances of input data and report the average objective value. The name comes from the fact that this input data is totally unseen by the optimization problem where the optimal decision variables are computed. This is an estimation of the generalization error.

Table 1 given above provides the summary statistics of the evaluations we perform. Fig.2, 3 and 4 shows the cost incurred under baseline, SAA-PPO and deterministic strategies, respectively. From the above, we observe that with baseline in general the cost incurred is much higher, however there is less performance degradation with generalization. On the other extreme with deterministic strategy in general the cost incurred is much lower however the performance degradation with generalization is much worse. However, the out-sample performance of deterministic strategy is still better than in-sample performance of baseline. This highlights the great potential of mathematical optimization-based procurement management.

Table: 1: Summary statistics

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As observed in demand forecast project we observe for some product the forecast error is very high while for some products it is very low [2]. The in-sample cost is more representative in the low forecast error arena whereas out-sample cost is more representative in the high demand forecast error arena. To standardize the variance around the mean we report the coefficient of variance (CoV), which is defined as:

{"mathml":"<math style=\"font-family:stix;font-size:14px;\" xmlns=\"http://www.w3.org/1998/Math/MathML\"><mstyle mathsize=\"14px\"><mi>C</mi><mi>o</mi><mi>V</mi><mo>=</mo><mfrac><mi>&#x3C3;</mi><mi>&#x3BC;</mi></mfrac><mo>&#xD7;</mo><mn>100</mn></mstyle></math>","origin":"MathType for Microsoft Add-in"} (15)

A higher *CoV* indicates greater dispersion around the mean, while a lower *CoV* indicates less dispersion. Fig.(5) provides the distributions of cost under different strategies. The nominal value of cost represents the effectiveness on an average case, whereas the spread represents the risk associated with the respective strategy. Experiments show that compared between SAA-PPO with baseline (both out-sample) there is 43.3% decrease in average cost computed across 100 instances of synthetic demand. In the context of *CoV* there is a decrease of 79.6% in SAA-PPO over the Baseline strategy for procurement management.

3.2 Evaluation with a PID device solutions business division

A PID device solutions BD is in the process of adopting our technology. We tested over one realized instance of actual demand. Some simplification is adopted, such as single supplier, due to information constraint. Under this simplistic setting we perform our experiment and compared the actual cost with the cost obtained from the deterministic optimization presented in (1) to (11). The result shows 24.8% reduction in operating cost. Some more experiments with SAA-PPO are under progress with the business users. The framework developed in this paper is comprehensive and considers the complex case with multiple suppliers, nevertheless it supports such simple cases as well resulting in significant operating cost reduction.

3.3 Technology roadmap

The theme of data driven risk averse multiperiod robust optimization is a new theme in PID company and the results presented in this paper is just middle fruit. With ongoing digital transformation initiatives, we are likely to have transition to AI powered inventory management of which procurement management is an instrumental component. The SAA-PPO model presented in this paper is a starting point for stochastic optimization and we wish to develop advanced robust optimization-based techniques to address this issue. We found some advanced and customized variant of distributionally robust optimization as the probability distributions of the input parameters are not known in advance [4] can be useful for our problem.

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Fig. 5: Total cost incurred by detrministic optimization with in-sample and out-sample evaluation

4 Conclusions

This paper presented a mathematical optimization framework for multiperiod procurement optimization with uncertain demand. We choose to quantify the risk through the coefficient of variance (CoV) which is observed to be 6.3 and 1.3, under baseline and SAA-PPO. This demonstrate that there is a substantial reduction in risk after implementation of SAA-PPO. We also applied our deterministic model in one instance of actual data and the result shows 24.8% reduction in operating cost. For a thorough evaluation, we analyzed 100 instances of demand samples generated with same mean and standard deviation of the actual data from a PID device solutions BD. The exhaustive evaluation demonstrated that the proposed strategy achieves 43.3% improvement over the existing strategy. To accurately calculate cost savings, it is essential to consider the actual storage costs and the risks associated with backlogs. This project is a steppingstone towards the broader theme of supply chain digitalization initiative, and we discuss the technology roadmap that leverages advanced variants of distributionally robust optimization. We hope this will serve as an incredibly valuable strategy for procurement management augmenting in terms of cost reduction with adequate control of operational risk.

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