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Research Article

Stochastic Reliability Measurement and Design Optimization of an Inventory Management System

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Inventory management systems and dynamic reliability measures and controls remain challenging at every stage, especially when time variances and operating conditions are considered. An inventory management system must maintain its adeptness over time while coping with the uncertainty of inventory flow. Unexpected delays during inventory movement can harm the reliability and robustness of the entire system. This paper introduces a method of quantifying the reliability of an inventory management system. Also, a novel, reliability-based robust design optimization model has been developed to optimally allocate and schedule time while considering uncertainty associated with inventory movement. The processes involved include purchasing, shipping, receiving, tracking, warehousing, storage, and turnover. A case study of a furniture company in Saudi Arabia is presented to demonstrate the efficacy of the model.

1. Introduction

The globalization of today's marketplace has brought new opportunities and challenges to industry. This new frontier allows businesses to reach more consumers than ever. However, it also increases the need for reliable, robust global inventory management systems. Technology has become an effective management recordkeeping tool. Many variables associated with managing stock can ultimately determine the success or failure of a business. Thus, an effective inventory management system is essential. Sani [1] revealed that inventory management is used to specify inventory inflows and outflows. It defines the quantity of stock arriving and being registered into the system. It must be able to recognize valuable information. The challenge is to develop a method that aids in evaluating inventory management while coping with unforeseen conditions. Inventory consists of stock, which may include raw materials, work-in-progress, finished, or value-added products or services [1]. Having a good inventory management system aids in maintaining a good record of stock keeping units (SKUs). Hence, maintaining a precise stock level where the system-recorded stock reflects the actual stock is essential to avoid errors [2].

Technology has advanced rapidly, improving several fields of endeavor such as education and business. During the mid-1990s, various companies started to evaluate inventory management system software. This software could document processes and changes as products were transported in and out of any business. In the early 2000s, inventory management solution technology expanded from the small scale to the large. Before this type of industrial innovation, many businesses had to record the products sold and received each day on paper and assemble the resulting documents into a folder for recordkeeping. Orders were placed using handwritten notes, resulting in inefficient business processes.

Inventory management systems are suitable for all types of businesses that deal with tracking and identification of inventory. The main objective of such a system is to determine and maintain the inventory level by preserving records of the products sold and by keeping sales records by date. Companies use inventory management systems to prevent out-of-stock and overstock issues.

An inventory manager might face two major problems: having an overstock of inventory or having a shortage. Excess inventory automatically becomes overstock. This causes problems for businesses and has many negative consequences. One important effect is an increase in cost. Storage and security fees increase and money is invested in nonessential goods. There is also risk involved in holding excess inventory. There are two costs associated with holding inventory. Carrying (or holding) cost is the cost of storage, insurance, material handling, and so forth. The second type of cost is ordering cost. This is the cost associated with placing orders and receiving goods such as transportation and shipping and receiving and inspecting materials. These two costs represent the core of inventory problems. An order size increase can lead to an increase in the average number of processed goods in inventory and thus increased carrying costs.

On the other hand, stock shortages can also have dire consequences. Business reputations rely on consumer trust. Providing high-quality, affordable goods in a timely and predictable manner is key to success. As a result, a stock shortage can lead to massive losses. These losses can stem from increased production times and purchasing costs, loss of sales, and ultimately the loss of customer goodwill. Inventory decision-making is very risky, as it may impact the supply chain [3]. An inventory management system is necessary to satisfy customer demand at the right time and in a cost-effective manner [4, 5]. Hence, maintaining too little stock may result in production problems while having too much means investing significant money unnecessarily. Inventory is one of the most expensive assets that many companies invest in. It is a critical investment and therefore the heart of any enterprise.

This research introduces a method that can be used to evaluate the reliability of an inventory system with regard to satisfying consumer demand. The resulting measure can be used in organizing and scheduling via reliability-based robust design optimization. The remainder of this section reviews current literature on inventory management system evaluation and design methods.

This paper develops a novel reliability measure and reliability-based robust design optimization (RBRDO) approach. Reliability focuses on the subset stimulation technique to achieve numerical efficiency [6]. Reliability is described as the tendency towards consistency of performance and responsibility or as the fulfillment of a service provider's promises to customers. Reliability deals with the performance and dependability of the service entity in meeting customer requests. A service is considered to be reliable if it repeatedly shows similar results using comparable measures [7]. Moreover, services have to be provided at the time promised in order to maintain credibility [8]. RBRDO provides both cost-effective manufacturing processes and target confidence [9, 10]. Probabilistic constraints are the key constraints in RBRDO. They create several numerical challenges with regard to numerical efficiency, stability, accuracy, and so forth [11–13]. RBRDO is very important for structural optimization because many of its practical applications involve at least two conflicting objectives, typically including low cost and high reliability [14]. The constraints are influenced by both functional and reliability requirements.

Reliability-based robust design optimization (RBRDO) combines of reliability-based design optimization (RBDO) and robust design optimization (RDO). In general, reliability is defined as the ability to start and continue to operate [15]. Robustness was first introduced by Taguchi in 1987 to help find solutions that are less sensitive to unknown variations. Taguchi's definition of a robust design is "a product whose performance is minimally sensitive to factors causing variability." Byrne and Taguchi [16] illustrated the main objective of RDO, which is to find a design with minimum scattering model variance in order to produce results near the mean values of the design parameters. Roos et al. mentioned that RDO can be treated as statistical variability in parameter design [17]. Different methods [18–21] were developed in order to systematically treat uncertainties in engineering analysis and more recently for RBRDO method development. RBRDO can be used a design tool when the function and performance of a product are relatively insensitive to variation [22].

There is limited research available on method development for inventory management system evaluation and design optimization. In [23], Axsäter showed how approximate evaluation can be applied to inventory system policies. Another research [24] investigated hybrid techniques for evaluating life-cycle inventories. In [25], Resurreccion and Santos developed multiobjective prioritization methodologies for inventory system evaluation. The study helped to determine inventory enhancement priorities with user preference and resource availability as new dimensions. Arıkan et al. [26] investigated the interrelation between transportation uncertainties and inventory system performance. In [27] researchers provided a new method which eliminates the unbalanced benefit distributions caused by vendor managed inventory and offers almost equal benefits to the participating firms. A modified particle swarm optimization to solve integrated location and inventory control problems in a two-echelon supply chain network was introduced in [28]. In [29] researchers proposed a long-term extreme price risk measure method for inventory portfolios. Despite numerous inventory management system evaluation studies, further research on inventory systems associated with design optimization and reliability evaluation has rarely been reported. Therefore, this paper presents a model for inventory management system evaluation. A RBRDO approach is developed to help in satisfying reliability requirements in every stage of the system, while coping with uncertainty and minimizing overall handling and management cost. The remainder of this paper is organized as follows: Section 2 introduces methods of evaluating inventory system reliability and presents the methodology developed to design reliable, robust inventory systems. Section 3 evaluates the model described in this paper by applying it to a case study of a furniture company in Jeddah, Saudi Arabia. Conclusions are presented in Section 4.

2. Materials and Methods

This section explains the research design, which includes the evaluation method, optimization model, and data collection procedures. Three key research questions were addressed to achieve the previously mentioned research objectives:

(1) How can all inventory system processes be evaluated using a single, unique measure?

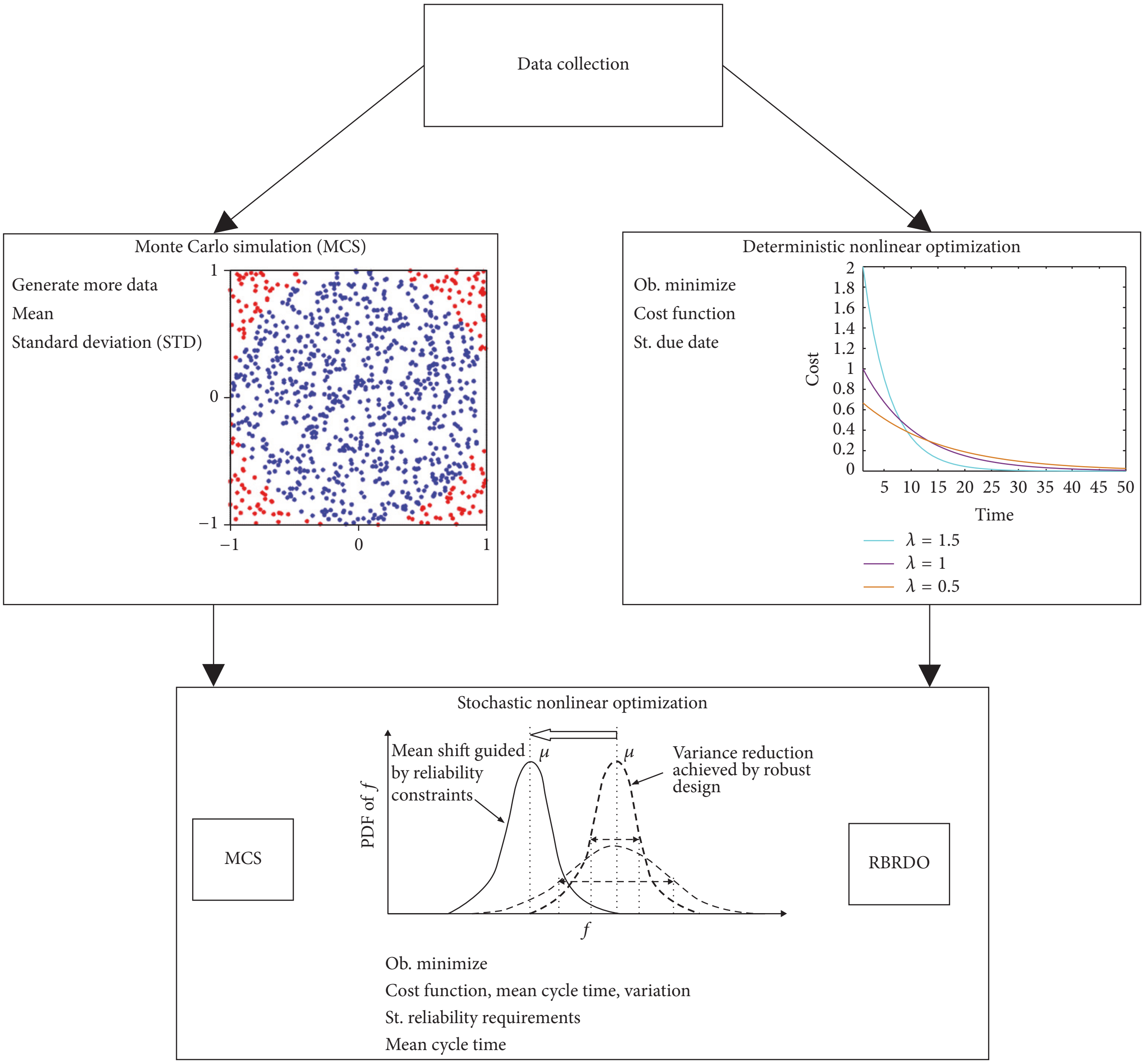

Figure 1: RBRDO procedure applied to an inventory management system.

(2) How to evaluate the reliability of an inventory management system?

(3) How to design a cost-efficient, reliable, robust inventory management system while coping with uncertainty?

Numerous techniques were considered in answering these questions. They include Monte Carlo simulation, linear programming, deterministic nonlinear programing, stochastic nonlinear programing, and RBRDO. Microsoft Excel solver and MATLAB were used for modeling and mathematical simulation. The goal was to investigate the most basic approach that can be used to achieve the objectives of this research. Thus, this investigation started by using basic tools such as linear programing and Excel solver and moved on to advanced technologies such as stochastic nonlinear programing and MATLAB. This helped us to understand a variety of available design and optimization tool capabilities. The methods and tools used to achieve the research objective are shown in Figure 1.

2.1. Inventory Management System Reliability (IMSR) Evaluation Model. Progression and development of an IMSR measure is affected by both internal factors and numerous external factors such as increasing globalization, information availability, global trade, and ecological concerns. The reliability of an inventory system can be defined as its ability to complete all required processes before they are due. Figure 2 shows the IMSR phenomenon.

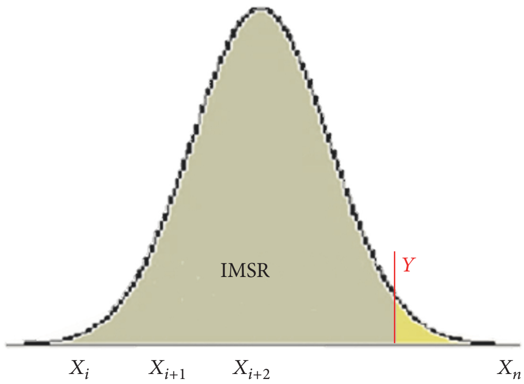

Figure 2: Typical IMSR phenomenon.

The IMSR should be measured and compared using a qualified set of performance measures. In order to control system performance, the process parameters must be kept within a limited range. This makes comparisons of target and actual performances possible. Once comparisons have been made, specific processes can be targeted to improve inventory management performance.

By using an appropriate set of measures, the overall IMSR can be closely monitored for performance. Successive improvements can be applied to each task in the system in order to determine their impacts on the overall IMSR. The IMSRs of suppliers, routes, factories, and the overall inventory management system can be used to achieve customer satisfaction. In general, the IMSR can be defined as the probability of completing all required process at time (X) before the due time (Y) and can be expressed statistically as shown in

$$\mathrm{IMSR} = \Pr\left(X_1 + X_2 + \cdots + X_n \le Y\right) \quad (1)$$

Mathematically, the IMSRs of suppliers, factory, routes, distribution centers, ports, and the overall inventory management system are represented by the ratio of the total cycle time minus the cumulative delay to the total cycle time. The total cycle time is the cumulative time taken from order placement until receipt and assembly at the customer location. Cumulative delay is the delay due to uncertainty during movement of products through the inventory system. The IMSR can be obtained using

$$\mathrm{IMSR}_{X(i,j)} = \left(Y - \left(f_{X(i,j)} \sum_{j=1}^{J} \sum_{i=1}^{I} \sigma_{X(i,j)} + f_{X(i,j)} \sum_{j=1}^{J} \sum_{i=1}^{I} \tau_{X(i,j)}\right)\right) \times \frac{1}{Y} \quad (2)$$

$$\text{when } Y \le \left(f_{X(i,j)} \sum_{j=1}^{J} \sum_{i=1}^{I} \sigma_{X(i,j)} + f_{X(i,j)} \sum_{j=1}^{J} \sum_{i=1}^{I} \tau_{X(i,j)}\right), \quad Y_{X(i,j)} = 0,$$

where $\mathrm{IMSR}_{X(i,j)}$ represents the reliability performance of node type X (e.g., port, supplier, and route), number i in level j. Y represents the time due and $\sigma_{X(i,j)}$ is the standard deviation (uncertainty) of the distribution function of node type X number i in level j. $\tau_{X(i,j)}$ is the external factor delay affecting the node. When the sum of the delay ($\tau_{X(i,j)}$) and uncertainty ($\sigma_{X(i,j)}$) are larger than the due time (Y), the reliability ($\mathrm{IMSR}_{X(i,j)}$) equals zero.

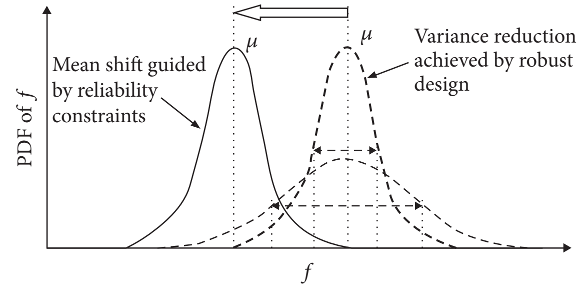

Figure 3: Typical RBRDO phenomenon.

2.2. RBRDO of an Inventory Management System. This subsection presents the RBRDO of an Inventory Management System. In general, this approach characterizes uncertainty variables and failure modes to optimize a design for higher reliability [30]. RBRDO accepts variability and uses the limit state function to separate the stress and strength probability density functions (PDFs) to achieve the desired reliability level. The objective of performing RBRDO on an inventory system is to minimize variation while satisfying inventory system requirements. It also helps to find the best compromise between cost and reliability by taking uncertainties into account. Furthermore, RBRDO is used to shift reliability and reduce variance by designing a multiobjective function that minimizes cost and cost uncertainty factors (variance) with the required reliability target as a constraint, as shown in Figure 3 [31].

The optimal design of an inventory system can be determined using RBRDO, which seeks to find designs that are less sensitive to the uncontrollable variations that are often inherent to the design process. RBRDO outperforms existing deterministic discrete optimization tools when change or uncertainty is involved in optimization problems. Application of RBRDO to the design of an inventory management system has three objectives: minimization of cost, inventory cycle time, and the impact of uncertainty.

RBRDO considers various uncertainties introduced by changes in specifications, transportation delays, raw material availability, manufacturing processes, and operational conditions. Ensuring performance reliability and robustness in terms of time and cost is of vital importance for inventory management systems.

The general formula for the RBRDO of an inventory management system is given by the following:

$$\text{Minimize:} \quad \mathbf{W}_c * f_{X(i,j)} \sum_{j=1}^{J} \sum_{i=1}^{I} C_{X(i,j)} + \mathbf{W}_{\mu} * f_{X(i,j)} \sum_{j=1}^{J} \sum_{i=1}^{I} \mu_{X(i,j)} + \mathbf{W}_{\sigma}$$

Table 1: Company design parameters.

Number	Step	Owner	Minimum	Average	Maximum
P_1	Production selection/quote	Sales team	5	7	9
P_2	Order confirmation between customer & company	Sales team	2	4	7
P_3	Placing order for production	Procurement	21	30	45
P_4	Containers ready for shipping	Procurement	7	14	21
P_5	Forwarder collects goods from the port	Procurement	7	10	15
P_6	Goods available in company warehouse	Procurement	1	7	21
P_7	Delivery	Project coordinator	2	4	14
P_8	Installation	Project coordinator	7	9	20
P_9	Inventory + photographs	Project coordinator	2	5	10
	Total		*53*	*90*	*162*

$$* f_{X(i,j)} \sum_{j=1}^{J} \sum_{i=1}^{I} \sigma_{X(i,j)}$$

$$\begin{aligned} \text{subject to:} \quad & \mathrm{IMSR}_{i,j}(x_s) \geq \mathrm{IMSR}^T, \quad i = 1, 2, \ldots, I \\ & x_s^L \leq x_s \leq x_s^U, \quad j = 1, 2, \ldots, J \\ & x_s \geq 0, \quad s = 1, 2, \ldots, S, \end{aligned} \tag{3}$$

where $\mathrm{IMSR}(x_s)$ is the reliability and the reliability target is $\mathrm{IMSR}^T(x_s)$. $C_{X(i,j)}$ is the cost function of node type X, number i, in level j. $\sigma_{X(i,j)}$ represents the standard deviation (delay due to uncertainty) of the inventory cycle time function of node type X, with the indices mentioned earlier. $\mu_{X(i,j)}$ represents the mean of the inventory cycle time function of node type X. $\mathbf{W}$ is the weight attached based on decision maker preference. x_s^L and x_s^U are the lower and upper limits of the design variable, respectively.

2.3. RBRDO of Inventory Management System Summaries. The procedure for RBRDO of an Inventory Management System can be summarized as follows.

Step 1. Collect data.

Step 2. (a) Generate more data points via MCS; (b) generate an initial set of sample points.

Step 3. Perform reliability analysis at the current design $\mathbf{x}$.

Step 4. Execute the developed RBRDO model.

Step 5. (a) Check the convergence criteria. (b) If they converged, the optimum design has been obtained. (c) If they did not converge, repeat Step 2(b) through Step 5.

3. Results and Discussion

3.1. Case Study. The developed method was applied to the inventory management system of a furniture company in Jeddah, Saudi Arabia. This company provides a wide range of furniture from North America, Europe, and the Far East to match client designs within budgets. The inventory management system consists of 9 stages, each aimed at different types of operations. Table 1 shows primary data collected from the company and describes the average, minimum, and maximum number of days that each entity (department) requires for each step in the process.

3.2. Data Collection. This study used primary data collected in coordination with the furniture company to verify and validate the model. Primary data was used via several techniques such as surveys, direct observations, and interviews. This data was collected directly via first-hand experience. Moreover, it included quantitative and qualitative attributes of variables obtained by the sales department.

One of the main obstacles faced during this research was the limited supply of data points. Monte Carlo simulations (MCSs) were used to overcome this problem. The Monte Carlo simulation is a mathematical technique that allows generation of data from limited data resources. The main aim of this technique is to help in decision-making via the range and possible outcomes generated. This method helps to obtain numerical solutions to problems that are too complex to solve analytically. It offers several advantages, including ease of use and the flexibility to use the probabilities generated from the model. In addition, the mathematics required are quite basic. MCSs were used to generate more than 50,000 extra numerical data points, which helped in developing the RBRDO model. The cost function was presented as an exponential distribution. Thus, nonlinear programming was used to solve the model. The exponential distribution $e^{-\lambda}$ is a probability distribution that describes the relationship between cost and time. Figure 4 shows that shipping and processing costs decrease when process durations increase (late due dates).

3.3. Case Study Results. The first step was to model the inventory system using MATLAB R2014a. Then the current performance of the inventory management system was evaluated using (2). The collected data and MCS indicate that the current total cycle time of an order is approximately 107 days, and the IMSR is 88.28%, as shown in Table 2. Thus, if a customer places an order it takes 107 days to complete, and the probability of completing the order on time is 88.28%. Thus,

Table 2: Initial design variables.

P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	Total cycle time (TCT)	Initial reliability
7.1	4.5	33	14	11	11	7.6	13.4	6	107.52	88.2%

Table 3: Optimized points required to reach the delivery target.

P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	Design Max TCT	Design IMSR
5	6.6	21	7.3	7	5.9	8	7	5.8	73.5	95%

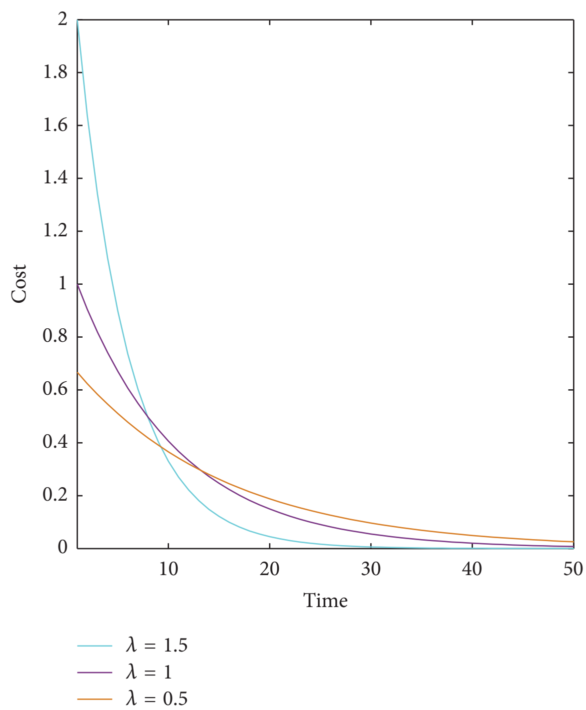

Figure 4: Relationship between cost and due dates.

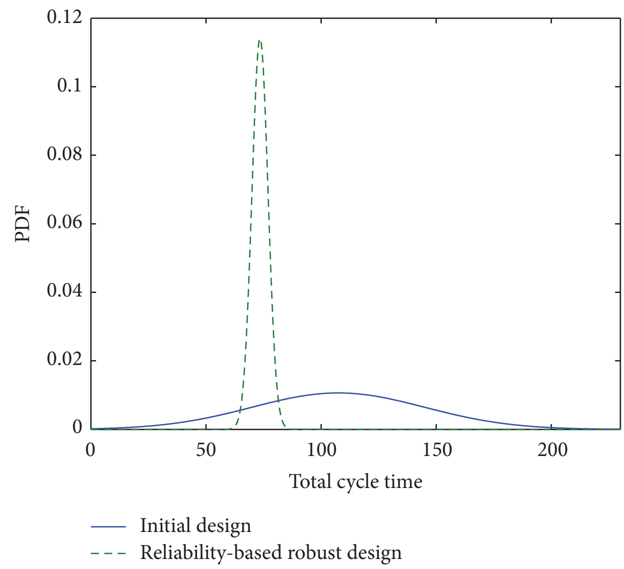

Figure 5: Results from the RBRDO model.

the company should tell their customers that the order will require approximately 107 days. After this initial reliability evaluation, the design optimization model was applied by using (3) to modify the design and find the optimum total cycle time and/or satisfy reliability requirements.

To improve the initial reliability, the company could reduce the cycle time or adjust the schedule or both. For the former, the company could expedite one of the processes by adding more workers to the installation phase (P_8). It could also change delivery methods to reduce P_7. Multiple scenarios have been implemented using MATLAB R2014a and (1)–(3). One such scenario improves the IMSR from 88.2% to 90.16% by adjusting the schedule without changing the actual cycle time. To achieve this, the company should tell the customer their order will require approximately 110 days instead of 107 days. Thus, the model is able to help with project scheduling in order to satisfy reliability requirements.

In another scenario, the company requests a design that can complete all processes in 70 days, with 95% of IMSR. Here, the model helps by assigning durations to each activity in order to satisfy due date and IMSR requirements. RBRDO was applied to this problem, and the results are shown in Table 3.

Table 3 shows the decision variable of each task (time needed to accomplish each task) required to complete the order on time with 95% reliability. For example, delivery (P_7) should not take more than 8 days and installation (P_8) should not take more than 7 days if a 95% IMSR is to be maintained. To determine the best result, model execution (optimization) was repeated several times to produce the optimized points shown in Table 3. The new design satisfies the reliability requirement. Also, the company is 95% sure that the order will be delivered on time. Table 4 shows the cost functions determined using MATLAB.

Table 4 shows the cost of completing the project while satisfying reliability requirements at every iteration during RBRDO. It also shows that the cost of maintaining 95% reliability decreases from $6.092591e^{+06}$ to 173393.6728. Figure 5 compares the PDFs of the initial design and the RBRD. The RBRD has less delay (variation) and a faster cycle time. Also, when comparing initial design and RBRD it is clear that the RBRD has the lowest cycle time while meeting reliability requirements. This optimization model determines the optimal IMSR value required for each stage of the IMS. Thus, we can conclude that developed RBRDO model can minimize costs while satisfying the reliability requirements.

Table 4: Cost functions obtained after each iteration.

Iteration	Cost ($)
0	6.092591e + 06
1	3.407595e + 06
2	2.819751e + 06
3	2.670462e + 06
4	2.603249e + 06
5	2.132391e + 06
6	1.343782e + 06
7	6.404783e + 05
8	5.742168e + 05
9	5.739864e + 05
10	5.405386e + 05
11	5.083312e + 05
12	4.506476e + 05
13	3.197391e + 05
14	2.860919e + 05
15	2.856679e + 05
16	2.850551e + 05
17	2.850489e + 05
18	2.850320e + 05
19	2.160011e + 05
20	2.159386e + 05
21	1.890276e + 05
22	1.806205e + 05
23	1.776129e + 05
24	1.767619e + 05
25	1.763392e + 05
26	1.748977e + 05
27	1.738370e + 05
28	1.734791e + 05
29	1.733999e + 05
30	1.733938e + 05
31	1.733937e + 05
32	1.733937e + 05
33	1.733937e + 05
34	173393.6728

By applying the developed RBRDO model, the required reliability is achieved, all constraints are satisfied, and the impact of uncertainty is minimized as shown in Figure 5.

To investigate how reliability influences the total cost, different scenarios with various reliability rates were simulated. This investigation is summarized in Figures 6 and 7.

Figure 6 shows that the cost increases nonlinearly with the reliability requirements. For example, if the required IMSR is 70% the cost is $27,500, and this cost increases to $100,000 if the reliability requirement increases to 90%. Figure 7 shows that applying the RBRDO achieves the reliability target and reduces variation. Moreover, the RBRDO can shift and adjust the total project cycle time based on the due date and reliability requirements. Figure 7 shows that the variation and cycle time decrease when reliability increases.

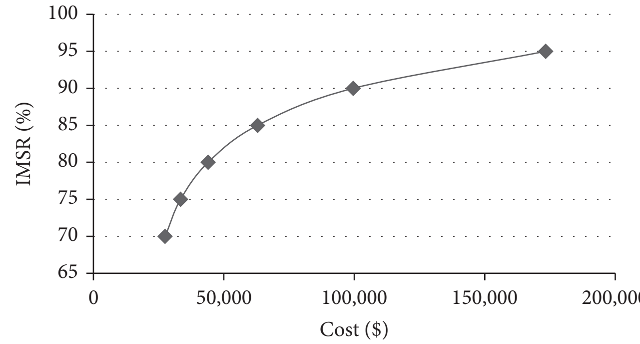

Figure 6: Cost of increasing the IMSR.

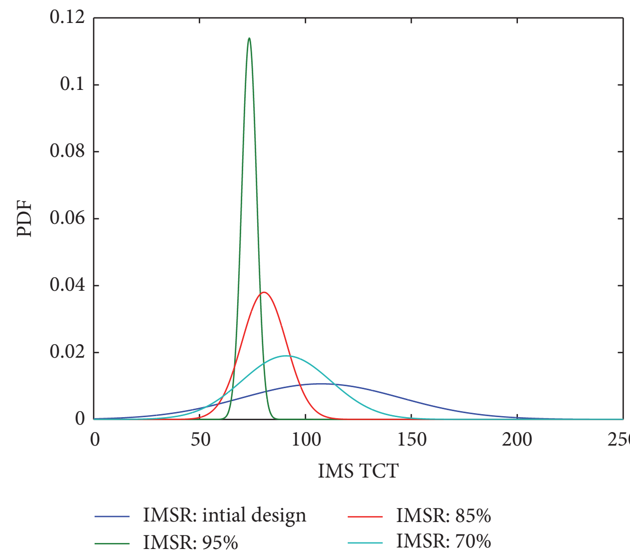

Figure 7: Distributions of the mean TCT at different IMSRs.

For example, a process with 95% reliability has lower cycle time and variation than one with 85% reliability.

Applying the RBRDO allows businesses to control reliability requirements while minimizing variation (impacts of uncertainty), while minimizing total cycle time and cost. This allows identification of activities that should be improved and the level of improvement required to achieve reliability targets. In addition, the proposed model helps to balance cost and reliability requirements, while also minimizing the impacts of product movement uncertainty.

4. Conclusion

IMSs are critical to many businesses. The primary objective of inventory management is to determine and control stock levels to minimize cost and achieve customer satisfaction. To achieve this, multiple design tools were applied to RBRDO development in order to help design a reliable IMS. These techniques include Monte Carlo simulation, deterministic nonlinear programing, and stochastic nonlinear programing. In addition, Microsoft Excel solver and MATLAB were used for modeling and mathematical simulation.

This research contributed primarily to IMS evaluation and design optimization. Equations (1) and (2) can be used to evaluate the reliability of each task in an inventory system, as well as overall IMS reliability. Equation (3) helps to design a cost-efficient, reliable, and robust system while coping with uncertainty. In other words, the RBRDO model can help with task scheduling to satisfy reliability requirements, as well as with determining time limits for each activity to satisfy due date and reliability requirements. The furniture company case study verified and validated the models. The case study showed that RBRDO can be used to design a reliable and robust IMS, while minimizing the impact of uncertainty. This positively impacts customer satisfaction. The model helps to determine the optimal time for each task, reducing delays and increasing the level of client trust and satisfaction.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this article.

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