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Application of Branch and Bound and Dynamic Programming in Demand Forecasting for Supply Chain Optimization

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Abstract: ***The implementation of inventory optimization tools enables businesses to make precise inventory allocation decisions, such as the categorization of distribution levels based on demand and constraints and the improvement of demand forecasting. Inventory optimization is a vital concern for retail establishments. Supply chain management forecasts have frequently been unreliable and imprecise due to insufficient optimization strategies and inconsistent alignment of information technology with business strategy. This article presents a technique for the formulation of constraints and the justification of demand forecasting optimization. The methodology is implemented by employing a Branch and Bound and Dynamic Programming approach that is compatible with Expert System extensions. Effective administration of business processes entails fostering coordination, presenting a variety of stakeholder perspectives, and facilitating participation and collaboration. These factors are essential for achieving successful results. Using algorithmic models and rapid prototyping approaches, the research identifies the fundamental factors underlying demand fluctuations and forecasts the most beneficial outcomes for demand and supply chain management. This study presents a comprehensive inventory optimization strategy that aims to improve inventory control throughout the entire supply chain. This strategy employs both the Branch and Bound technique and the Dynamic Programming Optimization Methodology as its methodology.***

Keywords: Constrained Optimization, Demand Forecasting, Supply Chain, Optimization Methodology, Dynamic Programming

1. Introduction

The optimization of inventory has evolved into a sophisticated mathematical approach to assess and measure the propagation of ambiguity in demand and supply across a multi-tiered supply chain. Inventory optimization is a supply chain management technique that aims to eliminate excess inventory while ensuring adequate inventory levels in strategic locations to meet customer demand and achieve revenue goals. The optimization of inventory is considered a crucial necessity for medium and large enterprises. It has the potential to produce substantial cost savings in working capital by decreasing inventory levels, while not adversely affecting business operations or sales. Dziri et al.,[1] note that traditional inventory cycles involve procuring excessive inventory to accommodate potential increases in demand, which is then followed by the disposal or sale of surplus inventory at a loss.

The objective of inventory optimization is to minimise the vertical demand for commodities throughout the supply chain [2]. To achieve a comprehensive comprehension of the factors contributing to suboptimal inventory levels, it is essential to possess a comprehensive understanding of the Order-to-Delivery process. This process concerns the internal management and procurement of inventory within the organization [3]. In order to optimise the inventory supply chain process, it is imperative to gather data pertaining to inventory and consumer trends from previous years, set objectives for inventory maximisation, and assign accountability to relevant entities for various tasks involved in the inventory process. According to Narmadha et al.,[4], there have been several catalysts that have propelled the ascendancy of inventory optimization over the past decade. Dziri et al.,[5] identified several factors that are relevant to the optimization of inventory management. These factors include the effectiveness of improvement initiatives that focus on operations, the manual synchronisation of supply and demand, the prioritisation of performance metrics related to the supply chain, and the availability of commercial platforms for Inventory Optimization [6]. Each of the aforementioned constraints exhibits unique attributes; however, they hold significance in the realm of Industrial Organisation (IO) as they establish a stringent correlation between the inputs and outputs of the supply chain [7]. Moreover, they can serve as a fundamental structure for accelerating the achievement of advantages associated with inventory optimization. By aligning capacity levels and material procurement plans with anticipated demand, there is an increased emphasis on accurately defining inventory objectives.

2. Inventory Optimization and Management

Many organizations strive to attain balance in their inventory levels by reconciling their needs and preferences, with the primary aim of cost reduction [5], [8]. The domain of inventory management concerns itself with forecasting demand, managing assets for both raw materials and finished products, computing inventory carrying costs, implementing forecasting and pricing strategies, and verifying the authenticity of goods to estimate future demand [6]. The crucial nature of inventory optimization and management in circulation businesses has attracted considerable academic attention. The subject matter has garnered substantial academic attention over the course of the last two decades. A study was conducted to develop an Economic Order Quantity (EOQ) model that considers the stock level-dependent demand. This study was conducted by Dziri et al. [4] and Shapiro & Wagner [9]. Additionally, a study was carried out on the production-inventory framework concerning perishable commodities characterized by a consistent level of output and demand that demonstrates a positive association with the inventory level [8]. A perishable goods model was formulated utilizing the Economic Order Quantity (EOQ) framework, with the underlying assumption that inventory levels have a direct impact on demand and that certain stock-outs may be replenished at a subsequent point in time. Chinello et al., [2] conducted an investigation aimed at identifying the most suitable resolution for a multiproduct Economic Order Quantity (EOQ) model. The study investigated the most effective approach for restocking perishable goods with the aim of maximizing profits. Additionally, the research explored an inventory optimization technique for perishable items that are susceptible to demand fluctuations based on stock levels. This work is comparable with Guo et al., [7] who constructed a model by combining replenishment strategies and subsequently solved and simulated said model using a genetic algorithm.

There have been several academic investigations conducted on the implementation of constrained optimization algorithms in the context of supply and demand. Despite the presence of inherent uncertainty in supply and demand, several unforeseeable variables influenced the optimization of inventory, as noted by Dziri et al., [4]. The representation of random variables in a discrete manner is deemed necessary for the majority of demand and supply in reality, as suggested by Hoppe [8] and Singh and Kumar [10]. Several scholars have conducted research on diverse subjects, including the improvement and administration of inventory systems by preserving supply-demand balance, and the development of algorithms to attain optimal inventory costs [1], [3], [11]. Furthermore, the integration of research findings contributes to the advancement of theoretical studies, as evidenced by the works of Keizer et al. [9] and Yadav et al., [12]. Previous studies have primarily concentrated on distinct industries within a specific region to address the unique difficulties linked to enhancing inventory management [10]. The lack of a widely accepted definition for supply chain optimization and its effects on organizational characteristics and practices [2] has led to difficulties in determining appropriate metrics for evaluating supply chain performance, due to the complex nature of these systems. The supply chain optimization philosophy has gained significant attention in both academic literature and practical applications. However, it is important to acknowledge that the theoretical foundation of this philosophy is somewhat restricted, as noted by Guo et al. [7]. The formulation of a supply chain strategy can be facilitated by adopting a valuable approach that entails conceptualizing the organizational structure of distribution channels as a network of flows that encompasses the transportation of goods, provision of services, and dissemination of information [1]. The potential benefits of integrating channels in the supply chain include improved operational efficiency for all participating entities and increased opportunities for effective collaboration.

3. Constrained Minimization Model

The formulation of a general constrained minimization problem can be expressed as follows; $\min \boldsymbol{f}(x)$

$$\mathit{subject\ to}\quad g_i(x) = c_i \ for\ i = 1, \ldots \ldots ., n \quad \mathit{Equality\ constraints}$$

$$h_j(x) \geqq d_j \ for\ j = 1, \ldots \ldots ., m \quad \mathit{Inequality\ constraints}$$

Where$g_i(x) = c_i \ for\ i = 1, \ldots \ldots ., n$ and$h_j(x) \geqq d_j \ for\ j = 1, \ldots \ldots ., m$ are hard constraints that require to be satisfied and $\boldsymbol{f}(x)$ is the objective function that needs to be optimized subject to the constraints.In the context of constraint optimization problems, the objective function can be expressed as a summation of cost functions. These cost functions are specifically formulated to penalise the extent to which a soft constraint is breached [13], a desirable condition that is not mandatory to fulfil. The penalty method is a commonly used approach to transform constrained optimization techniques into unconstrained ones. Penalty methods are an algorithmic approach employed for the resolution of optimization problems that entail constraints, as stated by Guo et al., [7]. The penalty method is a mathematical approach that converts a problem of constrained optimization into a series of unconstrained problems. The aim is to achieve a solution that exhibits convergence to the optimal solution of the initial constrained problem, as stated by Bon et al., [1]. Incorporating a penalty function, which is multiplied by the objective function, can generate unrestricted problems. The computation involves multiplying the penalty parameter by a metric that quantifies the degree of constraint violation. When constraints are violated, there is a measurable degree of noncompliance. On the other hand, in the realm where limitations are enforced, the degree of transgression is non-existent[4]. According to the hypothesis, in a situation with limited conditions; whereby

min $\boldsymbol{f}(x)$ is subject to;

$$c_i(x) \leq 0 \ \forall i \ \in I \qquad \text{Eq. 1}$$

The resolution of this matter can be achieved through the implementation of a series of unconstrained regression predicaments.

$$\min \Phi_k\,(x) = \boldsymbol{f}(x) + \ \sigma_k \textstyle\sum_{i \in I} g\big(c_i(x)\big) \qquad \text{Eq. 2}$$

$$\text{Where}\, g\big(c_i(x)\big) = \max(0, c_i(x))^2 \qquad \text{Eq. 3}$$

The aforementioned equations involve the utilisation of g(c_i (x)) as the external penalty function, with σ_k serving as the penalty coefficients. The method involves increasing the penalty coefficient σ_k in each iteration k, typically by a factor of 10. Subsequently, the unconstrained problem is resolved and the resultant solution is utilised as the initial point for the following iteration. Over time, the solutions to consecutive limitless challenges will ultimately lead to the solutions of the initial limited challenge.

4. Branch and Bound and Dynamic Programming Optimization

The Branch and Bound (BB, B&B, or BnB) methodology is a prevalent strategy employed in the development of algorithms that tackle problems pertaining to discrete and combinatorial optimization, as well as mathematical optimization [9]. According to Guo et al., [7], the utilization of a branch-and-bound approach entails a systematic enumeration of possible solutions via a state space search. The set of possible solutions is commonly conceptualized as a tree structure, with a primary node serving as the root, from which all potential solutions emanate [14]. The algorithm employs a systematic approach to traverse the branches of a tree, where each branch corresponds to a unique subset of the set of possible solutions. Prior to enumerating the prospective remedies for a given branch, it is subjected to a comparative analysis involving the upper and lower approximations of the optimal solution. In the event that the branch fails to produce a solution that outperforms the present optimal solution acquired through the given approach, it is eliminated from further consideration.

The primary aim of a branch-and-bound algorithm is to identify a value x that optimizes the value of a real-valued function $f(\chi)$, commonly known as an objective function, within a set S of feasible or permissible solutions [2]. The collection denoted by ***S*** is commonly referred to as the search space or feasible region in academic literature. The subsequent methodology assumes that minimizing the function $f(\chi)$ is preferable [13]. This assumption is made without any loss of generality, as the maximum value of $f(\chi)$ can be obtained by minimizing the function $g(\chi) = f(\chi)$. In order to operationalize these concepts for a specific optimization problem, it is necessary to utilize a data structure that can represent sets of potential solutions. The form of representation mentioned above is widely recognized as an exemplification of the problem, as noted by Dziri et al.,[4]. ***SI*** represents the feasible solutions for a specific instance, ***I***. According to [9], the B&B algorithm employs a series of procedures to perform a hierarchical exploration of the tree of instances generated by the branch operation. After the return of an instance I, an evaluation is conducted to ascertain whether the bounded value (***I***) surpasses the present upper limit. When this condition is satisfied, it is considered safe to remove ***I*** from the search, and the process of recursion is concluded. Typically, this methodology involves the preservation of a universal variable that encompasses the minimum upper bound observed among all instances examined up to the present moment.

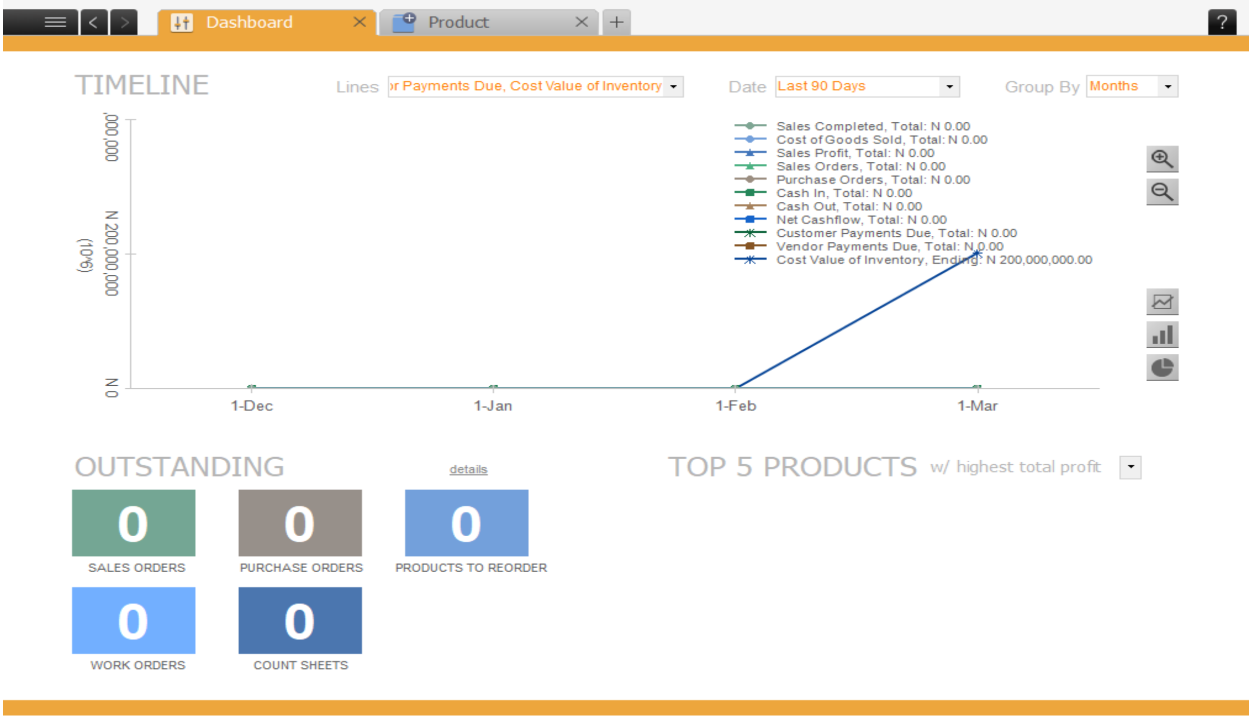
The subsequent content outlines the fundamental framework of a universal branch and bound algorithm aimed at minimizing an arbitrary objective function f.To derive a precise algorithm from this, it is imperative to fix a bounding function that can evaluate the least values of f on the diverse nodes present in the exploration tree. Furthermore, a branching rule that is customized to the particular problem under consideration is also required. The approach outlined within this particular context pertains to a function of higher order.

1) By applying a heuristic approach, determine the optimal solution χh for the given optimization problem. The value of ***B*** is stored as a function of $f.(\chi h)$. (If no heuristic is available, set ***B*** to infinity.) The variable denoted as "B" signifies the most efficient solution that has been identified up to the present moment and is intended to function as a maximum threshold for prospective solutions.
2) Create a queue to retain a partial solution without assigning any of the problem's variables.
3) Loop until the queue is empty following the sequence;
    - Take a node ***N*** off the queue.
    - If ***N*** denotes a singular candidate solution x and if $f(\chi)$ is less than B, then x can be considered as the optimal solution among the available solutions. The action to be taken is to record it and assign the value of f to variable **B**.(χ).Else, *branch* on *N* to produce new nodes N_i. For each of these:
    - If bound(N_i) > ***B***, do nothing; since the lower bound on this node is greater than the upper bound of the problem, it will never lead to the optimal solution, and can be discarded.
    - Else, store N_i on the queue.

The problem-solving methodology of dynamic programming entails decomposing a complicated problem into smaller sub-problems using recursive techniques to facilitate its simplification [7]. While some resolution-related concerns may not be amenable to deconstruction in this manner, decisions that span multiple temporal junctures frequently undergo iterative dismantling. The research methodology utilised in this study involves the implementation of a recursive stratification of sub-problems within larger problems. This approach facilitates the application of dynamic programming techniques and establishes a relationship between the value of the overarching problem and the values of the sub-problems, as outlined by [2]. The current investigation employs optimal substructure as the fundamental characteristic for dynamic programming. The principle of optimal substructure posits that the solution to a given optimization problem can be attained by combining the optimal solutions of its constituent sub-problems. The concept of optimal substructures is frequently elucidated by means of recursion, as noted by Dziri et al. [4].

5. Optimization Algorithm Archetype

Figure 1 illustrates an IOS that provides a comprehensive solution for the optimization of inventory management. The primary objective of its creation was to improve the precision of inventory management, streamline the allocation of human resources within the inventory system, and mitigate the expenses incurred due to the retention of outdated and low-demand stock. The IOS platform has been developed to cater to the diverse requirements of distribution centers of varying sizes, encompassing both small and large facilities that necessitate high-capacity operations.



Lines: r Payments Due, Cost Value of Inventory
Date: Last 90 Days
Group By: Months

SALES ORDERS	0
PURCHASE ORDERS	0
PRODUCTS TO REORDER	0
WORK ORDERS	0
COUNT SHEETS	0

Figure 1: Constrained Optimization

According to [2], the integration capability of IOS is distinctive and uninterrupted, allowing for effective coordination of stock and inventory movements. Consequently, the ability to select numerous orders within a solitary wave by one or more stock pickers can lead to noteworthy reductions in both time and expenses. The IOS platform enables the enhancement of inventory and personnel efficiency. The precise tracking of inventory movement in both "pick" and "overstock" locations can provide personnel with clear guidance to a specific bin, ensuring that the item will be accessible at all times. Moreover, the scheduling of replenishment requests management can be planned during off-peak hours or coordinated with the picking operations. The utilization of IOS results in optimized inventory operations, enabling enterprises to enhance order precision, eliminate paper-based errors, perform simultaneous picking and packing, fulfil multiple orders concurrently, monitor inventory in real-time, generate packaging slips on demand, and ultimately augment customer contentment [9].

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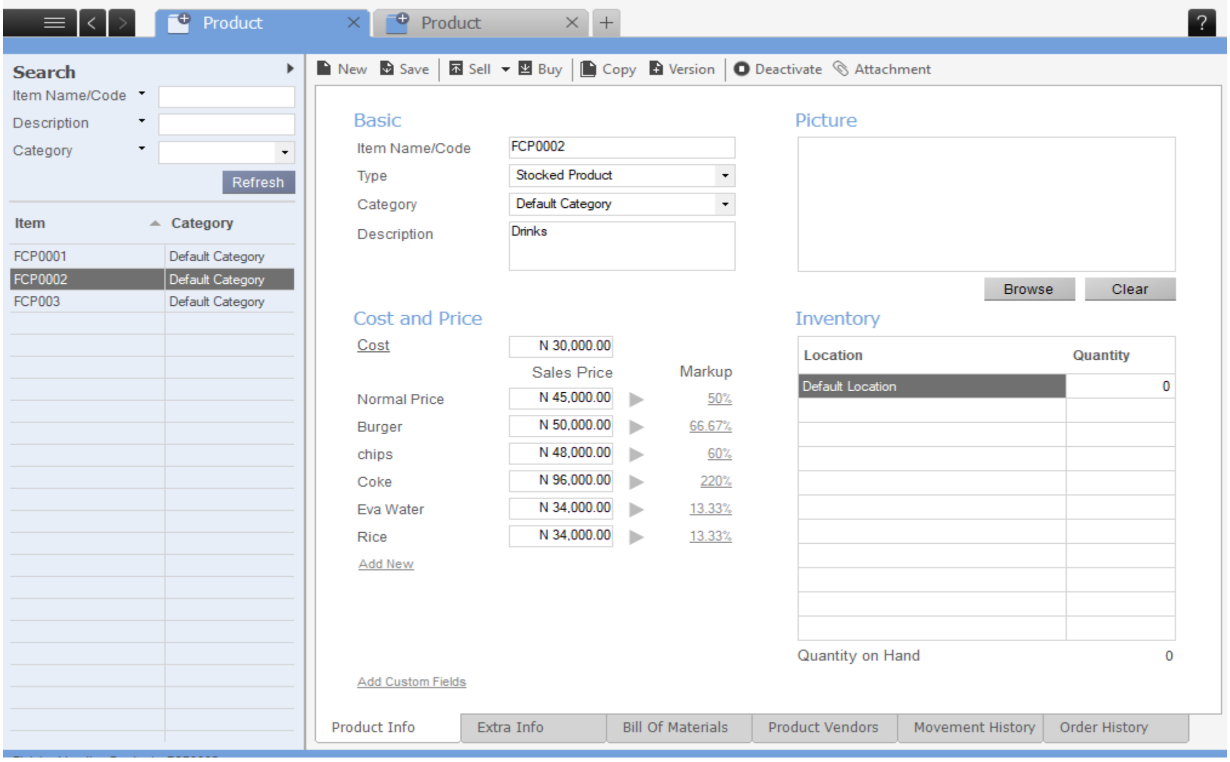


Item	Category
FCP0001	Default Category
FCP0002	Default Category
FCP003	Default Category

Item Name/Code: FCP0002
Type: Stocked Product
Category: Default Category
Description: Drinks
Cost: N 30,000.00

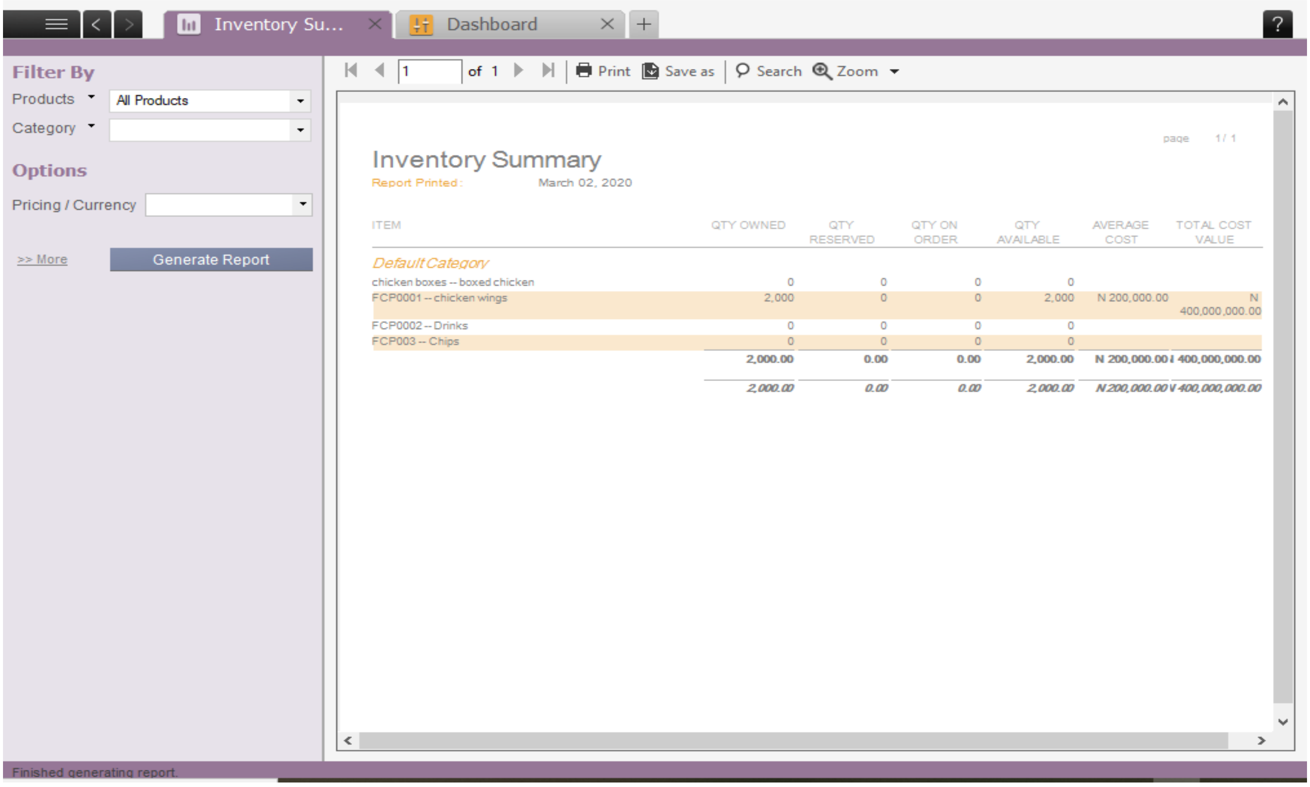
	Sales Price	Markup
Normal Price	N 45,000.00	50%
Burger	N 50,000.00	66.67%
chips	N 48,000.00	60%
Coke	N 96,000.00	220%
Eva Water	N 34,000.00	13.33%
Rice	N 34,000.00	13.33%

Location	Quantity
Default Location	0

Quantity on Hand: 0

Figure 2: Product Definition

The graphical user interface illustrated in Figure 2 serves the purpose of managing suppliers in the system. This includes the ability to assign prices to their products and allocate vendor product codes to the respective products. Moreover, the system grants access rights to specific system functionalities and facilitates the assessment of the organization's supplier list. The employment of IOS instruments enables the streamlining of inventory acquisition procedures and amplifies the effectiveness of logistics administration [15].



Products: All Products
Category:
Pricing / Currency:

1 of 1

page 1/ 1

Inventory Summary
Report Printed: March 02, 2020

ITEM	QTY OWNED	QTY RESERVED	QTY ON ORDER	QTY AVAILABLE	AVERAGE COST	TOTAL COST VALUE
Default Category						
chicken boxes -- boxed chicken	0	0	0	0		
FCP0001 -- chicken wings	2,000	0	0	2,000	N 200,000.00	N 400,000,000.00
FCP0002 -- Drinks	0	0	0	0		
FCP003 -- Chips	0	0	0	0		
	2,000.00	**0.00**	**0.00**	**2,000.00**	**N 200,000.00**	**400,000,000.00**
	2,000.00	*0.00*	*0.00*	*2,000.00*	*N 200,000.00*	*400,000,000.00*

Finished generating report.

Figure 3: Optimization Summary

By leveraging real-time access to the IOS, the procurement department is capable of promptly addressing customers' stock requisitions. The supply chain is furnished with accurate inventory information through the use of IOS technology, which empowers them to conduct preliminary investigations on pricing estimates. The utilisation of the Branch and Bound algorithm for the purpose of solving constrained optimization problems is employed. The algorithm integrates regulations that establish constraints for the acquisition of a commodity, constraints for ascertaining the quantities to be procured, constraints for determining the maximum expenditure, constraints for determining the quantities or count of components or commodities to be obtained from a particular vendor, and/or an algorithm that specifies the minimum and maximum count of vendors for the provision of commodities. The optimization algorithm allows for the nesting of rules. The utilisation of IOS optimization tools enables the deliberate positioning of the procurement department within the broader context of the product supply chain [11]. The deployment of automated inventory management systems not only assists in mitigating inaccuracies and delays that could have arisen from manual inventory processes, but also expedites the prompt delivery of merchandise to the ultimate consumer [13].

6. Demand Forecasting in Supply Chain

A forecast is a prediction or estimation made for a future period that is marked by uncertainty, as in the case of a weather forecast. Predictive models are commonly employed in the business industry to anticipate market demand, which justifies our focus on this particular facet. Two primary categories of forecasting methodologies have been identified as qualitative forecasting and quantitative forecasting [16]. Qualitative forecasting, also known as decision forecasting, entails the integration of subjective inputs such as executive opinions, sales force composites, consumer surveys, and stakeholder opinions. Conversely, the methodology of quantitative forecasting entails the utilization of empirical data [3] historical data, as well as associative models that incorporate explanatory variables, to produce forecasts for future occurrences. The current study utilized a time series methodology to make predictions regarding the supply and demand, as reported by Chinello et al., [2]. A time series is a collection of data points that are arranged chronologically and obtained at regular intervals during a specific time frame. The application of forecasting techniques has been based on time series is based on the assumption that future values of the series can be inferred from its past values [14]. The analysis of time series data facilitates the detection of the patterns exhibited by the series, encompassing its extended or abbreviated features, and its stochastic or deterministic properties, necessitating the utilization of appropriate techniques. The Moving Average approach is utilized for forecasting time series data through the utilization of a moving average, which is also referred to as a weighted moving average [5]. According to Duan and Liao, [5], the calculation of the moving average, represented as mt, entails computing the average of a group of data points that correspond to L periods and end at period ***t***.so that;

$$t-L+1, t-L+2, t-L+3, \ldots., t-1, t$$

$$m_t = \frac{Y_{t-L+1}+Y_{t-L+2}+Y_{t-L+3}+\cdots+Y_{t-1}+Y_t}{L}$$

The methodology proposed entails the utilization of the moving average approach for the purpose of forecasting forthcoming values that surpass the time period t, which is represented as mt. The objective of the model is to predict the outcome for the next time period and subsequently adjust the moving average by integrating the observed data for that specific time frame. The implementation of the system's algorithm reflects the way in which it has been executed.

7. Results and Discussion

The study successfully demonstrates the application of Branch and Bound and Dynamic Programming in demand forecasting, contributing to the optimization of supply chain management. The results highlight the potential of these methodologies in improving inventory control and business processes. In recent years, the practical application of inventory optimization has gained prominence as a means of improving corporate profitability, marking a shift from its previous status as a theoretical concept primarily taught in academic settings. The essential components of inventory, specifically the fluctuation of demand and supply, are present in all supply chains, making inventory optimization a pertinent strategy for all industries [17]). This study elaborated on the application of constrained optimization methods in the field of supply chain management, specifically in relation to forecasting demand. Maintaining a consistent inventory replenishment process is crucial for the efficient operation of a business. Neglecting to do so can lead to a considerable backlog, which can have adverse effects on the overall functioning of the business. Insufficient evaluations of requirements may result in either a surplus or a shortage of resources. Manual inventory management systems are deficient in their capacity to identify inconsistencies, anticipate future requirements, or leverage data to generate analytical patterns. The absence of real-time data updates and suboptimal inventory levels that do not meet demand are common issues observed in decentralized manual inventory systems, as noted by Bon et al., [1] and Radhakrishnan et al. [13]. The manual system poses administrative challenges that render the implementation of cost-cutting techniques, predictive analysis, or process efficiency unfeasible. The implementation of inventory optimization systems enables organizations to make well-informed decisions regarding inventory deployment. This is achieved through the utilization of various techniques, including the categorization of stocking levels (buffer, replenishment, and overage) based on historical demand, the enhancement of supplier management based on supplier performance, and the refinement of demand forecasting [9]. The optimization of inventory involves a wider range of activities that extend beyond the mere observation of variations in supply and demand. The Inventory Optimization Systems (IOS) platform offers businesses the ability to track and manage inventory, enabling the monitoring of inventory placement and utilization across multiple locations, including inventory sites, distribution centers, and retail outlets. Irrespective of the conventional guidelines pertaining to any improvement endeavor, there are two pivotal practices that are indispensable for attaining triumph in inventory optimization. The first step of the process entails the deconstruction of the inventory into its basic constituents. Comprehending that inventory is not a singular, uniform quantity is imperative for achieving optimal inventory levels [18]. The subject under consideration can be decomposed into individual components that serve distinct functions. The aim of this study was to evaluate the incorporation of the IOS platform in a multinational enterprise through the use of empirical measures and analysis of data related to the existing systems and resources employed to develop an inventory optimization system. The implementation of constrained optimization algorithms that adhered to industry norms and organizational protocols was a critical factor in achieving success. The extant framework has recognized several concrete benefits linked to the adoption of a system. Moreover, this study contributes to the existing literature by providing a case analysis that can serve as a prototype for other organizations facing comparable challenges in optimizing logistics. The research additionally demonstrates the effectiveness of the system that was created. In addition, contemporary research has the potential to significantly influence the implementation of vital studies related to inventory optimization and control models, as well as algorithmic progressions for continuous and discrete optimization.

8. Conclusion

The study successfully demonstrates the application of Branch and Bound and Dynamic Programming in demand forecasting, contributing to the optimization of supply chain management. The results highlight the potential of these methodologies in improving inventory control and business processes.Branch and Bound and Dynamic Programming offer several benefits when applied to demand forecasting. Both techniques allow for the consideration of multiple scenarios and factors, resulting in more accurate demand forecasts thereby enhance acurracy. The study demonstrated that by exploring different branches or subproblems, Branch and Bound and Dynamic Programming can identify the optimal solutions that minimize forecasting errors and optimize inventory planning. The methodology also helps in optimizing the allocation of resources such as inventory, production capacity, and workforce. By considering various constraints and objectives, these techniques can determine the most efficient allocation decisions over multiple time periods, leading to improved resource utilization and cost reduction.These techniques enable efficient decision-making by pruning unpromising branches or considering subproblems with dynamic programming. This reduces computation time and allows demand forecasters to focus on the most promising options, leading to faster and more effective decision-making. By combining the approaches, the interdependencies between different time periods, decisions, and variables were accounted for. This ensures that the forecasted demand and inventory planning decisions are consistent and optimized over the entire planning horizon, considering the impact of decisions made in previous periods.Overall, the application of Branch and

Bound and Dynamic Programming in demand forecasting offers improved accuracy, efficient decision-making, optimal resource allocation, and the ability to handle complex problems. By incorporating these techniques, organizations can enhance their demand forecasting capabilities and achieve better planning, inventory management, and customer service outcomes.

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