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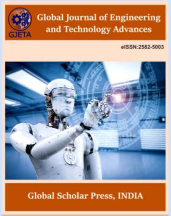

(RESEARCH ARTICLE)

A MATLAB platform for production planning in batch processing firms producing items that are jointly replenished

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Abstract

Rising levels of poverty have prompted manufacturers of non-durable consumer goods to explore opportunities at the lower end of the wealth spectrum. To enhance affordability for low-income consumers, these goods are often packaged in various sizes, including single-serve sachets. While numerous models and algorithms have been developed to determine the optimal frequency of manufacturing runs and packaging setups for the simultaneous replenishment of different pack sizes, there is a notable lack of literature addressing their implementation by small and medium-sized enterprises (SMEs) in this sector. This gap may be attributed to the absence of accessible source codes, a shortage of model experts, and the complexity involved in manual calculations. To address this issue, we developed a user-friendly MATLAB software platform based on Goyal's algorithm, tailored specifically for SMEs. The software prioritizes simplicity, interactivity, and flexible visual displays. It was validated against examples from existing literature and through randomly generated scenarios. Users can easily compute the optimal number of manufacturing setups, packaging frequencies for each pack size, and the associated costs by inputting relevant data such as manufacturing setup, inventory holding and packaging setup costs, and demand for each pack size. Importantly, users do not need expertise in modeling to operate the software. However, it is designed for single-product deterministic environments; future research should explore multi-product and stochastic modeling scenarios.

Keywords: Consumer goods; Economic order quantity; Decision support system; Inventory management; Software platform

1. Introduction

The manufacturing sector in many developing countries, particularly in Nigeria, has been grappling with significant challenges stemming from the economic downturn that began in the 1980s. This period of socio-economic change has resulted in diminished purchasing power, widespread job losses, and increasing unemployment, pushing many individuals below the poverty line [1–4]. In 2022, an additional five million Nigerians joined the ranks of the impoverished [4]. By 2023, Nigeria's share of the global population living in extreme poverty rose from 9% to 12% [3-5]. As a result, the demand for goods and services has declined, exacerbated by reduced consumer spending driven by the growing number of people experiencing poverty. Manufacturing firms are facing extreme difficulties as they navigate this challenging economic landscape. Extensive discussions among researchers, manufacturers, and policymakers have focused on creating a more favorable economic environment for the manufacturing sector [6–9]. However, most proposed solutions have primarily addressed national and macroeconomic issues, leaving firm-level challenges inadequately addressed [9]. Few studies have investigated strategies for individual firms, as many factors influencing a conducive economic environment are beyond their control [7–9].

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Manufacturers of food, beverages, laundry detergents, deodorants, spirits, and toothpaste have recognized the significant opportunity presented by the low-income consumer segment in Nigeria. This demographic represents over five trillion dollars in purchasing power globally, with Nigeria accounting for 12% of this population [3-5]. In response, manufacturers have strategically diversified their packaging, offering finished products in various container sizes to effectively reach different market segments. Following Promasidor Nigeria Ltd's success in targeting lower-income consumers by introducing milk powder in multiple pack sizes, including single-serve sachets, many other companies have similarly adopted this strategy. Producers of non-durable consumer goods now package their items in a range of sizes, from more affordable options such as single single-serve sachets weighing as low as 2 grams to larger family-sized packages—typically one liter or kilogram or more—in cans, bottles, and bags/kegs aimed at middle-income earners [10]. This approach has notably succeeded in reaching low-income consumers; in fact, the National Agency for Food and Drug Administration and Control in Nigeria intervened to halt the registration of alcohol in sachets, small PET volumes, and glass bottles under 200 mL and above 30% ABV to combat alcohol abuse and restrict affordability for underage individuals [11, 12].

Packaging products in multiple container sizes after manufacturing is classified as the Joint Replenishment Problem (JRP) [13, 14]. In JRP scenarios, the key objective for decision-makers is to determine the optimal frequency for manufacturing and packaging setups that minimizes costs while fulfilling the demand for each pack size. Since the foundational work by Shu [13], the JRP has been an active field of research for mathematicians, engineers, and operations research specialists, resulting in numerous proposed models and solution algorithms [15-17]. Recent research efforts have focused on developing more efficient and faster algorithms [18-22, 22-29]. Studies have produced models for JRPs in deterministic, stochastic, and dynamic contexts, as well as for cases involving multi-echelon and single warehouse multi-retailer structures, resource constraints, discounts, degrading products, and trade credits among others [16, 17]. However, despite the abundance of models and algorithms generated by researchers, their practical application remains limited, as evidenced by the lack of real-world implementations. Practitioners often encounter challenges in applying these algorithms due to (i) the absence of provided source codes for many of the algorithms, and (ii) the time-consuming and complex nature of manual computations that typically demand specialized expertise. Thus, production planners, managers, and purchasers increasingly require access to software platforms that can simplify the resolution of these complex problems [30-33].

Despite numerous attempts to integrate JRP solution algorithms into enterprise resource planning (ERP) software as add-ins, advanced ERP solutions remain largely inaccessible to small and medium-sized enterprises (SMEs) in developing countries [20-25]. There is a pressing need for a cost-effective and user-friendly software platform that can serve as a decision support system, enabling practitioners to utilize JRP algorithms to address their real-world challenges. The lack of such platforms has led to a scarcity of formalized production and inventory policies, which are essential for guiding decision-making in manufacturing, inventory management, and demand fulfillment while minimizing total costs in the JRP production environment. Currently, the packaging frequency for jointly replenished items relies heavily on the subjective judgments of experienced managers and employees, often resulting in system inconsistencies and imbalanced inventory levels, causing stock-outs or excess stock on hand [30-33]. Therefore, SMEs require straightforward, intuitive, and affordable software solutions to effectively tackle their operational issues [21-23]. In light of these observations, the primary objective of this study is to develop a decision support software platform specifically designed for SMEs to help them resolve their practical problems.

2. Methodology

2.1. Mathematical Model and Solution Procedure

Goyal algorithm [14] is selected for application in this study. The methodological details of the JRP mathematical model and the solution algorithm proposed by Goyal [14] are presented.

2.1.1. Problem formulation

Consider the following scenario: a manufacturer manufactures a product in batches, and the product is immediately packaged into different container sizes in order to reach various segments of the market with the product. Each batch has a manufacturing setup cost, and each container size (also referred to as an item in the JRP literature) has its own packaging setup cost and demand. Each item also has its own unit inventory holding cost. The problem is that of determining the economic number of manufacturing runs (Q_0) and the economic packaging frequency, $F_j(Q_0), for\ each\ j \in J$ (where J is the set of container sizes/items) such that the demand for each item is met at the minimum total cost. The decision situation under consideration has the following characteristics:

- The modelling environment is deterministic
- The planning horizon is infinite
- The setup cost (S) for manufacturing run is known and constant over time
- The packaging setup cost, $P_j \; for\; each\; j \in J$ is known and constant.
- The unit inventory holding cost, $H_j \; for\; each\; j \in J$ is known and constant
- The yearly demand, $D_j \; for\; each\; j \in J$ is known and constant
- Shortages are not allowed

Moreover, $Q, F_j(Q), A_j \; and \; C(Q, F_j(Q))$ are the number of manufacturing runs, packaging frequency for item j, annual variable cost for item j and the total cost respectively. According to Goyal [14], the total cost, $C(Q, F_j(Q))$ consists of the following:

Cost of the Q manufacturing runs (c_{ms}) is given by;

$$c_{ms} = Q \cdot S \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

The sum of the costs of packaging setups for all items (c_{ps}) is given by;

$$c_{ps} = \sum_{j \in J} \frac{P_j \cdot Q}{F_j(Q)} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

The sum of inventory holding costs for all items (c_{hc}) is;

$$c_{hc} = \sum_{j \in J} \frac{D_j \cdot H_j \cdot F_j(Q)}{2Q} \;\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

The total cost, $C(Q, F_j(Q))$ is given by;

$$C\left(Q, F_j(Q)\right) = c_{ms} + c_{ms} + c_{hc} \; = Q \cdot S + \; \sum_{j \in J} \frac{P_j \cdot Q}{F_j(Q)} + \sum_{j \in J} \frac{D_j \cdot H_j \cdot F_j(Q)}{2Q} \;\ldots\ldots\ldots\ldots\ldots \quad (4)$$

The economic number of manufacturing runs is given by;

$$Q_0 = \sqrt{\frac{\sum_{j \in J} D_j \cdot H_j \cdot F_j(Q_0)}{2\left[S + \sum_{j \in J} \frac{P_j}{F_j(Q_0)}\right]}} \;\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$$\text{The packaging frequency for } j^{th} \text{ item is} = \frac{Q_0}{F_j(Q_0)} \;\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

The JRP problem is NP-hard, and the solution procedures available for the achievement of optimal values are mostly enumerative approaches that are computationally prohibitive. As a result, many heuristic procedures have emerged. In this study, the algorithm proposed by Goyal [14] is used because it is a simple and an efficient heuristic. It is able to achieve an optimal solution for 95% of the problems it is used to solve, while the remaining 5% are suboptimal. The increase in total cost due to suboptimal solutions was less than 1% [14].

2.1.2. Solution Procedure

The determination of the economic number of manufacturing runs (Q_0) depends on the knowledge of economic packaging frequency, $F_j(Q_0), for\; each\; j \in J$ which in turn also depend on the prior knowledge of Q_0 see eq. (5 and 6). Hence, a search procedure is adopted to determine Q_0. The procedural steps of the algorithm proposed by Goyal [14] for this type of problem is presented below. See [14] for the details of the derivations of the equations and the procedure.

Step 1: Compute the upper and lower bounds of ratio, $\frac{r_j^2}{Q_j^2}$ for different values of $F_j(Q)$, i.e., 1, 2, 3…, n, using eq. (7) below.

$$\frac{1}{F_j\,(Q) \cdot [F_j(Q)+1]} \leq \frac{r_j^2}{Q_j^2} < \frac{1}{F_j\,(Q) \cdot [F_j(Q)-1]} \;\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Observe that $\frac{1}{F_j\,(Q)\cdot[F_j(Q)+1]}$ and $\frac{1}{F_j\,(Q)\cdot[F_j(Q)-1]}$ are the respective lower and upper bounds of the ratio. For instance, the lower and upper bound of $\frac{r_j^2}{Q_j^2}$ for $F_j(Q) = 1, 2, 3, \dots, 7$ are as presented in Table 1. Note that the values of $F_j(Q)$ may be less or more than 7 depending on a particular JRP situation.

Table 1 The lower and Upper Bound of Ratio $\frac{r_j^2}{Q_j^2}$

$F_j(Q)$	1	2	3	4	5	6	7
Upper Bound	∞	0.500	0.167	0.083	0.050	0.033	0.024
Lower Bound	0.500	0.167	0.083	0.050	0.033	0.024	0.0178

Source: Goyal [14]

Step 2: Assume $F_j(Q_0) = 1, for\ each\ j \in J$ and calculate the first trial value Q_1 such that,

$$Q_1^2 = \frac{\sum_{j\in J} D_j \cdot H_j}{2[S+\sum_{j\in J} P_j]} \dots\dots\dots\dots\dots\dots\dots\dots \quad (8)$$

Step 3: (i) Compute the ratio $\frac{r_j^2}{Q_j^2}\, for\ each\ j \in J$, where,

$$r_j^2 = \frac{D_j \cdot H_j}{2P_j} \dots\dots\dots\dots\dots\dots\dots \quad (9)$$

(ii) identify the bounds within which the ratio $\frac{r_j^2}{Q_j^2}$ fall $for\ each\ j \in J$ from Table 1 and determine $F_j(Q_1)\ for\ each\ j \in J$.

(iii) Next, calculate the second trial value such that;

$$Q_2^2 = \frac{\sum_{j\in J} D_j H_j F(Q_1)}{2\left[S+\sum_{j\in J}\frac{P_j}{F(Q_1)}\right]} \dots\dots\dots\dots\dots\dots\dots \quad (10)$$

Note: use the values of $F_j(Q_1)$ determined from Table 1

Step 4: (i) Check if $Q_1^2 = Q_2^2$. If yes, then convergence has been attained, else repeat step 3 till $Q_{i+1}^2 = Q_i^2$ at which stage we set $Q_{i+1} = Q_0$, which is the economic number of manufacturing runs.

(ii) Compute the economic number of manufacturing runs, packaging frequency $for\ each\ j \in J$, the total cost and other relevant costs using eqs. (1) - (6).

3. Software platform

The MATLAB platform was developed to aid intelligent decision making in production planning in JRP environment using the procedure described in Section 2.1.2. It was developed to function based on the criteria of simplicity, interactivity and visual display.

3.1. Graphical User Interface

(i) User Friendliness and Interactivity: The software provides a friendly GUI and also has many interactive tool-bars and buttons. Once the authorized user logs-in through his/her user's name and password, the software platform guide is displayed as in Figure 1 below. It is the software platform guide that collates the developed scripts and functions into an interactive and friendly environment which helps to interact with the user of the system in a dynamic mode. It has interactive tool-bars containing short-cut buttons for functions such as "Enter" for inputting the number of items, "Input Variables" for inputting the names of items, packaging setup cost, demand, stock holding cost for the item and setup cost of manufacturing run. There are buttons for "Compute" and "Compute-showing-Iteration". Compute-showing-iteration button is for users who may have interest in seeing the iterations. This feature may not be of interest to most practitioners since they do not provide any information of practical value to them. However, it may be of interest to the academic community particularly for teaching purposes.

(ii) Visual Display: The platform provides good visualization of input data, iteration tableaux and results. There are two modes of data display: (a) Data mode (b) Out-put mode. The input data such as the setup cost per manufacturing run, number of items, name of item, demands for the various items, packaging setup cost and stock holding cost per unit of each item can be displayed individually for the user to view after they have been entered (see Fig. 2 - 7). Apart from displaying the input data individually as in Figures 2 - 7, there is the option of displaying them together in a spreadsheet in the space under variables on Figure 1 where the user can see all entries at a glance. The user then clicks “Ok” when s/he is satisfied that the respective values have been correctly entered, otherwise, the wrong entry is edited accordingly. The output mode of display is also flexible. For instance, the tableaux may be displayed individually or together as shown in Figure 8. The display in Figure 8 shows the result of one of the problems used to test the software. It shows the three iterations and the economic packaging frequencies of the five items joint replenishment problem. The associated cost of this policy is in the background view which the user or decision maker will see if s/he closes the iteration tableaux.

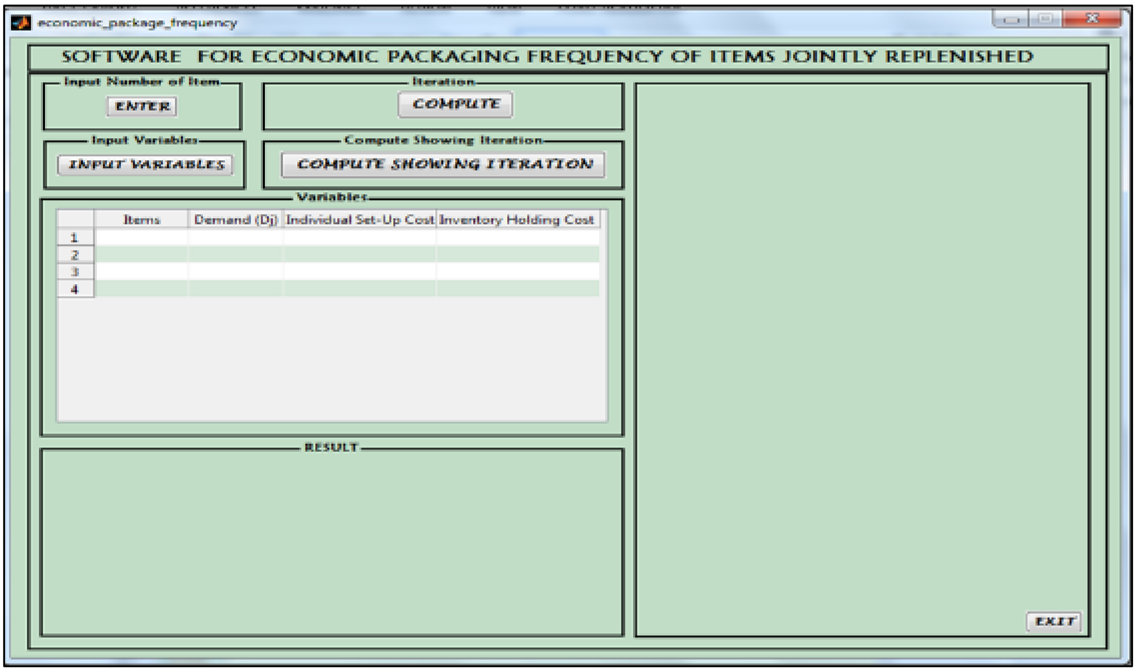
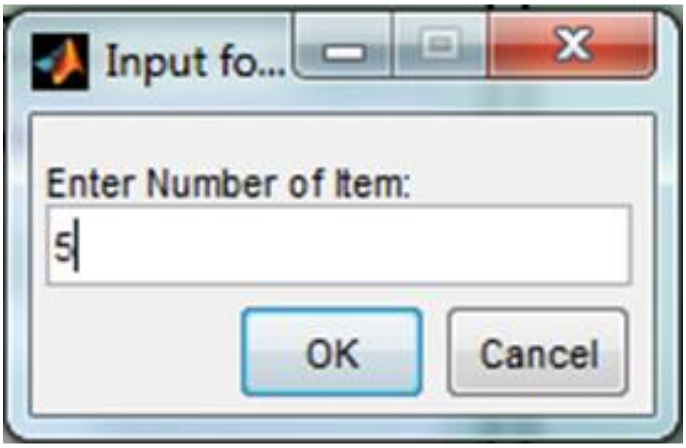
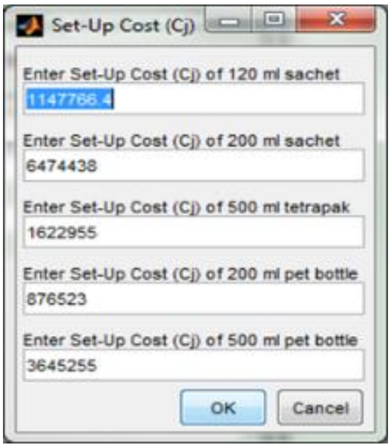


Figure 1 The GUI Software Platform



Enter Number of Item:
5

Figure 2 Input for Number of Item



Enter Set-Up Cost (Cj) of 120 ml sachet
1147766.4

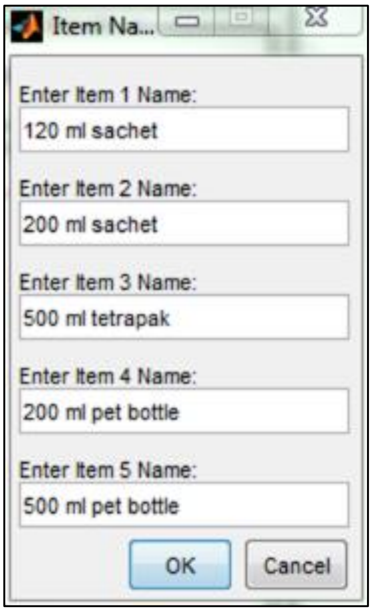
Enter Set-Up Cost (Cj) of 200 ml sachet
6474438

Enter Set-Up Cost (Cj) of 500 ml tetrapak
1622955

Enter Set-Up Cost (Cj) of 200 ml pet bottle
876523

Enter Set-Up Cost (Cj) of 500 ml pet bottle
3645255

Figure 3 Packaging Setup Cost



Enter Item 1 Name:
120 ml sachet

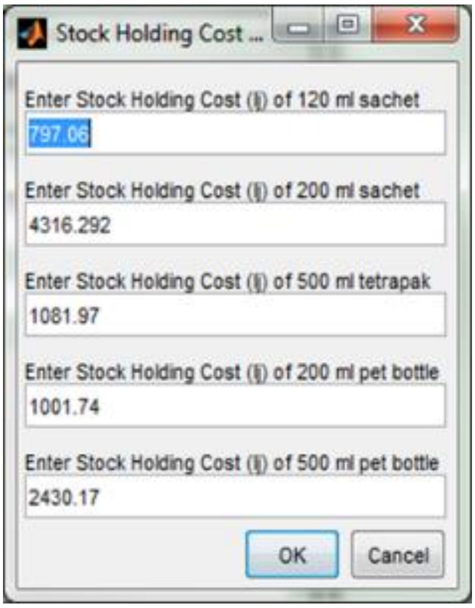
Enter Item 2 Name:
200 ml sachet

Enter Item 3 Name:
500 ml tetrapak

Enter Item 4 Name:
200 ml pet bottle

Enter Item 5 Name:
500 ml pet bottle

Figure 4 Item Names



Enter Stock Holding Cost (Ij) of 120 ml sachet
797.06

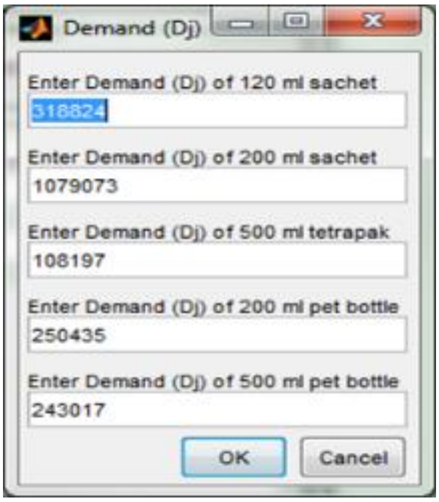
Enter Stock Holding Cost (Ij) of 200 ml sachet
4316.292

Enter Stock Holding Cost (Ij) of 500 ml tetrapak
1081.97

Enter Stock Holding Cost (Ij) of 200 ml pet bottle
1001.74

Enter Stock Holding Cost (Ij) of 500 ml pet bottle
2430.17

Figure 5 Stock-holding Cost



Enter Demand (Dj) of 120 ml sachet
318824

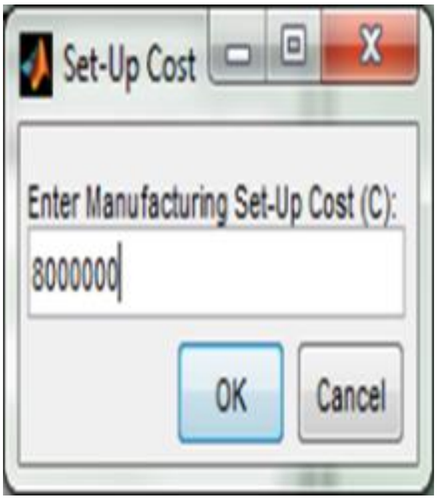
Enter Demand (Dj) of 200 ml sachet
1079073

Enter Demand (Dj) of 500 ml tetrapak
108197

Enter Demand (Dj) of 200 ml pet bottle
250435

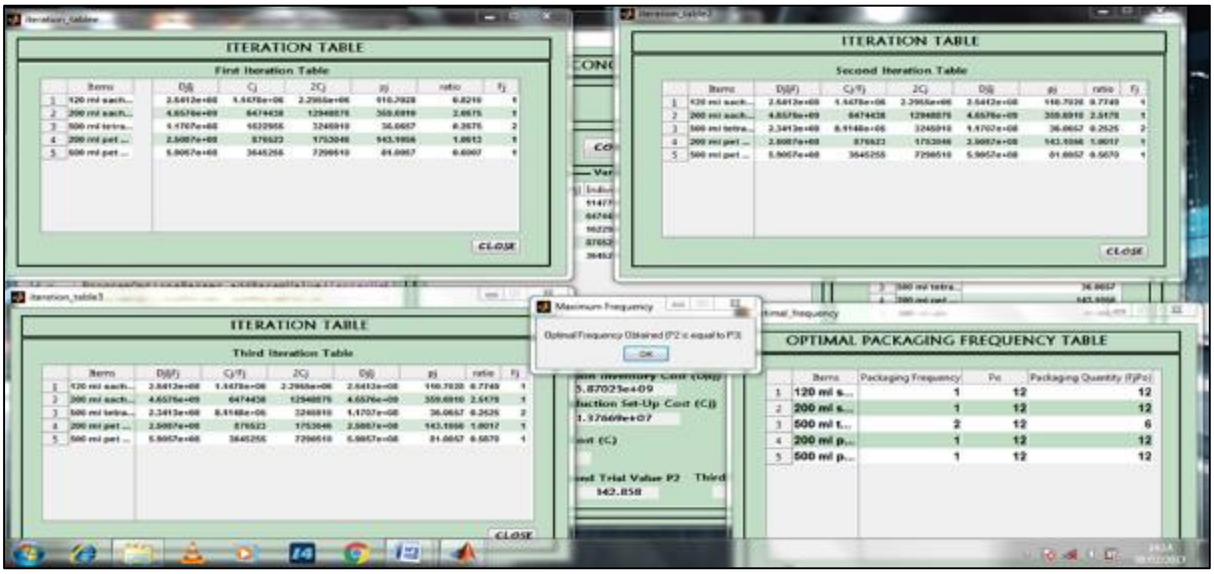
Enter Demand (Dj) of 500 ml pet bottle
243017

Figure 6 Input for Demands



Enter Manufacturing Set-Up Cost (C):
8000000

Figure 7 Manufacturing Setup Cost



Optimal Frequency Obtained (P2 is equal to P3)

	Items	Packaging Frequency	Pc	Packaging Quantity (Fj/Pc)
1	120 ml s...	1	12	12
2	200 ml s...	1	12	12
3	500 ml t...	2	12	6
4	200 ml p...	1	12	12
5	500 ml p...	1	12	12

Figure 8 Display of Result with Iterations

3.2. Numerical Verification

The software was tested with data from the literature and the results were found to be the same. Also some fictitious but realistic problems with different number of items/packs were generated and solved both manually and with the software. The manufacturing runs and packaging frequencies obtained for all the items through manual computations and those obtained by using the software were identical for the all the problems. The software is limited to the calculation of economic manufacturing setup, packaging frequencies for each pack and the corresponding total cost when the relevant input parameters are known with certainty. It is also limited to situation where the company produce single product which is packaged into various pack or container sizes. It is developed for SMEs that may not be able to afford ERP software while big companies with more sophisticated and complex production systems may purchase the license of any relevant ERP software.

4. Conclusion

An affordable, easy-to-understand, user-friendly software based on Goyal's algorithm with flexible input and output displays was developed for production planning in a small and medium scale batch production enterprise producing items that are jointly replenished. It allows the economic number of manufacturing runs and packaging setups for each item to be obtained at reduced effort and time. The software meets the needs of small and medium scale industries which are not able to afford the cost of ERP software, and the user need not be a model expert.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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