Bose QuietComfort Headphones
Final Report

Production Management - ME-419

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Executive Summary

This report analyzes Bose QuietComfort headphones' production management strategies, emphasizing the integration of demand forecasting, aggregate planning, and inventory management to optimize operations. The approach aligns with Bose's objectives of maintaining operational efficiency, meeting market demand, and supporting its sustainability and customer satisfaction goals.

The demand forecast was developed using the Holt-Winters exponential smoothing model, capturing trends and seasonality effectively. This forecast served as the foundation for aggregate planning, enabling the creation of production schedules that address the company's commitment to balancing cost efficiency and workforce stability. The automated hybrid plan was selected for its ability to align production capabilities with demand fluctuations, ensuring robust operational performance.

The inventory management strategy was carefully designed to complement the aggregate plan and reflect Bose's Just-in-Time (JIT) principles. While theoretical models like EOQ and EPQ provided a framework which was not feasible, practical solutions such as the Quantity Discount Model optimized procurement costs for outsourced components, and the Periodic Review System ensured reliable stock levels under varying demand conditions. These methods addressed both cost efficiency and resilience, ensuring operational readiness and avoiding disruptions.

By integrating these approaches, Bose achieves streamlined operations, enhanced supply chain resilience, and alignment with its broader strategic objectives, reinforcing its position as one of the leading companies in the premium audio industry.

Contents

1 Bose History & Background

Bose Corporation is an American multinational audio technology enterprise with a long tradition of dedication to quality research for superior products and a continuous commitment to customer satisfaction, making it one of the leading audio companies in its 60th year in 2024 ("Our 60th", 2024). In 1964, Dr. Amar Bose, a MIT professor, started Bose with two-MIT educated engineers at the East Natick Industrial Park, United States, with a vision ***to deliver the best audio experience possible through cutting-edge scientific research*** ("Our 60th", 2024).

Innovation is the key that drives the company throughout the decades; notably, Bose's patented the world's first ever noise-canceling headset was introduced in the 1980s and evolved into many products today including the ***QuietComfort headphones*** ("Our 60th", 2024). In the current decade, scientists and engineers continued quality research AI applications for Bose's products ("Our 60th", 2024). Technical excellence apart, Bose is unique such that it builds a long-term customer engagement which foster continuous product refinement and creation of a loyal customer base.

Today, Bose is positioned in the high-fidelity (hi-fi) audio market with a global revenue of around 3.0 billion USD in 2023 (Forbes, 2023); its product lines include headphones, earbuds, speakers, home theater, portable public address system, and aviation headsets ("Our 60th", 2024). For businesses and professionals, Bose provides customizable audio performance experience such as initial system design and product installation/deployment ("Our 60th", 2024). Furthermore, Bose has customer support for technical issues and multiple warranty programs for repairs and refurbishment ("Our 60th", 2024). Overall, Bose offers a variety of top quality audio products which are accompanied by staunch and professional customer care services.

2 Product Overview: Bose QuietComfort

The Bose QuietComfort (QC) headphones line are Bose's noise-canceling hi-fi audio wireless headphones with remarkable features including adjustable noise-canceling modes – such as total quite mode, aware mode or custom modes (such as only blocking wind noise) – fully adjustable sound levels and both Bluetooth and wired connectivity possibilities. Available in 6 different colors (depending on the market) and two versions: QuietComfort and Ultra QuietComfort, which is an upscale version of the former. QC headphones are priced just under CHF 400 in Switzerland (Bose Corporation CH, 2024).

The target customers for QC headphones products are high-end costumers in the hi-fi market, who enjoy very effective noise-canceling, top-quality audio in all musical styles, comfort and long battery life (up to 24 h) (Bose Corporation CH, 2024).
Bose is the largest noise-canceling headphones manufacturer with 23% of the global revenue (Reports, 2022). The sales of QC headphones is derived to be around 1 million units per year worldwide with available information (Ferjan, 2023).

2.1 The Elements of Value

QuietComfort headphones' functional and ergonomic design ensures comfort and adaptability that well satisfy customers ***physiological needs*** Moreover, the relaxation enabled by QC's noise-canceling technology appeals to customers' ***emotional needs*** such as anxiety reduction, and even improved focus on continuous goal achievement which could eventually lead to ***self-actualization***.

2.2 From Product to System of Systems

QuietComfort headphones are established as a Smart and Connected Product following the classification(Porter & Heppelmann, 2015):

- *product:* they are a physical manufactured object, which contains both hardware and software.
- *smart:* they have sensors and algorithms that autonomously regulate features such as the noise canceling or the sound parameters.
- *connected:* they have antennas and software that communicates with external independent devices, in this case providing the actual music track.

However, QC headphone lacks integration in an ecosystem of alike products; they only communicate to receive the essential data for their own task, not delivering nor generating data for other devices.

2.3 Competitor Analysis

Bose QuietComfort headphones are consistently placed among the best noise-canceling headphones on the market. However, companies like Apple, Beats Electronics (acquired by Apple in 2014), Sony, Sonos, Anker, Sennheiser and JBL are the primary competitors, with similar quality and price range. More than 35 active competitors, but only a few are consistently ranked close to or above Bose QC Headphones, especially Sony's headphones. Figure 24 in the Appendix shows the characteristics, the advantages and the disadvantages of Bose's main competitors (Scarrott, 2024) (TechRadar, 2024).

3 Bose Production Chain Management

Effective management of the production chain partly sustains Bose Corporation's competitive advantage in the global audio equipment market.
Bose Corporation **headquarter** is situated in **Framingham, Massachusetts, USA**, which serves as the central hub for Bose's research, product development, and corporate operations. Bose's has two key **manufacturing sites**: one in Tijuana, **Mexico** for North American markets and another in Penang, **Malaysia** for Asia-Pacific. Additional contract manufacturers are found in China for certain components. Warehousing and distribution sites are spread across the world, with a particular focus on the Americas where key locations are in California and Pennsylvania (Bose Corporation, 2024c). In Europe, a central warehouse located in the Netherlands serves as a hub for product distribution throughout the continent (Bose Corporation, 2024a). Warehousing facilities in Singapore and Hong Kong support distribution across Asian markets (Bose Corporation, 2024b) (Bose Professional, 2024).

3.1 Supply Chain

Bose Corporation is notorious for having introduced in 1987 the Just-in-time II (JIT II) vendor-managed supply chain management strategy, a solution that involves supplier representatives called 'in-plants' working directly inside customers' facilities. As a consequence, companies can obtain cost reductions, better inventory control and shorter operational times (Dixon, 1999)(Cargoz, 2024)(Pragman, 1996).

Presumably JIT II is still in operation at Bose (Segars et al., 2001). Since natural disasters that disrupted the supply chain in 2011, a supply chain resilience program was implemented, moreover, a management software system from Resilience Corporation was employed at Bose in 2013 (O'Donnell, 2020). The software aides Bose's supply chain in the five areas (O'Donnell, 2020):

- *Site mapping.* It allows to track supplier and partner locations, and records which components and products might be involved by eventual disruptions in specific areas.

- *Financial analysis.* It allows to gain insight into suppliers' financial health and cash flow. It is based on a risk analysis software developed by RapidRatings International Inc..
- *Social responsibility.* Bose is a member of the Responsibility Business Alliance and checks its suppliers' social risks.
- *Business continuity planning.* Bose works with its suppliers to draft robust business continuity and backup plans. This approach has been improved during COVID-19.
- *Crisis management.* It consists of a three-level plan on how to take action in case of irrelevant disruptions, solvable disruptions and damaging disruptions.

3.2 Vertical Integration

In recent years, Bose Corp. has acquired and invested in multiple companies to strengthen the vertical integration of its production as well as reinforce partnership within its global network of suppliers, contract manufacturers, and distributors (Crunchbase Inc., 2024a). Figure 1 provides Bose's supply chain integration scheme.

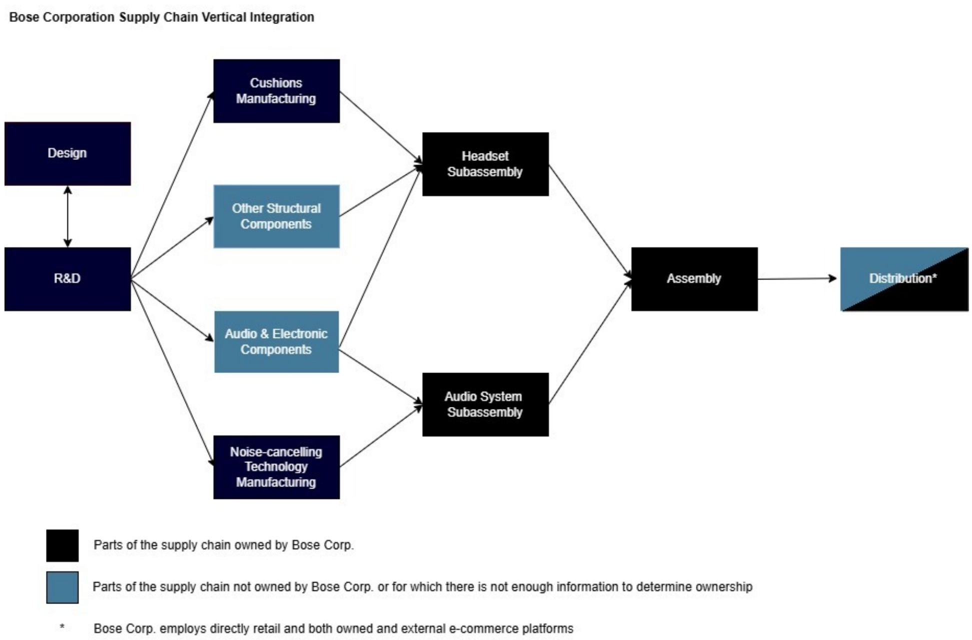


Figure 1: The vertical integration of headphones production chain in Bose Corp.

In 2017, Bose Corp. acquired Hush Technology, a developer of smart earbuds born to mask noises during sleep. Then, in 2018, it acquired The Sync Project, a platform that studied the therapeutic power of music health, and Detour, an audio tour application whose audio-transcription linking technology was sought after for its possible incorporation into Bose's AR platform. Finally, in 2019, Bose Corp. acquired ZiipRoom, that developed a software for multivendor meeting rooms, hence with virtually any hardware or service. With this strategic move, Bose could equip the huddle rooms with its sound technology, enter the business conferencing market and add a new connectivity feature to its products. Bose Corporation owns more than 2,000 patents, proving the integration of R&D within the corporation (Crunchbase Inc., 2024b).

3.3 Value Adding Network (VAN) & Material & Information Flow

As shown in Figure 2, the manufacturing and the 2 assembly phases are done within the company's sites upon receipt of raw materials from main suppliers. The finished products are then distributed through Bose's stores, third-party retailers, and independent distributors to reach end customers. The *detailed Material and Information Flow* can be found in Figure 25 (see Section 16.1 in the Appendix).

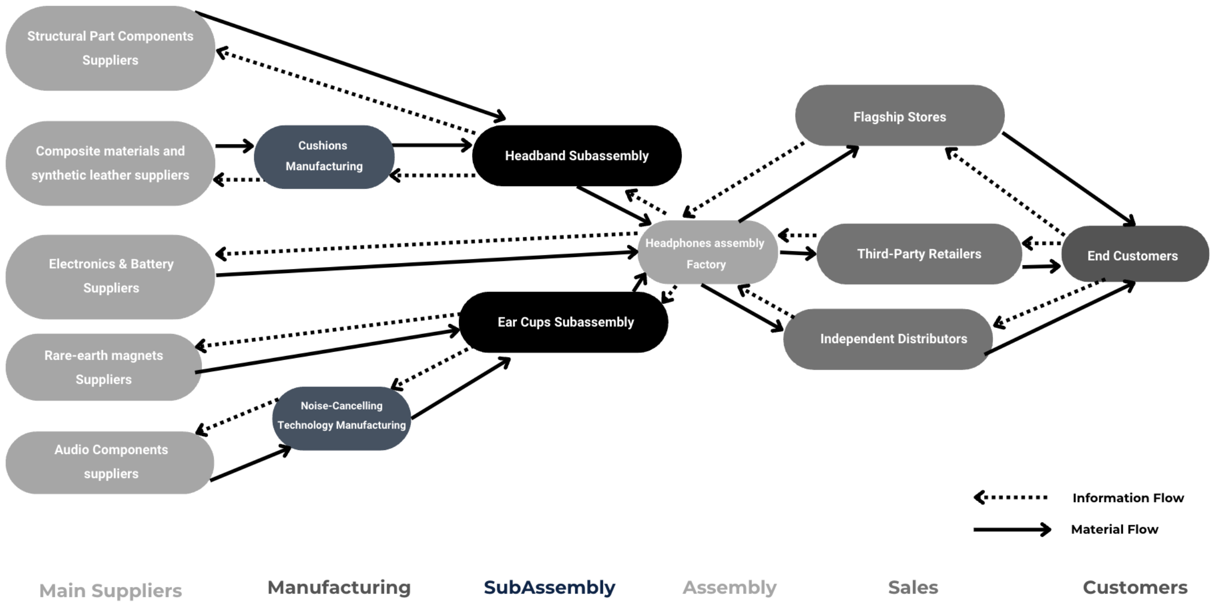


Figure 2: The VAN of Bose Corp. solid arrows indicate physical material flow and dotted arrows indicate information flow

3.4 Bill Of Materials

As shown in Figure 3, the BOM of this product considers the main parts that compose the product and breaks them down into the principal sub-components (Discovery UK, 2019) (How It's Made, 2023).

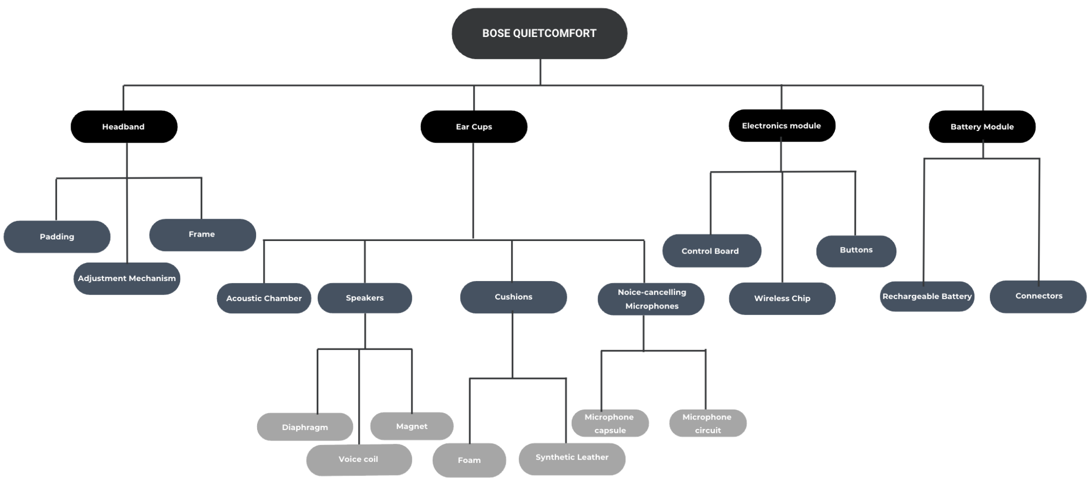


Figure 3: The BOM of Bose QuietComfort

4 Current & Future Challenges

Bose faces several significant challenges in the current market environment, as well as potential future obstacles.

Intense Market Competition: The audio technology market is increasingly competitive, with companies such as Sony, Apple, Sennheiser, and Beats introducing noise-canceling headphones that match or surpass Bose in terms of quality and features. Competitors are incorporating advanced technologies like adaptive noise cancellation, AI-driven functionalities, and seamless integration with smart devices, which challenges Bose's market position. Additionally, the industry is experiencing price wars, where competitors offer comparable or superior products at lower prices, compelling Bose to substantiate its premium pricing strategy (Sony Corporation, 2024).

Supply Chain Disruptions: Global component shortages, particularly in semiconductors, have caused disruptions in production schedules. These shortages are exacerbated by global events, leading to delays and increased costs in manufacturing processes (Wishart-Smith, 2024).

Technological Disruption: The rapid development of technologies such as Augmented Reality (AR) and Virtual Reality (VR) may shift consumer interests toward devices that provide immersive experiences beyond traditional audio functionalities. Furthermore, advancements in spatial and 3D audio technologies will require investment from Bose in research and development to maintain its competitive edge (Marketandmarkets, 2024).

5 Demand Plan: Forecasting Goal Definition

As a leading enterprise in the audio industry, Bose continues serving the market and meeting customers' demands through an efficient, resilient and sustainable production management. A high-level meticulous demand plan is key to the well-functioning of the entire company as well as to the attainment of Bose's governance goal to become socially and environmentally responsible by achieving a 42% reduction carbon emissions by 2030 ("Environmental, Social & Governance Report 2024", 2024). Bose's resilience directives stipulate three significant components in building a resilient production management plan for the global chain: ***1) supplier diversification***; ***2) improvement in inventory management***; ***3) optimization of logistic operation***.

Furthermore, it is reinstated in Bose's latest ESG 2024 Report the importance of establishing close collaboration with different suppliers to ensure transparency and resiliency to prevent supply chain disruption – as part of the company's resiliency plan – while upholding environmental and social governance standards ("Environmental, Social & Governance Report 2024", 2024).

Employment of an appropriate **forecast model** facilitates demand anticipation in the near future by simulating orders' fluctuations in the market based on real orders' data in the past: it allows proactive production management decisions to minimize delays and shortage, to better adjust inventory levels and to optimize operational shipments.

Moreover, forecasting orders is part of Bose's sustainability strategies in reduction of waste and carbon emission, promotion of products' circularity, and optimization of energy usage. For instance, at Tijuana facility , 90% recycling rate is achieved by minimizing waste and reusing materials.This is complemented by initiatives such as eliminating single-use plastics and enhancing e-waste recycling efforts, notably at facilities such the Yuma Arizona site ("Environmental, Social & Governance Report 2024", 2024).

Three demand plan goals are outlined at Bose: 1) ***an efficient and flexible supply chain*** , 2) ***supply chain resilience*** and 3) ***a sustainable production to reduce waste and carbon emission***.

6 Historical Data

Raw data used to establish the forecast model is real time number of orders for each product in the product family over a period of more than three years up until present September 2024. The time series data is cleaned to remove abnormal orders and a series of treatment is applied to render the data applicable and comprehensible for the purpose of the establishing a forecast model.

6.1 Data Cleaning

Upon first visualization of the raw time series data for both products, very obvious accidental order data are observed. These outliers are replaced by the average between the order immediately before and after. Raw real-time orders are placed at different times during one day – several orders exist in one day. Daily aggregated data are obtained by combining all orders of the day into one single value (see the data series in blue in Figure 4).

Initially, the mean $\bar{Y}$, standard deviation σ, and the confidence interval (CI) are found for the entire data in the whole planning period using:

$$\bar{Y} = \frac{1}{n} * (Y_1 + Y_2 + ...Y_n) \tag{1}$$

$$IC = \bar{Y} \pm \ 1.96\sigma \tag{2}$$

where σ represents the standard deviation of the series. The upper bound is $\bar{Y} + 1.96 * \sigma$ and the lower bound is $\bar{Y} - 1.96 * \sigma$ (see Table 1).

Model	Mean	Standard Deviation σ	Confidence Level	Z-score	Upper Bound	Lower Bound
Black QC	25571	10285	0.95	1.96	45730	5411
Beige QC	13041	5329.9	0.95	1.96	2594	23488

Table 1: Statistics over the entire series in time

The upper and lower bounds calculated using the entire series are colored in orange and green respectively in Figure 4 (a) for QC black and in orange and blue respectively in Figure 4 (b) for QC beige.

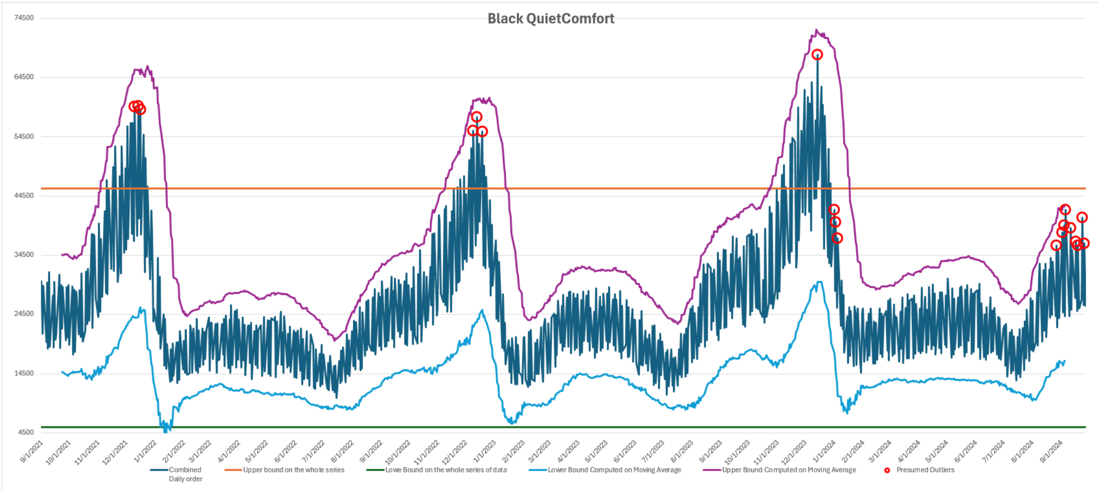
Since clear seasonal fluctuation is observed in Figure 4, the majority of the data peaks would be excluded with the fixed average and confidence interval method described above; hence the time series is divided into periods according to decreasing/increasing trends – September to December period has a sharp increasing trend, January to February period has a sharp decreasing trend, March to June period is relatively stable and July to August period has a minor decreasing period – for a more representative analysis through the computation of the **confidence interval** using Equation 2 for each specific period as shown in Figure 4.

Using this approach, outliers are identified only if they fall outside both the yearly and quarterly confidence bounds. These "presumed outliers" are marked in red circles in 4.
Nonetheless, many of these points, especially those occurring during peak sales periods, do not appear to be true outliers when plotted; in fact they represent the highest sales volumes of the year.

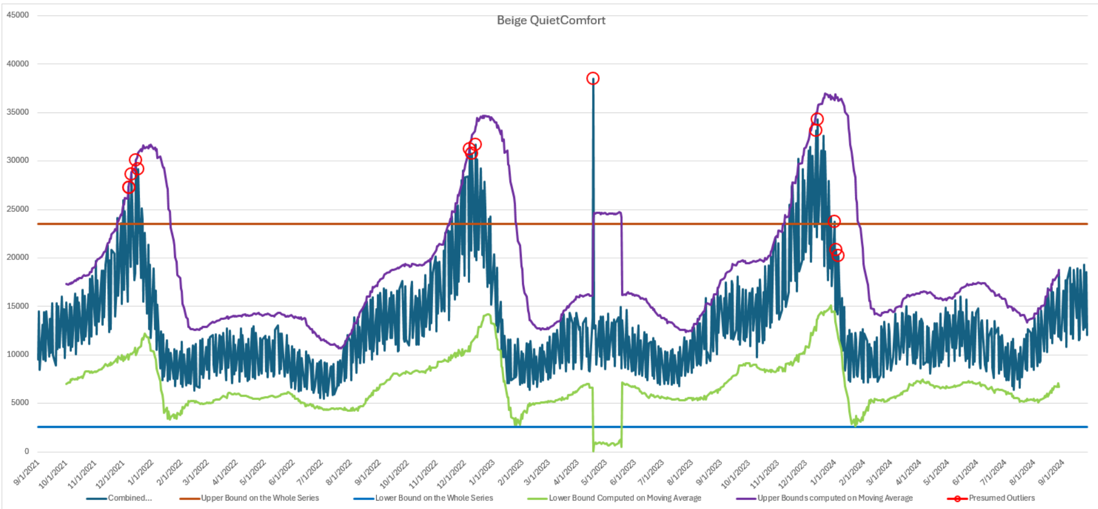
Therefore, in order to further refine our analysis, we apply a moving average on a monthly basis through 3, recalculating the confidence intervals for each observation.

$$\bar{Y}_t = \frac{1}{c}\left[\sum_{i=t-\frac{c-2}{2}}^{i=t+\frac{c-2}{2}} Y_i + \frac{1}{2}(Y_{t-\frac{c}{2}} + Y_{t+\frac{c}{2}})\right] \quad \text{for } c \text{ even} \tag{3}$$

This allow to accurately detect outliers that truly fall beyond these newly established bounds. As seen in Figure 4, while no outliers are identified for Black products, one is detected for the Beige category.



(a) Black QC: purple line and blue line delineate the upper and lower bound using the moving average method for the four periods.



(b) Beige QC : purple line and green line delineate the upper and lower bound using the moving average method for the four periods.

Figure 4: Data cleaning process in progress for both black and beige QC. Blue series line represent the daily combined time series orders. Red data are data points identified with a moving average.

6.2 Reference Planning Period & Data Aggregation

Since Bose uses the MTS (Make to Stock) approach, it is critical to have all the products available to meet the customer's demand, avoiding the risk of falling into stock-out. Thus, the Lead Time (i.e. the total time taken from the initiation of a process to its completion) must be closely aligned to reference planning period. For instance, if lead time is shorter than the reference planning time, the company might overestimate its schedule, leading to inefficiencies and costs such excess inventory. According to these notions, and considering the Lead time of other competitors, total Lead time for QC (including procurement and assembly) is firstly estimated to be around one-to-two months due to high customization and few quality suppliers for all competitors. After, it is computed specifically at **7 weeks** ("Honsenn Production Process", 2024). Moreover, given the information provided on the Materials and Information Flows Diagram (see Figure 25 in Appendix), it is assumed that subsidiaries provide a monthly forecast demand per product family, and that the Production Planning team prepares a weekly Master Production Schedule (MPS). In both cases, the considered horizon is **12 months.** Moreover, given the previous reasons and the fact that forecasting based on weekly data results in less robust predictions than with monthly data, data is aggregated on a monthly basis (see Figure 5).

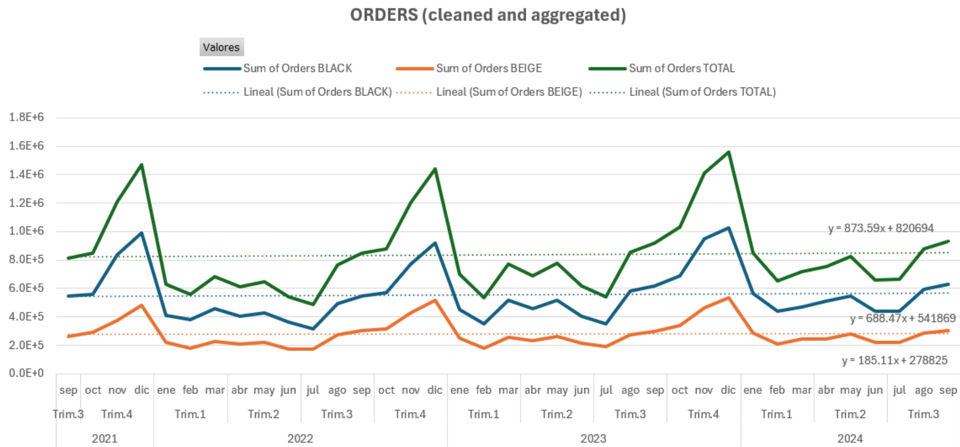


Figure 5: Monthly aggregated data chosen to be used in forecasting model

6.3 Trend and Seasonality

The sales data from 2021 to 2024 reveals a modest upward growth trend for both QC Black and QC Beige. The linear regression analysis indicates slopes of 688.47 for QC Black and 185.11 for QC Beige, representing the average monthly growth in units sold. In addition, QC black has nearly double sales compared to QC beige (see tab "Cleaned data" in the Excel).

Figure 5 shows a recurring seasonal pattern aligned with certain periods of the year. Peaks in sales are consistently observed in the weeks leading to the Christmas holidays. Conversely, the lowest sales are regularly recorded during the summer months, particularly between July and August.

This cyclical behavior suggests that sales are influenced by seasonal factors, such as holiday gift-giving periods and seasonal promotions. Additionally, weather conditions may significantly impact sales. Further analysis could explore the effects of external events, like marketing campaigns or new product launches, on sales patterns.

Overall, comparing the two models, it is evident that while both models follow the same seasonal pattern, the black version shows a steeper overall growth trajectory. This might be attributed to consumer preferences, marketing strategies, or possibly price positioning in the market, as Black QC is usually cheaper.

6.4 Autocorrelation Analysis

In order to analytically determine the seasonality period, which is visually evident in Figure 5, an Autocorrelation Function (ACF) analysis is performed, with a monthly (30 days) lag, using Equation 4.

$$r_k = \frac{\sum_{t=1}^{N-k}(Y_t - \overline{Y})(Y_{t+k} - \overline{Y})}{\sum_{t=1}^{N}(Y_t - \overline{Y})^2} \tag{4}$$

Figure 6 confirms a periodicity of 12 month. ACF values above 0 corresponds to a positive normalized correlation and 1 is the maximum normalized correlation between lagged data. The ACF in Figure 6 has positive peaks at every 12 month cycle. The dampening effect of the ACF is due to effect of normalization factor in the denominator in Equation 4.

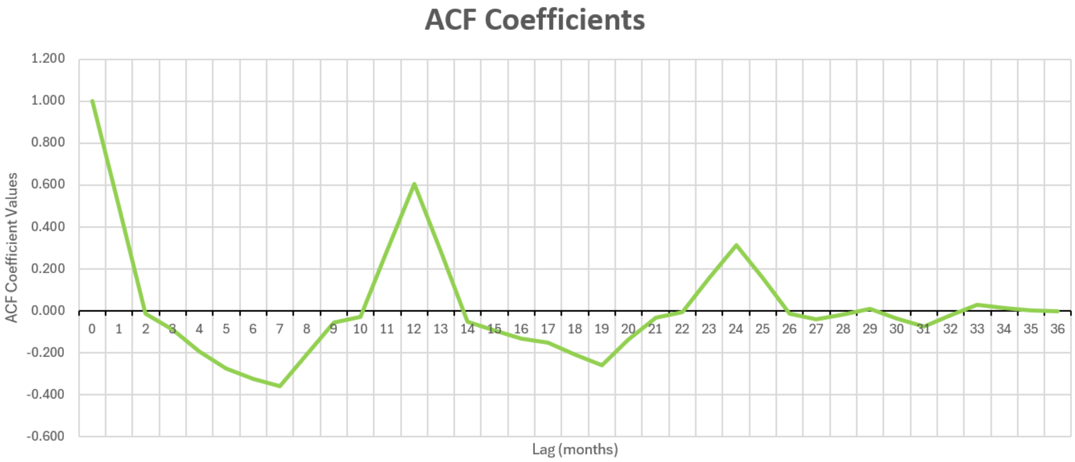


Figure 6: Autocorrelation Coefficients computed by implementing by hand the formula in Excel. A clear peak can be seen at month 12, indicating a yearly seasonal pattern.

7 Forecast Model Initialization

The following section describes the steps to obtaining an initial version of the forecasting model. The first approximation of the forecast error is also evaluated.

7.1 Choice of Forecasting Model

Following the decision flowchart for forecasting models selection in (Glardon, 2017), after the trend and seasonality are identified in the previous sections, the Holt & Winters Model is selected as the best choice, since fits our data's additive trend and a multiplicative seasonality. Although the multiplicative seasonality is not immediately clear from the graph, qualitative reasoning supports it: the seasonal variations (such as during Christmas and Summer) appear proportional to the trend, rather than constant or independent of it. Still, a multiplicative model would also perform effectively if the seasonality were additive.

7.2 Initial Components

The trend coefficient obtained T' corresponds to the **initial trend component**. For the total aggregated orders:

$$T' = +6,800.1 \, \text{orders/year} \tag{5}$$

Seasonal effects are removed using:

$$\tilde{Y}_t = Y_c + T'\left(t - t^\circ - \frac{c-1}{2}\right) \tag{6}$$

where cycle is defined as $[t^\circ; t^\circ + (c-1)]$ and the cycle average is given by

$$\bar{Y}_c = \frac{1}{c}\sum_{t=t^\circ}^{t^\circ+(c-1)} Y_t \tag{7}$$

Seasonal components are computed by dividing actual demand by the de-seasonalized demand. The **initial seasonal components** for each month, S_t, are then determined by the ratio of actual demand Y_t over the de-seasonalized demand $\tilde{Y}_t$.

Finally, the orders, the cycle moving average, the de-seasonalized components and the linear regression of the cycle moving average for the total number of orders are displayed in Figure 7. The trend and seasonality analysis are also done for both the black and beige headphones (see "Initial Components" tab in the Excel file).

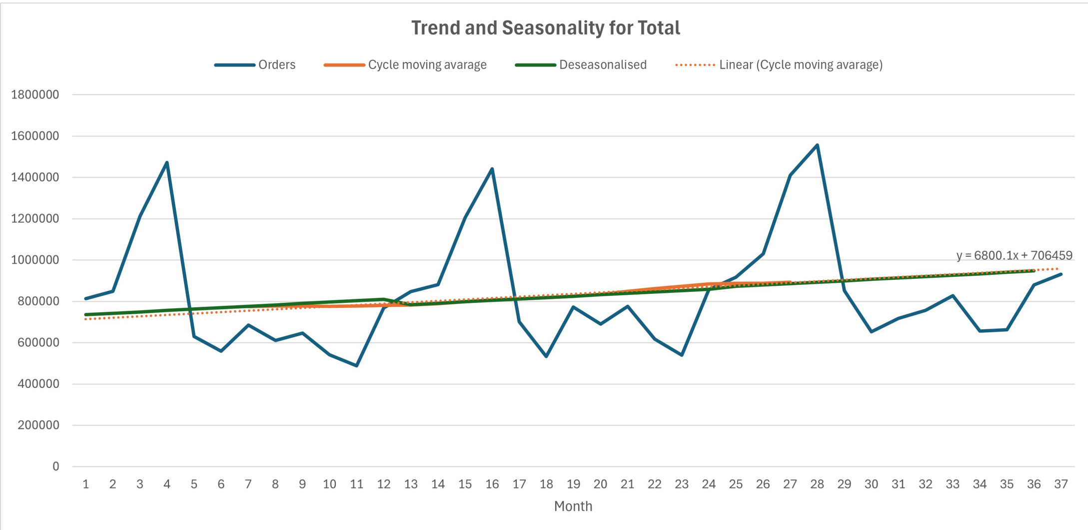


Figure 7: Trend and Seasonality For Total

Moreover, according to the initiation and validation process in (Glardon, 2017), the **initial base** B' can be computed from the average value of cycle 2, Y_2, and the initial trend T:

$$B' = Y_2 + \frac{c-1}{2}T' = 859,100 \tag{8}$$

7.3 Model Validation

In order to initially validate the model, a forecast prediction model must be computed. The forecast can then be fully initialized according to the $[a; m]$ model :

$$F'_{t+h} = (B' + h) \times S'_{t+h} \tag{9}$$

where $h \in \mathbb{N}$.

A comparison between the real orders and the forecasted ones on cycle 3 was plotted (see Figure 8) in order assess the validity of our model.

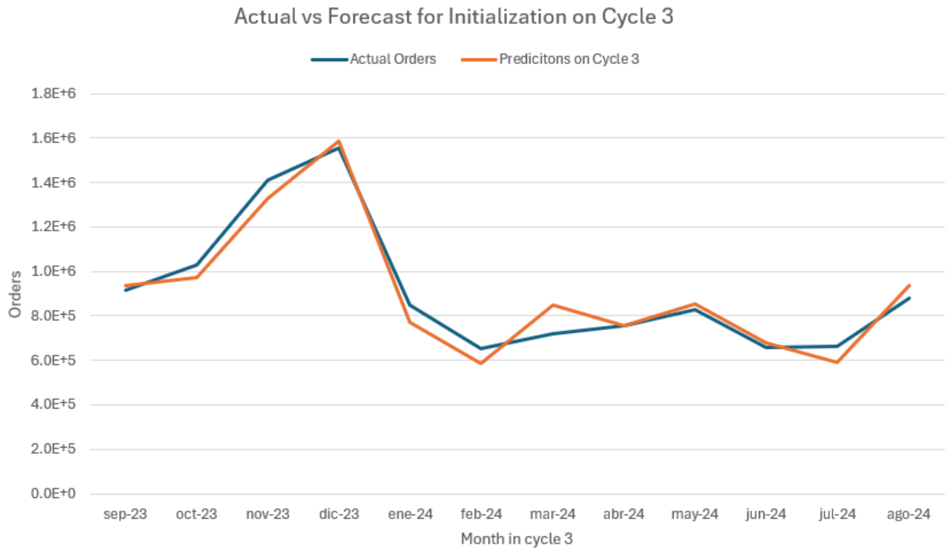


Figure 8: Actual vs Forecast Demand

A control, standard errors and percentage errors charts were plotted and analyzed. The control chart can be seen in Figure 9, while the others are available in the "Validation Initial Model" tab in the Excel file.

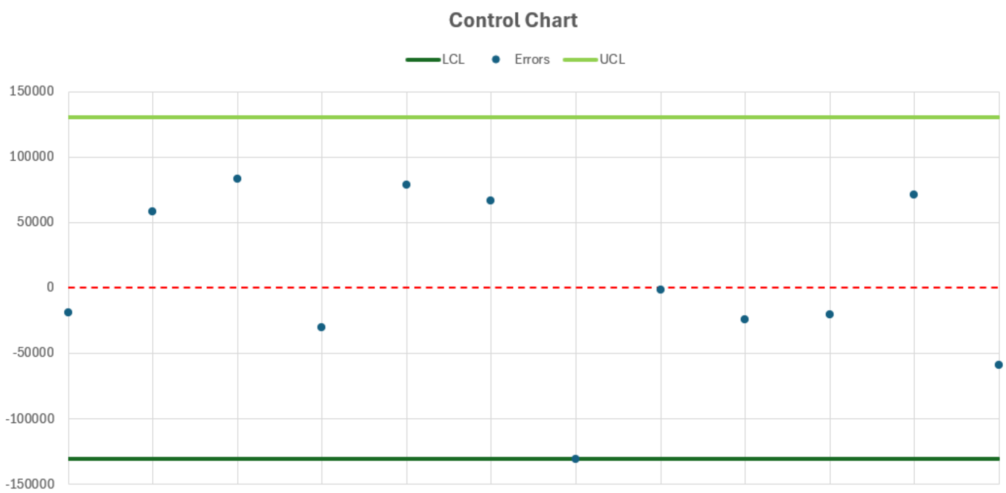


Figure 9: Control chart to check for bias. Indeed, there is a slight stock shortage bias.

The initial model demonstrates strong performance in capturing the overall data pattern, with monthly percentage errors generally below 10% and consistently under 20%, resulting in a MAPE of **6.4%**.

However, two key aspects require attention:

1. **Systematic Underestimation**: The model tends to underestimate actual orders, increasing the risk of stock shortages. This systematic under-prediction suggests a need for adjustment, particularly by increasing the baseline component of the Holt-Winters model to better align forecasts with real demand.

2. **Weaker Seasonal Effect**: The point on the lower bound of the control chart stems from a weaker-than-expected seasonal effect in March 2024 compared to the previous year. This discrepancy would have led to preparations for higher demand than materialized, resulting in an overstock situation.

8 Forecast Model Running

The following section runs the previously-determined initial model to refine it. Then, the final model is run to forecast the demand.

8.1 Smoothing coefficients

Fine tuning the smoothing coefficients (α, β, γ) is needed to minimize the forecast error.

The γ coefficient, which adjusts the evolution of the seasonal component, is 0.9 for seasonal cycles of one year or more. As previously stated, our seasonal cycle is one year (12 months), therefore: $\gamma = 0.9$.

The coefficients α, and β adjust the reactivity of the base and the trend, respectively. To find α, β; a forecast for 4 different horizons in our available data is needed for one set of α, β. This procedure is repeated multiples times with different sets of α, β so that a discrete number of all the possible values (0 to 1) is covered.
The goal is to select the α, β that produce a lower Mean Absolute Percentage Error (MAPE).

For each set of values, the base and the trend are computed for each horizon with respect to the previous base and trend following

$$B_t = \alpha_j \frac{Y_t}{S_{t-c}} + (1 - \alpha_j)(B_{t-1} + T_{t-1}) \tag{10}$$

$$T_t = \beta_k (B_t - B_{t-1}) + (1 - \beta_k) T_{t-1} \tag{11}$$

The forecast for every month in the horizon is then computed with the previously computed base and trend, and the Holt-Winter model:

$$F_{t+h} = (B_t + hT_t) S'_{t+h-c} \tag{12}$$

Plotting the MAPE error in Figure 10 as a function of the α, β values, a clear tendency of the error to increase with the increase of α, β is observed.

Adjusting the coefficients with more resolution, the optimal smoothing coefficients to use in the forecast are the following. The low value of α, β as optimal suggest that the forecast performs better with low reactivity to the most recent base and trend (robustness), while mainly last cycle drives the seasonality (high γ).

$$\alpha = 0.11; \beta = 0.11; \gamma = 0.9 \tag{13}$$

These combination provides the minimum error in the validation cycle, which corresponds to (compared to the previous 6.40% from the initial model):

$$MAPE_v = 5.81\% \tag{14}$$

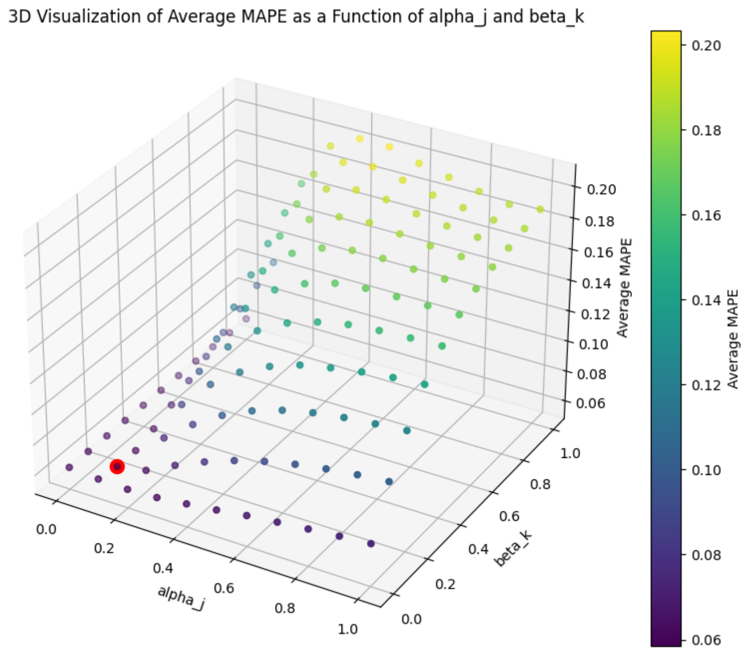


Figure 10: MAPE as a function of alpha and beta coefficients.

8.2 Final Model

The final Holt-Winter model for Bose QuietComfort's data results (with c = 12 months):

$$B_t = 0.11\frac{Y_t}{S_{t-c}} + (1-0.11)(B_{t-1} + T_{t-1}) \tag{15}$$

$$T_t = 0.11(B_t - B_{t-1}) + (1-0.11)T_{t-1} \tag{16}$$

$$S_t = 0.9\frac{Y_{t-12}}{B_t} + (1-0.9)S_{t-12} \tag{17}$$

$$F_{t+1} = (B_t + 1T_t)S'_{t+1-12} \tag{18}$$

8.3 Running the model

With the Holt-Winter model for our data complete and ready, an initial forecast is done for cycle 3 (for which the actual data is available) in order to validate it and measure the performance. To do this validation forecast, the initial components of base (based on cycle 2), trend and seasonality are used. Therefore, direct application of the aforementioned Holt-Winter Equation 18.
The resulting performance was discussed in detail in the Model Validation subsection. α, β apply to forecast from cycle 4 onward (based on the Initial Components), so no real data is yet available to measure the performance of the model in forecasting with the smoothing coefficients.

Finally, the model is run to forecast the following 18 months. Forecasting 18 months means forecasting cycle 4 (12 months) plus 6 months from cycle 5.
Firstly, the base and trend are computed updating the initial ones using cycle 3 (the most recent known), with Equations 15 and 16.

The seasonal component for each forecast month is the one computed on the same month of the previous cycle using the real known orders, however after cycle 4, forecast seasonal components are used because no more real seasonal components are available.

The base and trend for cycle 5 are not updated with cycle's 4 since the real data is not available. So, it is preferred to continue with the base and trend based on the known cycle 3 which is reasonably precise since it is less than 2-cycles distant from the one considered.

9 Forecast Results and Performance

The forecasting results as a continuation of the real orders is shown below.

The validation in cycle 3 can be seen with the close overlap between the actual and forecasted orders. Afterwards, the model predicts a behavior similar to the available data, with slight increasing trend and, consequently, an increase in the seasonal pics' amplitude. Therefore, the model respects the previously analyzed behavior of Bose QuietComfort's data, resulting in a coherent forecast. Note the switch between from the real to the forecast orders is remarkably smooth.

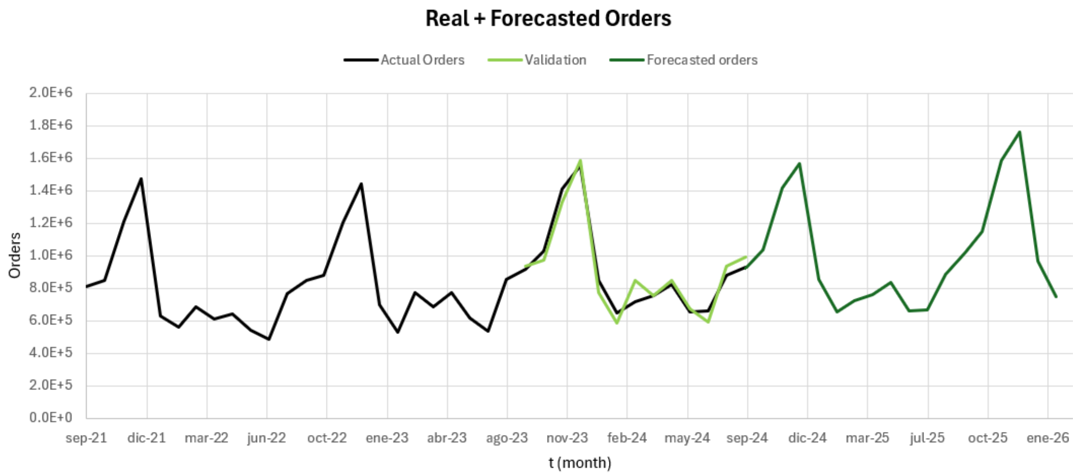


Figure 11: Actual orders, validation cycle and 18 months forecast.

With the real customer orders already available for September and October 2024, accuracy analysis on real forecast can be performed. The overall, most recent MAPE gets down to 5.90% (from the initial 6.4%). Locally, error computations show a remarkable improvement from the already accurate MAPE: the months in which the smoothing coefficients are implemented obtain an error below 1%. Furthermore, evaluating the performance with a full cycle including the most recent data shows a non-absolute mean percentage error (compensating overstock with shortage) of 0.26%. This means that there is no longer a noticeable bias for the forecast to shortage. Actually, there is a desirable slight tendency to stocking (MPE positive).

10 Supply Plan

The robust demand forecast generated through the Holt-Winters model serves as the foundation for developing Aggregate Planning (AP) strategies, which translate demand predictions into actionable production schedules on the ground.

11 Capacity Planning

Bose's capacity planning is the highest-level planning for the aggregated production (AP) of both QC black and QC beige headphones. The aggregate planning, once set, will provide the overarching framework for all the sequential supply management activities within Bose - all other finer scale planning must operate within limits stipulated by the AP.

Note that a 12-month horizon, which aligns with the 12-month Bose demand forecast, has been used, with data aggregated on a monthly basis.

Two pure aggregate planning schemes: 1) level-plan and 2) chase demand plan are considered as a first step in the development of Bose's AP. Then, an hybrid plan has also been implemented.

Bose has two manufacturing centers; one in America and one in Asia pacific. The AP takes into account both centers. The information needed for AP development is presented in Table 11 and Table 12 (see Subsection 16.2 in Appendix).

11.1 Assumptions for Inventory and Workforce Calculation

- Bose operates two primary manufacturing centers: one located in Mexico for the American market and the other in Malaysia for the Asian market. The allocation of workers between these two factories follows a 60-40 distribution, based on the relative sizes of the respective markets.
- The total number of workers at both factories is found to be 3,500 "WB Journal - Bose sells two overseas manufacturing plants", 2024 "Bose Corporation Employee Directory", 2024. However, only 10% of the workforce is dedicated to production. To account for the difference in the magnitude of orders, a coefficient of 9 is applied to scale the workforce based on the actual order volume, which is approximately 1 million units per year, compared to Bose's original production capacity of 9-10 million units.
- The allocation of workers dedicated to the production of the headphones is proportional to the share of the sales of this product relative to Bose's total revenues. Given that Bose's total turnover in 2023 is approximately $3 billion, and the headphone product generates approximately $300 million in sales (1 million units per year), the percentage of workers dedicated to this product is estimated at 10%.
- The labor costs at both factories are derived from the some Databases ("Statista", 2024) ("Federal Reserve Economic Data", 2024) ("Trading Economics - Indicators", 2024), which provides the average wages in Mexico and Malaysia. The resulting labor cost per unit is a weighted average of the labor costs in both centers, based on the proportional sales share of the product in each market.
- The typical working week consists of 40 hours, and the typical working month consists of 4 weeks.
- The anticipated workforce changes are calculated as with Equation 20 and Equation 21 (see Subsection 16.2 in Appendix).The results in workforce changes are categorized into one of the following in order to determine the action taken regarding the workforce:
  - A positive percentage change ($\geq 15\%$) corresponds to hiring.
  - A percentage change below 15% corresponds to using overtime or subcontracting to cover excess production.
  - A negative percentage change ($< 0\%$) corresponds to layoffs.

- Bose implements a Just-in-Time (JIT) inventory strategy, for which the beginning inventory is assumed to be zero (in October).
- The inventory holding cost, which for manufacturing companies ranges typically from 15% and 30% (“cogsy - Inventory Holding Costs Explained”, 2024) of the item’s production cost. Given that Bose has implemented a policy aimed at maximizing inventory efficiency, a 20% inventory holding cost is assumed for the company. A gross margin of 60% is assumed given Bose’s premium pricing and high-end quality products. The inventory holding cost per unit is calculated as follows:

$$\text{Inventory Holding Cost} = (1 - 0.60) \times 349\,\text{USD} \times 20\% = 27.92\,\text{USD per unit per year.}$$

  where 349 USD is the selling price of the product in the American market (“Amazon USA”, 2024), and the 60% gross margin is based on both industry averages and Bose’s premium positioning.
- In order to avoid backorders, Bose aims to maintain sufficient inventory to meet demand at all times. Backorders are considered more costly than inventory holding costs and hiring costs Mweshi, 2022, as they not only result in lost sales opportunities but also have a higher strategic cost in a highly competitive market. Failing to meet customer demand leads to not only the direct opportunity loss from not fulfilling an order but also the potential loss of customers to competitors, significantly increasing the cost of backorders.
- The hiring and layoff costs are based on the values provided during the lecture, which account for legal expenses, basic training for hiring, severance pay, and the loss of expertise associated with layoffs. These costs are assumed to be reasonable within the context of Bose’s operational environment.
- The total cost (TC) is computed as the sum of the following components:

$$\text{TC} = \text{IHC} + \text{HFC} + \text{OSC} + \text{RLC}$$

  where:
  - HC (Inventory Holding Cost)
  - HFC (Hiring and Firing Cost)
  - OSC (Overtime/Subcontracting Cost)
  - RLC (Regular Labor Cost)

11.2 Level Plan

The approach maintains a leveled (i.e. constant) production regardless of the fluctuations in the demand plan. Conditioning on the assumptions mentioned previously, Bose Level Plan could be found in Table 2 which gives an example of the pure level strategy for the first three months. The rest of months’ detailed calculations follows the same calculations provided in the tab "AP" in the Excel file.

However, this simple plan incurs backorders, which is not consistent with Bose’s backorders assumption. Hence, a revision of the pure level production plan has been done to eliminate them: Table 3 shows the modified pure level strategy for the first three months.

Figure 12 shows a graphical representation of level plans in relation to demand.

Production/Inventory Planning	October 2024	November 2024	December 2024
Production	1 020 808	1 020 808	1 020 808
Cumulative Production	1 020 808	2 041 616	3062424
Inventory (Excess units)	0	0	0
Backorders (Unit shorts)	15 655	415 449	963 124

Table 2: Detailed simple pure leveled strategy

Production/Inventory Planning	oct-24	nov-24	dec-24
Production	1 341 849	1 341 849	1 341 849
Cumulative Production	1 341 849	2 683 698	4 025 547
Inventory	305 386	226 634	0
Backorders	0	0	0

Table 3: Detailed level strategy avoiding backorders

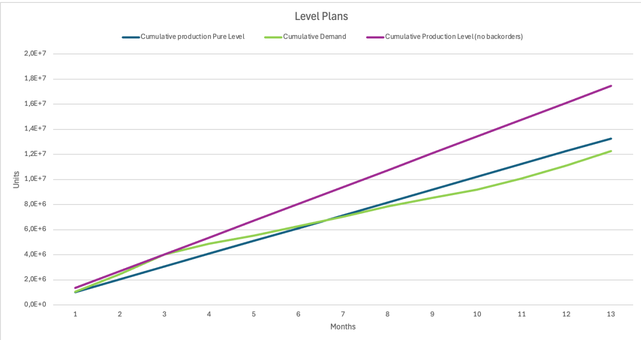


Figure 12: Level Plans with Forecast Demand

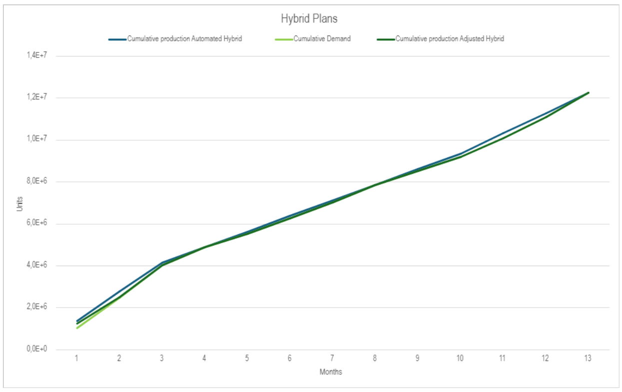


Figure 13: Hybrid Plans with Forecast Demand

11.3 Chase Demand Plan

The chase demand plan adjusts capacity flexibly to meet exactly the demand needs, meaning that production is equal to the monthly demand. In this plan the production level is simply equal to the forecast demand. Inventory is therefore always zero. Table 4 is an example of the pure chase plan for the first 3 months.

Production/Inventory Planning	oct-24	nov-24	déc-24
Production	1 036 463	1 420 602	1 568 483
Cumulative Production	1 036 463	2 457 065	4 025 547
Inventory	0	0	0
Backorders	0	0	0

Table 4: Detailed pure chase AP for first 3 months

11.4 Hybrid Plan

Bose demand forecast shows seasonality, with the following characteristics:

- High season (highest demand): October to December

- Low season (lowest demand): January to July
- In-between season (medium demand): August to September

Leveled production is prescribed to each month of the three sections by taking the average demand level over all the months in the section.

However, this method leaves some months with backorders and accumulate inventory. Hence, further modification have been done to avoid backorders and reduce inventory, leading to a automated hydrid plan. In this way, Bose manages to avoid backorders while minimizing inventory during the period (please note that the ending level of inventory is 0). Table 5 shows this automated hybrid plan details for the three seasons.

Production/Inventory Planning	High	Low	Medium
Monthly Production	1 381 640	743 663	966 377
Cumulative Production	4 144 920	10 316 940	12 249 694
Inventory	119 372	154 830	0
Backorders	0	0	0

Table 5: Details of the automated hybrid plan

Figure 13 shows a graphical representation of hybrid plans in relation with demand.

The automated hybrid plan serves as a template which can be reused for the next planning horizon because the demand is relatively stable with little increasing trend.

Moreover, for each planning period, the experienced capacity planning manager could manually adjust the automated plan to achieve a lower costs. The comparisons of costs of all AP plans developed are summarized in Figure 14.

	"Manual" Hybrid Plan	Hybrid Plan I	Chase Plan	Level Plan
Inventory Cost	$ 606.225,44	$ 3.693.961,47	$ -	$ 68.407.082,55
Hiring Cost	$ 579.000,00	$ 250.500,00	$ 867.500,00	$ -
Lay Off Cost	$ 1.517.250,00	$ 1.107.000,00	$ 1.951.500,00	$ 98.250,00
Overtime/Subcontracting Cost	$ 1.869.192,27	$ -	$ 2.224.987,07	$ 1.804,50
Regular Labor Cost	$ 17.545.446,57	$ 18.792.120,04	$ 17.306.881,39	$ 26.752.017,67
Total Cost of the Plan	**$ 22.117.114,27**	**$ 23.843.581,50**	**$ 22.350.868,46**	**$ 95.259.154,72**

Figure 14: Cost analysis of AP considered

The manually adjusted plan is the cheapest plan. However, it is not sustainable nor even feasible to implement as it would involve large amounts of hires or layoffs within short periods of time. The chosen plan for the planning horizon is therefore the ***automated hybrid plan***, which provides a better balance between keeping a steady workforce, which is crucial to manage properly the production site, and achieving a relatively low cost. Figure 15 shows the cost breakdown of the chosen automated hybrid AP.

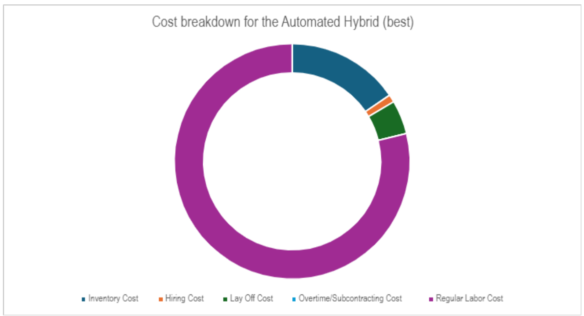


Figure 15: Cost breakdown of the chosen automated hybrid plan

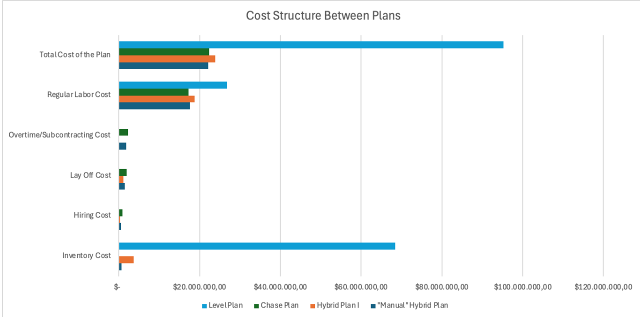


Figure 16: Cost breakdown of the chosen automated hybrid plan

Given that production takes place in regions with relatively low labor costs, the expenses associated with firing and hiring employees are lower than the costs incurred from inventory management. As a result, hybrid and chase production plans outperform the level production plan, particularly due to the substantial inventory holding costs associated with the latter. In contrast, the hybrid and chase plans, which align production with demand fluctuations to reduce inventory costs, consequently result in more cost-effective plans (see Figure 16).

12 Master Production Schedule

The Master Production Schedule (MPS) is a plan that specifies when and in what quantities the product family considered, Bose QC Headphones in the case of this report, must be produced. Hence, it acts as the basis of production planning by linking market demand with the operational capabilities of the organization.

It is important to note that a series of assumptions and data provided by the line manager has been taken into account in the process of creating the MPS.

First, in order to fulfill the received customer orders (huge with respect to the forecast) with the previously decided capacity from AP (see Section "Aggregate Planning"), a maximum delivery date (of all units together) is proposed for each set of orders (in the Excel attached, see notes in the original orders cells). In particular, after negotiating with the customers, they allowed a maximum of 2 weeks of variance with respect to the desired week as acceptable. Moreover, for simplification, Bose decided to divide each month into 4 operating weeks, and, consequently, the forecasted monthly demand and production following the selected plan in AP were also divided uniformly into 4 weeks each months.

Then, according to the information given by the line manager, the computations for the MPS were made considering an improvement in production line labor of 10%, an amount of labor hours per unit (until now) of 0.4 and an amount of machine hours per unit of 0.12. Moreover, since Bose Inc. has historically adopted a Just-in-Time II approach, the initial inventory for the month of October was set to zero.

Lastly, based on historical data (CPOPF), the following values have been used in the completion of the MPS:
- Labor hours per unit, including the 10% production line improvement: 0.36;
- Capacity allocation for production center 1: 60%;
- Capacity allocation for production center 2: 40%.

In order to create the MPS, two other important concepts are the projected available, which is the anticipated inventory levels at the end of a specific time period (in this case one week), and the Available to Promise (ATP), that is the quantity of inventory or production that can be promised to customers beyond current customer orders.

Given all this information, a finalized MPS is shown in Figure 17.

Month	Week	Forecast	Original Customers Orders	Customer orders	Projected Available	ATP without modification	ATP	MPS shipment	Labor hours	Machine hours	Center 1 units	Center 1 labor h	Center 1 machine h	Center 2 units	Center 2 labor h	Center 2 machine h
					345177				0.36	0.12	60%			40%		
nov-24	1	355,150		690,587	0	690,587	0	345,410	124,347.6	41,449.2	207,246	74,608.6	24,869.5	138,164	49,739.0	16,579.7
	2	355,150		345,410	-9,741	345,410	0	345,410	124,347.6	41,449.2	207,246	74,608.6	24,869.5	138,164	49,739.0	16,579.7
	3	355,150	1,500,000	345,410	-19,481	-1,154,590	0	345,410	124,347.6	41,449.2	207,246	74,608.6	24,869.5	138,164	49,739.0	16,579.7
	4	355,150		345,410	-29,222	345,410	0	345,410	124,347.6	41,449.2	207,246	74,608.6	24,869.5	138,164	49,739.0	16,579.7
dic-24	1	392,121	*1,500,000*	345,410	-75,932	-1,154,590	0	345,410	124,347.6	41,449.2	207,246	74,608.6	24,869.5	138,164	49,739.0	16,579.7
	2	392,121		345,410	-122,643	345,410	0	345,410	124,347.6	41,449.2	207,246	74,608.6	24,869.5	138,164	49,739.0	16,579.7
	3	392,121		345,410	-169,354	345,410	0	345,410	124,347.6	41,449.2	207,246	74,608.6	24,869.5	138,164	49,739.0	16,579.7
	4	392,121		345,410	-216,064	345,410	0	345,410	124,347.6	41,449.2	207,246	74,608.6	24,869.5	138,164	49,739.0	16,579.7
gen-25	1	214,493		185,916	-244,641	185,916	0	185,916	66,929.7	22,309.9	111,549	40,157.8	13,385.9	74,366	26,771.9	8,924.0
	2	214,493		185,916	-273,218	185,916	0	185,916	66,929.7	22,309.9	111,549	40,157.8	13,385.9	74,366	26,771.9	8,924.0
	3	214,493	700,000	185,916	-301,795	-514,084	0	185,916	66,929.7	22,309.9	111,549	40,157.8	13,385.9	74,366	26,771.9	8,924.0
	4	214,493		185,916	-330,371	185,916	0	185,916	66,929.7	22,309.9	111,549	40,157.8	13,385.9	74,366	26,771.9	8,924.0
feb-25	1	164,458		185,916	-330,371	185,916	0	185,916	66,929.7	22,309.9	111,549	40,157.8	13,385.9	74,366	26,771.9	8,924.0
	2	164,458	700,000	185,916	-330,371	-514,084	0	185,916	66,929.7	22,309.9	111,549	40,157.8	13,385.9	74,366	26,771.9	8,924.0
	3	164,458		185,916	-330,371	185,916	0	185,916	66,929.7	22,309.9	111,549	40,157.8	13,385.9	74,366	26,771.9	8,924.0
	4	164,458		185,916	-330,371	185,916	0	185,916	66,929.7	22,309.9	111,549	40,157.8	13,385.9	74,366	26,771.9	8,924.0
mar-25	1	180,906		185,916	-330,371	185,916	0	185,916	66,929.7	22,309.9	111,549	40,157.8	13,385.9	74,366	26,771.9	8,924.0
	2	180,906	850,000	185,916	-330,371	-664,084	0	185,916	66,929.7	22,309.9	111,549	40,157.8	13,385.9	74,366	26,771.9	8,924.0
	3	180,906		45,432	-325,361	185,916	140,484	185,916	66,929.7	22,309.9	111,549	40,157.8	13,385.9	74,366	26,771.9	8,924.0
	4	180,906			-320,351	185,916	185,916	185,916	66,929.7	22,309.9	111,549	40,157.8	13,385.9	74,366	26,771.9	8,924.0

Figure 17: Master Production Schedule

In the initial months up to mid-March, the Available to Promise (ATP) remains consistently at 0. This occurs because the production is fully committed to meeting the substantial orders received during this period. However, from the second week of March onward, production capacity begins to allow the fulfillment of potential new orders, indicating improved flexibility.

Regarding the Projected Available inventory levels, these remain negative throughout the analyzed period. This is primarily due to the computation method, which uses the maximum between forecasted demand and actual customer orders. While this approach ensures a conservative estimation of inventory, it leads to a pessimistic view, particularly in the earlier months, where even in the absence of concrete orders, the possibility of last-minute demand is accounted for. Although this scenario is unlikely, it helps prepare for unexpected surges in demand. Furthermore, the quantity ordered for one single week accounts for the forecasted quantity of the whole month. Therefore, although all the weeks of that month are used to produce for one single-week order, this order is expected to be all the demand for the month according to the forecast. This fact is not taken into account by the Projected Available, leading to negative numbers.

The MPS allows all orders to be accepted, except the one for December week 1, for which we are able to produce just 1,262,814 out of 1,500,500 (84%) on time. Overall, 95.5% of the total orders received during the first five months could be promised and delivered on time (within customer's acceptance range).

Furthermore, to fulfill the huge demand, notice that all MPS shipments are committed to promise for nearly the first 5 months (no remaining available).

Finally, for this work, it is assumed that capacity can no longer be changed since real orders are received in Frozen (latest Slushy) time, so changes are kept to minimum. However, if the maximum subcontracting capacity (set in AP) of 15% for December was added, 99.1% of all the units could be produced on time. Anyway, this adjustment would only be possible if subcontracting is not considered a change in the AP capacity, given that the latter is already frozen. In general, timely planning (1 month in advance) may be enough to find an external company to outsource the production.

13 Material Requirements Planning

The material requirement planning schedule (MRP) aims to provide sufficient material to meet the MPS while optimizing the inventory level. The quantity and timing of materials delivery are determined. The MRP works with ***backward scheduling*** and ***dependent items demand planning***. Four item materials of QC's BOM, accounting for one branch, are scheduled. From highest level 0 to lowest level 3: 1) Level 0 Bose QC; 2) Level 1 Earcups Assembly; 3) Level 2 Speakers; 4) Level 3 Diaphragms.

The lead time for each level is estimated according to the distance between manufacturing centers in Bose's global value-adding networks and the personalization required for each. For instance, diaphragms need to be custom made when ordered to reach Bose sound-quality standards, its products main value. Furthermore, the supplier may also work for other brands, so not always producing for Bose.

Higher levels are depended on the lower levels' items and with higher cumulative lead times. Bose QC as the finished product has a cumulative lead time of 7 weeks, that is justified by the customization specific components (in particular, the diaphragm), and is in any case consistent with competitors' lead time ("Honsenn Audio Lead Time", 2024).
Bose JIT approach assumes zero inventory at the beginning of the planning horizon.
Gross requirements are given by the MPS for the highest level item. The lower level items' gross requirements are determined multiplying its usage quantity by the parent's gross requirement.
The orders are placed in advance according to the item's lead time. It is also assumed that some orders have been placed in advance, before the start of the period analyzed, and so the associated schedule receipts are accounted for in the first weeks of November, to allow continuous production.
The order's quantity is determined following the supplier's lot size policy. In the finished product, the fixed order quantity forces Bose to order more items than needed. The other effect is seen in level 3, for which the requirements of 2 consecutive weeks are placed in each order.

LEVEL 0

Item: Bose QC — **Parent:** none
Lot size policy: FOQ 50,000 — **Children:** Earcups Assembly
Lead time (weeks) 1 — **Beginning Inventory:** 0
Usage quantity 1

Month	Week	Gross Requirements	Schedule Receipts	Projected Available	Planned orders
nov-24	1	345,410	350,000	4,590	350,000
	2	345,410		9,180	350,000
	3	345,410		13,770	350,000
	4	345,410		18,360	350,000
dic-24	1	345,410		22,950	350,000
	2	345,410		27,540	350,000
	3	345,410		32,130	350,000
	4	345,410		36,720	150,000

LEVEL 1

Item: Earcups Assembly — **Parent:** Bose QC
Lot size policy: L4L — **Children:** Speakers
Lead time: 1 week — **Beginning inventory:** 0
Usage quantity 1

Month	Week	Gross Requirements	Schedule Receipts	Projected Available	Planned orders
nov-24	1	350,000	350,000	0	350,000
	2	350,000		0	350,000
	3	350,000		0	350,000
	4	350,000		0	350,000
dic-24	1	350,000		0	350,000
	2	350,000		0	350,000
	3	350,000		0	150,000
	4	150,000		0	200,000

LEVEL 2

Item: Speakers — **Parent:** Earcups Assembly
Lot size policy: L4L — **Children:** Diaphragm
Lead time: 2 week — **Beginning inventory:** 0
Usage quantity 2

Month	Week	Gross Requirements	Schedule Receipts	Projected Available	Planned orders
nov-24	1	700,000	700,000	0	700,000
	2	700,000	700,000	0	700,000
	3	700,000		0	700,000
	4	700,000		0	700,000
dic-24	1	700,000		0	300,000
	2	700,000		0	400,000
	3	300,000		0	400,000
	4	400,000		0	400,000

LEVEL 3

Item: Diaphragm — **Parent:** Speakers
Lot size policy: POQ 2 weeks — **Children:** none
Lead time: 3 week — **Beginning inventory:** 0
Usage quantity 1

Month	Week	Gross Requirements	Schedule Receipts	Projected Available	Planned orders
nov-24	1	700,000	1,400,000	700,000	
	2	700,000		0	700,000
	3	700,000	1,400,000	700,000	
	4	700,000		0	800,000
dic-24	1	300,000		400,000	
	2	400,000		0	700,000
	3	400,000		400,000	
	4	400,000		0	800,000

Figure 18: MRP summary and 2 months exemplification.

Figure 18 shows the requirements for each level and two months planning as exemplification of the procedure followed.

Details and final results of weekly MRP is available in the Excel file attached, under the tab "MRP".

The main limitation noticed is the high cumulative lead time, which causes a need for ordering well in advance the required level 3 item (diaphragms). Furthermore, this lowest item is the one with highest lead time (3 weeks), being the bottleneck for the overall production.

Lastly, it is worth noticing that based on the partial information available, the orders for diaphragms appear to be managed by the supplier responsible for providing the speakers, who coordinates directly with the sub-supplier producing the diaphragms. Consequently, Bose does not directly intervene in the material planning for this item. However, due to the limited clarity on this process, we have still computed the MRP for the diaphragms to ensure a comprehensive analysis.

14 Inventory Management

This section covers the strategies employed to manage effectively the inventory of each item within a specific branch of the Bill of Materials (BOM) (i.e Bose QC - Earcups Assembly - Speakers - Diaphragm), ensuring smooth production flow and timely assembly of the final product in our factories.

14.1 Economic Order Quantity

Materials replenishment orders schedules are given by the MRP. Next, the order quantity needs to be determined. One replenishment order decision is modeled with Economical Order Quantity (EOQ), that is, the simplest model to find the ***quantity to order (Q) with minimal costs.***

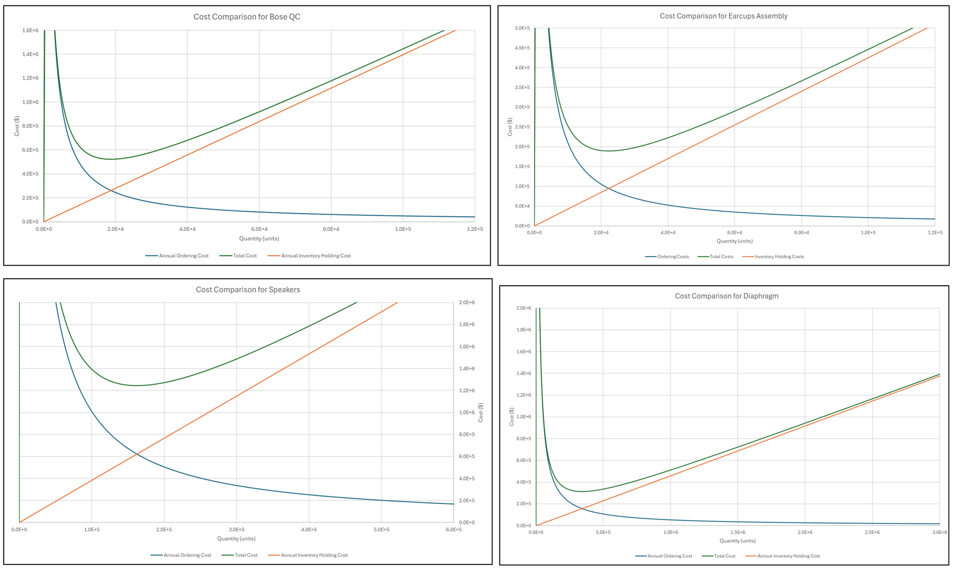


Figure 19: Cost comparison showing the optimal order quantity for each BOM component: Ear-cups Assembly (top right), Bose QC (top left), Diaphragm (bottom right), and Speakers (bottom left)

The results obtained for both the EOQ and the reorder point in relations to all the levels of the Bill of Materials are presented in Table 6.

Based on the parameters estimated for the model - which are deeply covered in the Excel File - it becomes evident that the EOQ model does not align with our operational realities and requires adjustments. Specifically, the optimal order quantity derived from the EOQ model is significantly

Item	Theoretical EOQ	Reorder Point
Bose QC	18,717	226,418
Earcups	22,283	224,468
Speakers	162,468	886,957
Diaphragm	342,817	1,295,455

Table 6: EOQ and Reorder Point for each item

smaller than the Reorder Point, making the strategy impractical. The discrepancy between the Reorder Point and the EOQ is so vast that achieving a feasible EOQ would be virtually impossible, even if lead times (LT) were negotiated with suppliers. The extreme mismatch would necessitate placing orders with delivery timelines as short as one day, which is unfeasible given the volume of each order.

Please note that for the diaphragm EOQ and EPQ as well have been calculated; however, based on the partial information gathered, the diaphragms appear to be produced by a sub-supplier and delivered directly to the supplier responsible for providing us with the speakers. As a result, Bose does not hold this item in inventory, and inventory models are not applicable in this case.

14.2 Economic Periodic Quantity

The Economic Periodic Quantity (EPQ) is a method used to determine the optimal production or order quantity over a given time period. Unlike Economic Order Quantity (EOQ), which focuses on minimizing costs for a single order, EPQ balances inventory and production costs over multiple periods, ensuring, in particular, that production or order quantities align with demand, while minimizing holding and setup costs.

In order to compute the EPQ for each component of the Bill of Materials for the Bose QC Headphones, some assumptions have been made:

- The production rate for each component has been assumed to be equal to the highest order issued over the period from the MRP (i.e., the maximum sustainable production rate).
- The consumption rate has been computed using the MRP gross requirements for each level.
- The holding cost has been computed, per standard, as 20% of the manufacturing cost.
- The setup costs per order are the same as in EOQ (see section "Economic Order Quantity").
- The total number of operating weeks in a year for the assembly of Bose QC Headphones is 48 and the corresponding number of operating days is 5.

All these assumptions have been used for the computation of the EPQ, the reorder point, and the theoretical maximum inventory. It is also possible to find the exact data values used for the computations for each level of the Bill of Materials in the Excel file, under the tab "EPQ".

Table 7 shows the results obtained for each component.

As highlighted both in Table 7 results and in the inventory evolution graphs (see Subsection 16.3 in the Appendix), once again as in EOQ, an optimal order quantity below the Reorder Point is obtained, thus making this strategy impracticable since out-of-stock is going to occur.

Metric	BOSE QC	Earcups Assembly	Speakers	Diaphragm
EPQ	205,090.00	37,207.00	268,383.00	454,798.00
Reorder Point	226,418.00	224,468.00	886,957.00	1,295,455.00
Theoretical Max Inventory	1,708	13,345	98,352	258,408

Table 7: EPQ Metrics for BOSE QC Headphones and its Components

14.3 Discount Model

The **Quantity Discount Model** is an extension of the basic Economic Order Quantity (EOQ) model. It has been done for the hightest level outsourced item, the speakers (level 2), based on the discount table (see Table 8) negotiated with the supplier. It incorporates the effect of price reductions for purchasing larger quantities. The model aims to determine the optimal order quantity that minimizes the total cost, taking into account the Ordering Costs, Holding Costs and Purchase Costs.

Range	Quantity	Unit Price ($)	Holding Cost ($)	Order Cost ($)	Annual Demand
1	> 1000k	31	6.20	$4,960$	$20,400,000$
2	[1000k – 500k)	34	6.80		
3	[500k – 300k)	35	7.00		
4	[300k – 200k)	37	7.40		
5	≤ 200k	39	7.80		

Table 8: Discount Table

First, the order quantity using the basic EOQ model was computed, gradually increasing the cost per unit (hence the annual holding cost) to find the first feasible order quantity result that falls between the price range of input. In this case, the first quantity that falls within the price range in the fifth range, the most expensive (Q5 in Table 13 in Appendix).

Then, the total annual cost is calculated for both this order quantity and the minimum order quantity for each of the cheaper ranges (4 to 1), in order to check if there is any cost reduction by ordering a higher quantity. Indeed, the minimum total annual cost is achieved by ordering the minimum quantity which allows us to take advantage of the cheapest price.

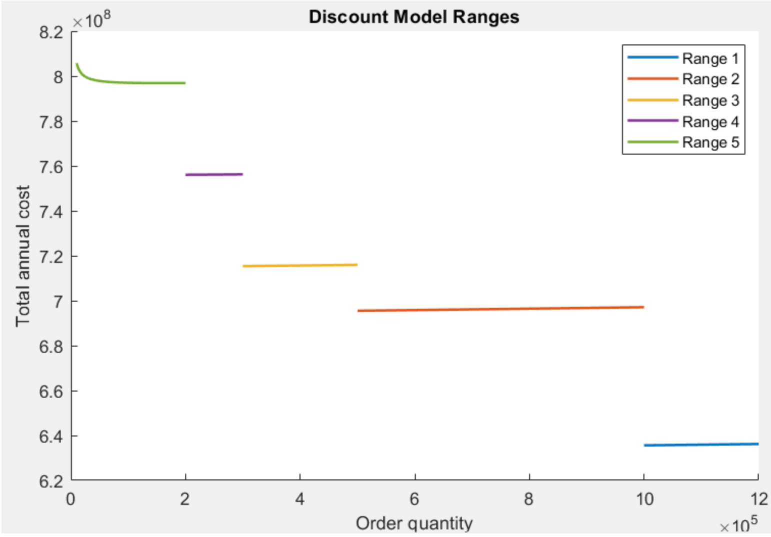


Figure 20: A visual representation of the discount model ranges.

Following the calculations, this is achieved by ordering 1,000,001 units, corresponding to the **minimum quantity of Range 1 (cheapest range)**, and the total annual cost is 635.6 M$.

Please note that the trend of the graph for each quantity range seems almost steady given the fact that the item's cost (decreasing with the quantity) nearly offsets the holding cost (increasing with the quantity). The scale of the graph due to the high order of magnitude for the costs also makes the trend less noticeable.

This result underscores the limitations of the simplified EOQ model. As demonstrated, the basic EOQ model provides an order quantity that would be deemed optimal in the absence of such discounts, but does not reflect the advantages gained by ordering larger quantities. By integrating the discount structure and optimizing the order quantity to achieve the lowest total annual cost, the process not only ensures cost efficiency but also maintains alignment with the previously calculated reorder point. Thus, this strategy not only meets the operational requirements but also represents the **optimal approach** for managing outsourced items in this context.

14.4 Safety Stock

Safety stock is the additional inventory held to account for variability in demand or supply, ensuring that our company can meet customer demand even when there are unexpected fluctuations.

The demand was modeled using a lognormal distribution, as it appropriately reflects the characteristics of the historical demand. This behavior is clearly identified using the software *Rstudio* (see Figure 21.

Service Level (%)	z	Safety Stock (units)	Reorder Point
90%	292,457	86,965	313,383
95%	325,821	96,886	323,304
98%	367,946	109,412	335,830

Table 9: Service Level, Safety Stock, and Reorder Point

Note that z, the value corresponding to the desired **service level** in the lognormal distribution, is computed using the 'LOGNORM.INV' Excel function. To select the optimal service level to apply, Table 9 was computed for a range of typical service levels.

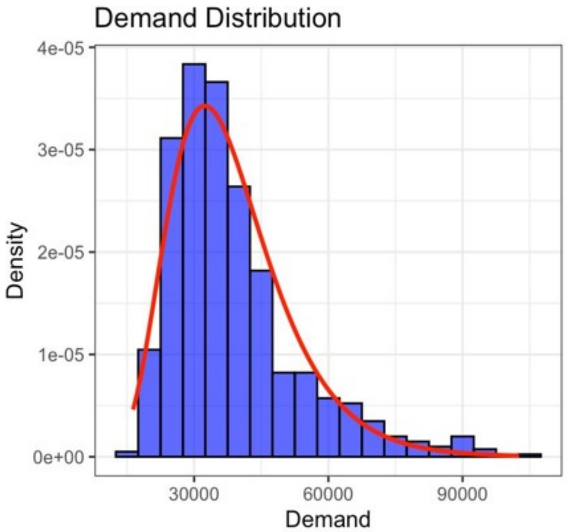


Figure 21: Lognormal Distribution

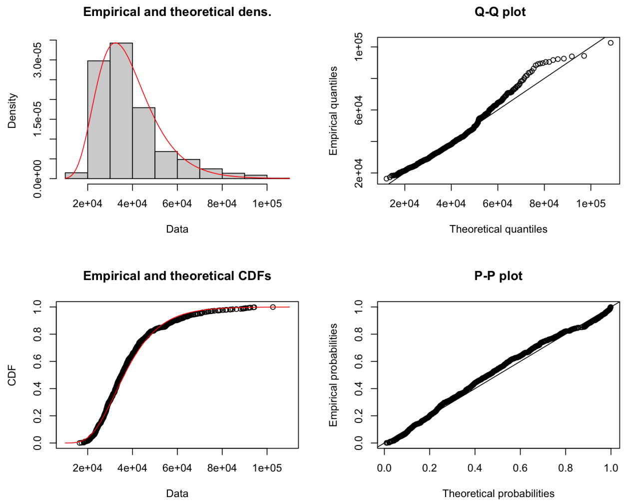


Figure 22: Model Fit Evaluation Test

Given Bose's focus on a Just-in-Time (JIT) strategy, increasing the service level from 90% to 95% is essential to strike the right balance between maintaining sufficient stock to meet demand and minimizing excess inventory. A 5% improvement in service level, achieved with approximately 3% increase in stock, is a manageable trade-off. This is particularly critical in a highly competitive market, where customer loyalty is fragile, and even a 5% loss of orders could lead to significant market share erosion. In such an environment, the ability to fulfill orders promptly and reliably is key to retaining customers, who have high mobility and can easily switch to competitors.

However, increasing the service level to 98% is not advisable, as it requires a further 4% increase in stock for only a 3% improvement in service level. This diminishing return on inventory investment makes such an approach impractical, especially when factoring in the constraints of a JIT policy. The optimal strategy lies in preventing the loss of a small but critical portion of orders, while avoiding overstocking, which could otherwise undermine operational efficiency.
Therefore, **service level is set at 95 %**.

14.5 Periodic Review Inventory Model

With the **periodic review system**, an item's inventory quantity is determined at fixed-time intervals. If this on-hand quantity is below a target inventory, an order for the item is placed so that safety stock is not consumed during the lead time plus next review time. The quantity of this order is the difference between the on-hand inventory and the target inventory, taking also into account any other lot policies that may apply. In this section, the model is applied to the finished product: QC headphones.

Firstly, a review period needs to be determined. The Review Period (or Time Between Orders) has been set at 1 day (every working day at closing time) since it is the minimum non-continuous review period which is constant every week (to avoid mistakes due to changing review day every week), because of the low inventory level and high depletion rate. It can be determined mathematically with EOQ, but it is not used since this method does not present a feasible approach (review every 0.4 days).

Safety stock is established using the information from last section: 95% service level as optimal and a log-normal demand distribution (daily in this case, instead of weekly). The lead time is the one determined in MRP for the finished product: 5 working days (1 week).

Finally, the target inventory level, which is the desired inventory level, is computed. The overall summary of information is displayed in Table 10.

Parameter	**Value**
Lead Time (working days)	5
Average Demand (units per working day)	45,284
Review Period (working days)	**1**
Standard Deviation (lognormal distrib.)	0.146
Safety Stock (95% service level)	47,464
Target Inventory (units)	**298,652**

Table 10: Key Parameters and Calculations for Periodic Review System

Next, an hypothetical inventory simulation using this model and some assumptions is presented, representing the worst-case scenario: the transition between different demand-level seasons.

Assumptions needed to be made for the simulation: during the first week, the quantity of the orders that arrive from last week is is 80% of the demand (not 100% to challenge the model's adaptability). In the morning (opening) orders from last week arrive. In the evening (closing), the review is performed and, if necessary, orders are placed.

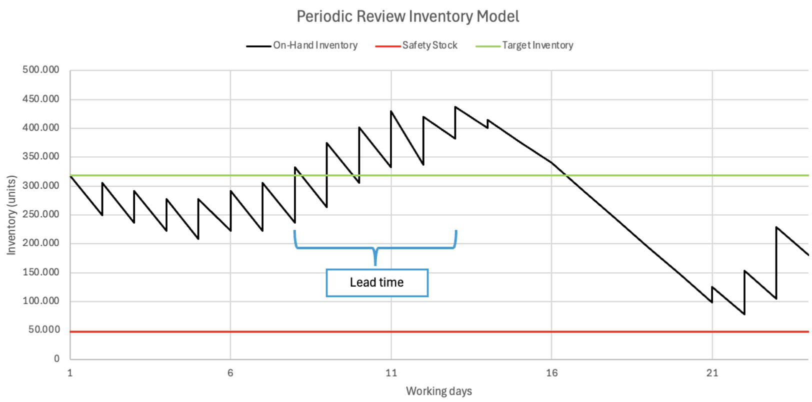


Figure 23: Periodic Review simulation.

Overstocking can be observed in the season after higher demand due to the orders performed during the high demand season (low stock levels), which is corrected afterwards. It is worth noting that the safety stock is never consumed, even during high demand, and maximum overstock is of 33%. Furthermore, during one same demand season (which lasts for months not just one/two weeks), the inventory level gets stabilized.

Further analyzing the results, since we have 3 clear demand periods: High (November and December), Medium (August to October) and Low (the rest), it would be interesting to establish one target inventory level for each demand-level period instead of using an average overall demand. This could

correct the overstocking during low demand and avoid the risk of consuming safety stock during high demand.
All in all, this model presents a behavior that makes it so far **the most suitable for the inventory management** of the final product.

Moreover, since it has proven effective for the final product, it **can be extended to Level 1 of the BOM**. Provided that the demand for this item directly follows the demand for the final product, and with a usage quantity of 1, the same parameters and periodic review strategy can be applied to ensure consistent inventory management.

14.6 Single-Period Inventory Model

Regarding the Single-Period Model, most of its major assumptions are not satisfied by our product's data. Therefore, implementation was unsuitable. The major reasons are:

1. **Product Availability Over Multiple Periods:**
   One of the model's main assumptions is that the product is sold at a regular price for a single time period. This is not the case for the QC headphone product family, which remains in the market for two years (two cycles) from its release date. It is sold at the same price on the Bose website and through official retailers, except for some discount policies that are implemented, but not to dispose a perishable product instead to incentivize demand over certain periods.

2. **Salvage Value Exceeds Production Cost:**
   Another important assumption behind the model is that the salvage value is below the original cost of the product. On the marketplace as well as on the Bose website, previous versions of our product are sold at a 40% discount (with respect to the original selling price) [1,2], which—according to our assumption of a gross margin of 60% (as explained thoroughly in the section for AP)—is still higher than the production cost, even after a period of two years from the product launch. Hence, this assumption is also invalid.

3. **Just-in-Time (JIT) Strategy Implementation:**
   Moreover, a Just-in-Time (JIT) strategy is already implemented, which allows to release orders very close to the actual demand. This strategy ensures that problems of overstocking do not incur, and produces quantities that prevent stockouts. This JIT approach aligns production closely with demand forecasts, enhancing the ability to meet customer needs promptly. However, it leaves little room for accommodating additional orders, even in low-demand seasons, as production for the high-demand season takes precedence.

15 Conclusion

The Bose QuietComfort headphones remain a strong competitor in the hi-fi audio market, distinguished by superior noise-canceling capabilities, high-fidelity audio, ergonomic design, and long battery life. Bose's inventory management adaptability and supply chain resilience are reinforced by advanced programs such as JIT II and the Resilience Program. Sustaining this success requires continuous innovation, strategic vertical integration, effective demand planning, and resilient supply chain management to navigate the challenges of an evolving, competitive audio industry. To achieve so, implementing the analyzed techniques summarized in this conclusion is recommended to Bose.

Demand Planning was executed using refined raw data, with outliers managed through confidence intervals and moving averages. An additive upward growth trend and multiplicative yearly seasonality are identified, providing a clear basis for accurate demand forecasting. The Holt-Winters exponential smoothing model is selected for its suitability in capturing these dynamics. The small optimal parameters of the model suggest that low-reactivity to the most recent fluctuations achieves the best accuracy, reaching a Mean Absolute Percentage Error (MAPE) of 5.9%, reducing further to less than 1% with fine-tuned coefficients. This forecast provides a reliable 12-month baseline, extended to 18 months, ensuring robust demand anticipation.

In Capacity Planning, leveled, chase, and hybrid aggregate production plans were evaluated. The automated hybrid strategy emerge as the optimal choice, balancing workforce stability with cost efficiency. This was further integrated into a Master Production Schedule and Material Requirements Planning, ensuring alignment between demand forecasts and operational execution. The plan enables 95.5% order acceptance under existing production capacity, increasing to 99.1% with subcontracting if feasible.

Inventory Management leveraged various models to optimize stock levels. While EOQ, EPQ and Single Period Model highlighted theoretical constraints which prevented them to be applied, the Quantity Discount Model offers cost efficiencies for outsourced items, and the Periodic Review System ensures reliable finished product inventory with no shortages under adverse demand scenarios. Notably, the periodic review approach could extend to Level 1 of the BOM, given their direct dependency on the final product demand. Additionally, setting the Service Level at 95% was found to be optimal.

Finally, the Level 3 diaphragms, produced by sub-suppliers managed by Bose's direct suppliers, present a critical supply chain risk due to long lead times and their foundational role in the BOM. Strategic measures, such as near-sourcing or diversifying sub-suppliers, could strengthen supply chain resilience.

By leveraging these techniques, Bose is well-positioned to enhance its supply chain, maintain competitive edge in the high-end audio market, and uphold reputation for quality and customer satisfaction.

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16 Appendix

16.1 About Bose

Company	Country	Noise-cancelling Headphones Features	Price range	Pro	Cons
Bose Corp.	United States		High	+ detailed sound, rich bass + high noise-stopping power + comfortable, folding design + great smart features	+ improvable battery life + limited features on the app
Sony	Japan		Medium/ High	+ very good noise-cancellation + many features on the app + multipoint pairing + auto-play/pause and conversation awareness	+ lacking microphone and call system + no water resistance + new design is less portable
Sonos	United States		Low	+ excellent battery life + incredibly comfortable + good ANC and sound	+ boring design + not intuitive controls + worse noise-cancellation than Bose's
Apple	United States		Really High	+ excellent audio performance + brilliant extra features for iOS + great noise cancellation	+ very expensive + no 3.5mm audio port + limited features for Android
Beats Electronics	United States		Medium	+ good sound quality + good battery life + light	+ bad fit + confusing controls
JBL by Harman	United States		Medium/ Low	+ good sound quality and noise-cancelling performance + strong feature set + strong battery life	+ voice-calling suffers in windy environments
Sennheiser	Germany		Medium	+ good sound + good battery life + comfortable, with portable case + touch controls	+ not suited for every head shape
Bowers & Wilkins	UK		Really High	+ detailed, exceptional sound + supreme comfort + classy design	+ average battery life + noise cancellation is average + expensive
Dyson	Singapore		High	+ excellent battery life + customizable design	+ audio lacks dynamic punch + non-breathable cushions + heavy
Anker	China		Medium	+ 5 levels of noise cancellation + multi-device pairing	+ high noise floor with ACN on + average fit
Logitech	Switzerland		Medium/ High	+ detailed audio quality + great soundscape + robust app + great AI features + lightweight	+ spotty AI features + not sturdy construction + average battery life

Figure 24: Main competitors of Bose QuietComfort Headphones

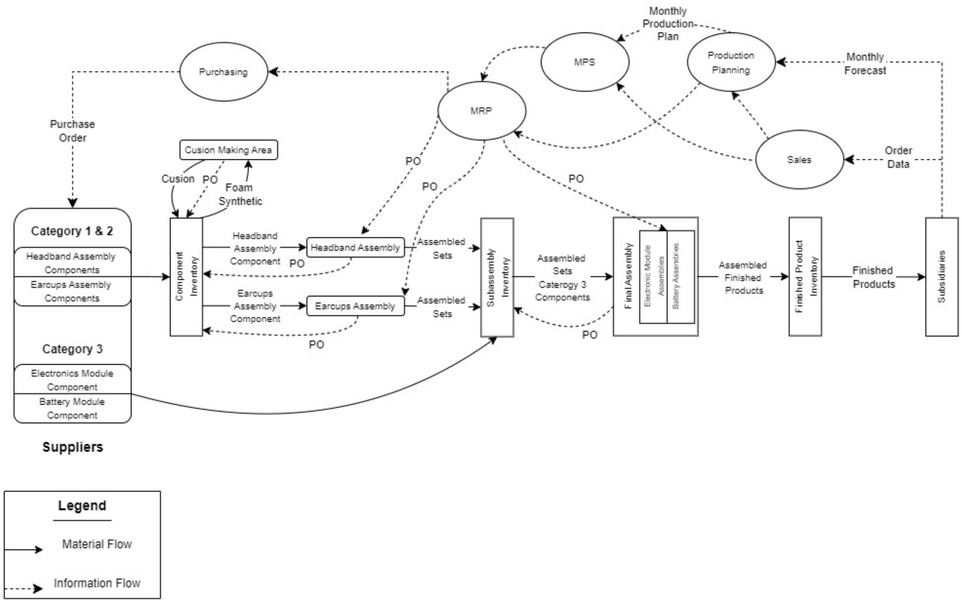


Figure 25: Material and Information Flow Diagram

16.2 Aggregated Planning - Formulas and Tables

$$\delta workforce = \frac{Production - RegularCapacity}{RegularCapacity} * 100\% \tag{19}$$

$$Hired = \frac{(\delta workforce - 15\%) * RegularWorkforce}{LabourStandard} \tag{20}$$

$$Layoff = \delta workforce * \frac{RegularCapacity}{LabourStandard} \tag{21}$$

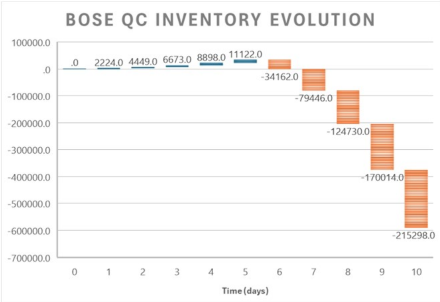
Total workers	3500
Percentage on production	10%
Workforce Adjustment Factor	9
Allocation for Asian_Pacific center	33,33%
Allocation for American center	66,67%
Total hours per worker	160
Productivity [h/unit]	0,36
Overtime factor	1,5
Asian factory Regular Labour Cost [$/unit]	1,79
American factor Regular Labour Cost [$/unit]	1,40
Labour Standard [units/worker]	444,4
Beginning inventory	0
Beginning workforce	3150
Gross margin	60%
Selling price [$]	349
Inventory holding value	20%
Planning Horizon [months]	12

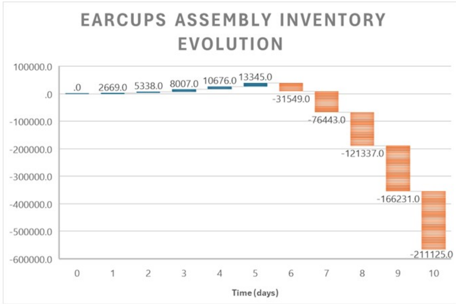
Table 11: Workforce and Product Information

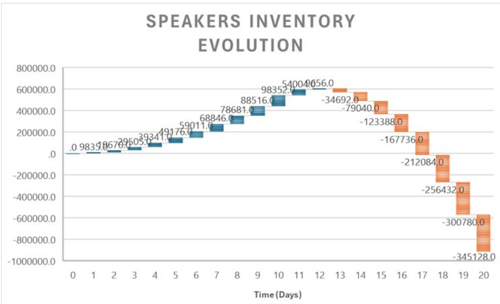
Cost	Cost [$] / unit
Weighted Regular Labour	1,53
Overtime/Subcontracting	2,30
Inventory Holding per planning horizon	27,92
Backorder	To avoid (infinite)
Hiring	500
Layoff	750

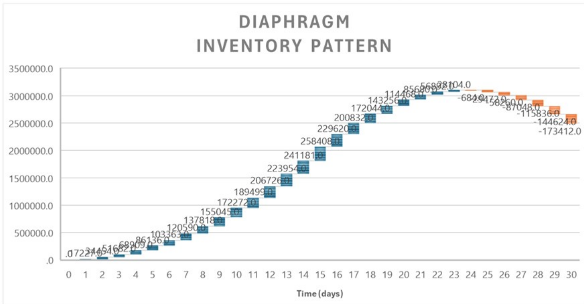
Table 12: Cost Information

16.3 EPQ Inventory Evolution









16.4 Discount Model Quantities for Different Ranges

Range	Quantity (units)
EOQ-1	180, 665
EOQ-2	172, 511
EOQ-3	170, 029
EOQ-4	165, 369
EOQ-5 (only in range)	161, 073
minQ4	200, 001
minQ3	300, 001
minQ2	500, 001
minQ1	**1,000,001**

Table 13: Discount model quantities for different ranges