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Enhancing The Fulfilment Process of a Smart Semiconductor Manufacturing Company: An Integrated Lot-sizing Simulation Approach

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Abstract

Fulfilment process is important for operational efficiency in semiconductor manufacturing, particularly for Company A, a leader in wafer processing equipment for thin-film deposition. This study investigates methods to enhance Company A's fulfilment process through the integration of a lot-sizing simulation into their existing ERP system, focusing on optimizing order quantities amid fluctuating demand. The research addresses three primary objectives: identifying inaccuracies in the current simulation, exploring ERP system integration methods, and evaluating fulfilment process improvements through enhanced demand forecasting and data accuracy. A mixed-method approach was adopted, incorporating qualitative insights from surveys with Company A's stakeholders and quantitative data analysis for pain point identification. A SWOT analysis, along with a Fishbone Diagram and Monte Carlo simulations, supported the identification of key areas for improvement and the validation of proposed solutions. External market research enabled better insights to potential integration efforts and functions. Additionally, the study employed a Non-Linear Programming (NLP) model to evaluate multiple lot-sizing scenarios based on metrics such as cost efficiency, safety stock, demand accuracy capacity utilization, and service level. The findings indicate significant potential for reducing inaccuracies and optimizing fulfilment through ERP integration, improving both forecast precision and process adaptability. While the proposed integration shows clear benefits in operational efficiency and cost savings, challenges around real-time data synchronization and user training. This research highlights the value of ERP-integrated lot-sizing for achieving resilience and efficiency in semiconductor manufacturing supply chains.

Keywords
Semi-conductor wafer processing, Simulation, Lot-sizing, Inventory Management.

1. Introduction
The semiconductor manufacturing industry is central to the digital revolution, producing integrated circuits (ICs) or sometimes called microchips. These chips are essential components for electric devices across all global sectors (Semiconductor Industry Association, 2024). In 2023, the industry was valued at USD 611.35 billion globally, projected to increase to USD 681.05 billion in 2024 and a Compound Annual Growth Rate of 14.9% through 2032. As a result, Burkacky et al. (2022) projects the industry to become a trillion-dollar industry come 2030 based on macroeconomics trends. The Covid-19 pandemic exposed multiple vulnerabilities within the industry, from manufacturing shutdowns to supply chain disruptions which led to production delays and a global chip shortage (Alam et al., 2021; Marinova & Bitri, 2021). Given it's notorious rapid technological advancements, fluctuating demand and short product lifecycles, maintaining a robust and efficient supply chain is crucial for meeting global microchip demand (Ravi, 2020).

Company A is one of the global leaders in the semiconductor industry, specialising in producing and supplying wafer processing equipment for the deposition of thin films. With facilities in 16 counties, the company aims to remain their position as a leader in producing the equipment for faster smaller and more efficient chips. Between 2023 to 2024, the supply chain functions have faced significant scrutiny from internal and external stakeholders due to a 35% increase in late order placements to suppliers, driven by inaccurate demand forecasting, and a 22% rise in sudden cancellations, disrupting procurement and production schedules. These challenges have led to delays, strained supplier relationships, and increased costs, affecting the overall supply chain efficiency. This issues stem from poor information visibility and fragmented process, hindering efficient operations. A key process is the annual lot-sizing simulation initiative, which helps determine optimal order quantity for production runs (Jiao et al., 2016). It is developed in Microsoft Excel, spearheaded by the purchasing department, where many lack advanced Excel knowledge to configure meaningful simulations.

Currently, the simulation is used to forecast ordering patterns to reduce costs and improve fulfillment for the next fiscal year. This initiative, which began in 2019, has experienced frequent changes in administration which led to inconsistent updates which has negatively impacted the initiative. However, the simulation only uses the previous fiscal year's purchase data without accounting for changes to the Material Requirement Planning (MRP) and Bills of Materials (BOM) which are integrated into their ERP system. This then creates forecasting inaccuracies due to the lack of real-time data.

Although not directly involved in the semiconductor manufacturing, Company A plays a key role in providing deposition equipment. As a global leader in this field, any delays in producing the equipment can halt the entire manufacturing process. Hence a poorly managed fulfilment causes delays, missed deadlines, increased cost and strained relationships (Nguyen et al., 2016).

As such, this study seeks to address the current pain points of their fulfilment process through the current lot-sizing simulation. The aim is to integrate the lot-sizing simulation into existing systems to improve data accuracy, enhance transparency, and create a more efficient, resilient fulfillment process in a stochastic demand market.

1.1 Objectives
As we seek to understand how an integrated lot-sizing simulation can help improve fulfilment processes, we first must define the fulfilment processes that we aim to improve. Order fulfilment process or fulfilment process for short, operates as a two-way channel for Company A, both as a buyer and seller (Figure 1). Hence, it needs to ensure efficiency at both ends of the fulfilment process. Understanding this, we can then delve further into the possible areas of the fulfilment process that we improve on using lot-sizing:

- **Inventory Management**
    - An efficient inventory management effort in ensuring enough supply to meet demand without overstocking or stock-out situations (Song et al., 2020).

- **Order Processing**

- A streamlined order processing can help to reduce lead time from both ends of the fulfilment process (De Treville et al., 2003). Suppliers receive orders in batches that they can fulfil in an agreed time and Company A has more confidence in setting a deadlines.

- **Demand Forecasting**
    - An accurate and proactive forecasting helps to make better strategic and tactical decisions to ensure fulfilment processes continue to operate efficiently and provides more confidence in expectation setting (Green & Armstrong, 2012).

- **Capacity Utilization**
    - A well utilized manufacturing plant will be able to efficiently ensure their space is optimally utilized with lesser likelihood of overutilization or underutilization (Singh et al., 2021).

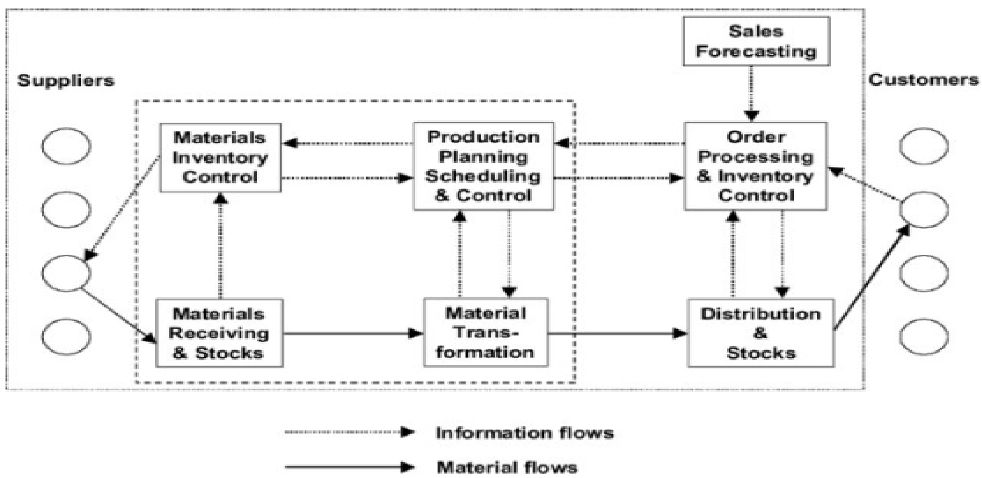

Figure 1. Fulfilment Process (Shaw et al., 2002)

Additionally, it is also important to understand the pain points of the current lot-sizing simulation. Identifying these issues will enable more effective improvements and optimization for the integration. This can ensure that the lot-size simulation better supports overall operational efficiency and fulfilment processes.

As such, these are the research questions (RQs) that we will focus on to guide this study:

(1) What are the factors that contribute to inaccuracies within the current lot-sizing simulation results in Company A?
- The aim is to understand what the current limitations of the lot-sizing simulation and understand how an ERP integration can help to reduce the inaccuracies.

(2) How can the lot-sizing simulation and Company A's ERP system be integrated?
- The aim is to understand the different methods of integration through understanding what is currently available in the market and taking inspiration on integration methods.

(3) How does an integrated lot-sizing simulation improve the overall fulfilment process of Company A with an improved demand forecasting
- The focus is to understand how the integration can improve Company A's overall fulfilment process through improving the overall logic of the simulation to include the MRP and BOM.

The scope of the study focuses on the fulfilment process challenges within a single multinational organization in the semiconductor manufacturing industry, Company A. It will specifically examine the company's lot-sizing simulation initiative and will attempt to improve on its current logic (Figure 2) through ERP integration. It is important that this analysis considers Company A's current capabilities and organizational goals to ensure that this project aligns with their needs and supports their strategic growth. In return, this can help to enhance data accuracy and reliability for forecasting and fulfilment processes which focuses on the end-to-end aspect of the company's supply chain.

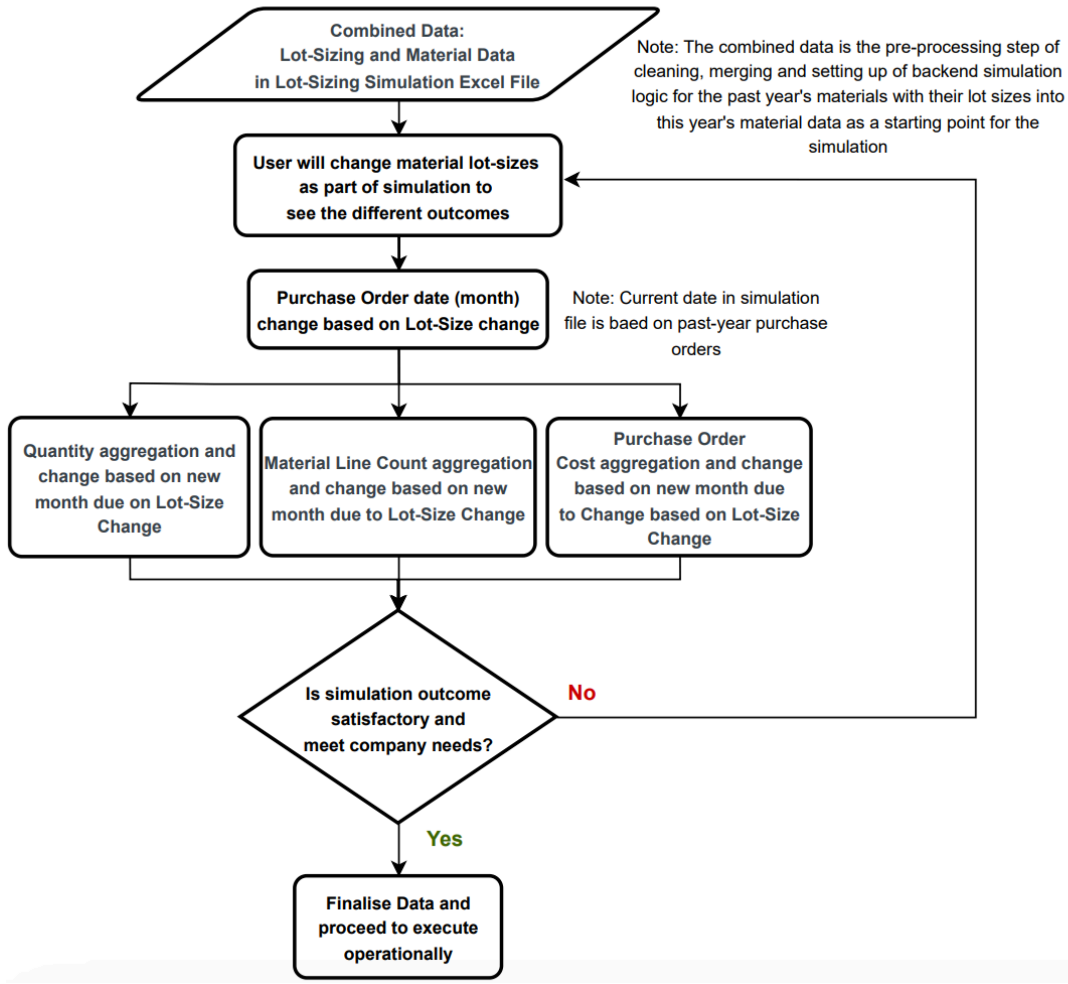

Figure 2. Overview of Company A's Current Lot-Sizing Simulation Logic

3. Literature Review

3.1 A two-stage stochastic programming model for lot-sizing and scheduling under uncertainty

The paper by Hu and Hu addresses RQ **(1) – "What are the factors that contribute to inaccuracies within the current lot-sizing simulation results in Company A?"**, where it tackles the uncertainty in lot-sizing and sequence-dependent set-ups in production planning systems which causes inaccuracies. Efficient production planning is essential for resource optimization for an organization to meet production goals over a planning horizon. Hence, the study aims to find the best sequence of production quantities for an optimal production plan that minimizes cost in uncertain demand, through the formulation of a two-stage stochastic programming model; through the comparison between a deterministic model as a baseline, assuming all parameters are known, and the two-stage stochastic model

The stochastic model extends from deterministic model by incorporating uncertainties in demand. The first stage involves baseline production decisions such as product production quantity and sequence of production. The second stage focuses on the possible updates to baseline production in stage one such as overtime production based on realised demand. As such, the model was formulated using the mathematical notations used in the deterministic model.

The study finds that the two-stage stochastic programming model does indeed optimize production planning under uncertainty by outperforming the deterministic model through total cost reduction; especially in scenarios with high demand variability. Additionally, the Value of Stochastic Solution (VSS) indicated that the stochastic model is more beneficial when the value is larger. This is especially when maximum production quantity increases.

Overall, this paper concludes that incorporating demand uncertainties into lot-sizing and scheduling problems is crucial and allows for effective production planning. The two-stage stochastic programming model provides a robust framework in addressing uncertainties. However, it does come with limitations where the model assume that demand for the different products are independent and does not take into account other variables of uncertainty such as manpower and lead time.

3.2 Integrating Lot-Sizing problems under uncertainty

The paper by Curcio addresses RQ **(1) – "What are the factors that contribute to inaccuracies within the current lot-sizing simulation results in Company A?"**, where it explores the uncertainty factors that affects the accuracies lot-sizing and production planning processes. The study focuses on how demand variability and lack of dynamic adjustments to production schedules are the main factors that contributes to inaccuracies, particularly in complex, multi-stage production environments.

The objective of the study was to identify the key sources of inaccuracies in production planning systems when used under uncertain demand conditions. To achieve this, Curcio proposed integrating stochastic programming and robust optimization techniques to account for demand uncertainty to generate more accurate lot-sizing decisions. These techniques can help to mitigate inaccuracies by enabling real-time adjustments based on updated demand data rather than using static models.

The study compares the deterministic, where demand is known and constant, and two-stage stochastic programming model, where demand uncertainties are implemented. While simpler, the deterministic model introduces significant inaccuracies due to its lack of adaptability to post-production plan demand changes. The inaccuracies are further exacerbated on environments that have high variability in customer demand and lead time which leads to excess inventory or stockouts.

Conversely, the stochastic model provides a more adaptive framework allwoing production plans adjustments, in tandem with real-world demand changes. The first stage of the model sets a baseline production decisions such as initial lot sizes and production sequences. The second stage allows for dynamic adjustments such as overtime production, based on actual demand. This helps to mitigate the inaccuracies caused by the demand variability (Curio, 2017). The findings reveal that the two-stage stochastic model can significantly reduce inaccuracies compared to deterministic models. Accounting for demand uncertainty and enabling dynamic schedule adjustments allows the stochastic model to reduce total production cost and improved service levels in high-demand variability scenarios. However, the study also acknowledges the limitation of the model. Its computational complexity will require more operating cost and the need for accurate demand forecast can affect its capabilities to achieve optimal results.

Overall, the paper reiterates that addressing demand uncertainty and allowing dynamic real-time adjustments in lot-sizing simulations can help to reduce inaccuracies. Additionally, it also highlights that inflexibility in adapting to real-time demand changes are often the main cause of inaccuracies which is aligned with the current issues faced by Company A.

3.3 Integration of a Heuristic Method into an ERP Software: A Successful Experience for a Dynamic Multi-item Lot Sizing Problem

The paper by Gutiérrez et al. addresses RQ **(2) – "How can the lot-sizing simulation and Company A's ERP system be integrated?"**, integrating new methods and logic into an existing ERP system to improve overall processes and lot-sizing. It focuses on improving the lot-sizing decisions within ERP systems using heuristic methods. Traditionally, ERP systems often rely on deterministic methods that do not handle complex and stochastic environment. This can result in high costs, poor inventory and service levels to customers. A heuristic method provides a different approach to generate near-optimal solutions for complex problems with multiple constraints and variables. The integration of such methods is proposed as a solution to improve decision-making processes and improve overall supply chain.

Gutiérrez et al. developed a prototype system to integrate the heuristic algorithms. There were several algorithm added such as the genetic algorithms, simulated annealing and the Mixed-Integer Optimization Problem with Penalty and Stochastic Constraints (MIOPPSC) algorithm. The MIOPPSC algorithm was used to handle mixed-integer problems and incorporate stochastic constrains, allowing for better adaptability to demand uncertainties.

With the integration, the modified ERP system is more adaptable in making dynamic decision-making, which were simulated and evaluated through real-world scenarios. These simulations assessed the MIOPPSC's algorithm against traditional deterministic approaches which focuses on inventory costs, service level and computational efficiency.
The study found that while integrating heuristic methods into ERP systems can enhance performance, it is only at an average of 5% better than commercial solvers. However, it highlights that the total integration can provide procurement schedule in advance to avoid both shortages and overstocking. It also optimises replenishment and delivery services to customer. Nonetheless, the limitations were also highlighted. Increased computational cost and rigidity of certain algorithms can limit long-term adaptability to changing market and business conditions.

3.4 Demand uncertainty and lot sizing in manufacturing systems: The effects of forecasting errors and mis-specification

The paper by Fildes and Kingsman addresses RQ **(3) – How does an integrated lot-sizing simulation improve the overall fulfilment process of Company A with an improved demand forecasting?** where it gives a glimpse of how poor forecasting causes a negative downstream affect within the supply chain. It focuses on the challenges of forecasting demand uncertainty and optimizing lot-sizes in manufacturing systems that utilizes the MRP system. It highlights the importance and impact of accurate forecasting to reduce costs associated with demand variability in the MRP systems.

In manufacturing, MRP systems are essential for production planning, assuming demand is stable. In reality, demand is stochastic. Demand uncertainty stems from random order variations, market changes and forecasting inaccuracies, causing poor inventory management and MRP efficiency. Fildes and Kingsman used a detailed simulation study of over 20,000 periods to analyse the demand uncertainty effects and forecast errors on lot sizing methods in a two-level MRP system, using unit cost and service levels as metrics. The simulation used two demand generation processes with commonly used lot-sizing rules in manufacturing:

- **Constant Demand Model (CDM):** generates demand as random variations from a normal distribution with a normal mean
- **Autoregressive Demand Model (ADM):** uses an autoregressive process to introduce a demand pattern that is more realistic with a higher variability (Table 1).

Table 1. Lot-Sizing Used (Fildes & Kingsman, 2005)

Lot Sizing Rule	**Description**
Economic Order Quantity (EOQ)	Optimal order quantity by minimising costs.
Period Order Quantity (POQ)	Order quantity to cover a specific number of demand periods
Least Unit Cost (LUC)	Minimises cost through increasing lot size
Least Total Cost (LTC)	Equals ordering and holding cost
Silver-Meal Heuristic	Minimizes costs by dividing total costs by periods covered.
Wagner-Whitin Algorithm	Optimizes costs over a given planning horizon.

From the simulations ran, the study found that demand uncertainty significantly affects lot-sizing performance. The EOQ lot-sizing rule performs best under conditions of demand uncertainty, where it is not a typically favoured rule in deterministic scenarios.

This study highlights the importance of forecasting accuracy in minimizing cost and optimizing inventory level in MRP systems. It reflects the exponential increase in unit cost with demand uncertainty where the EOQ rule is most effective under a stochastic condition due to its safety stock feature. It also emphasizes on substantial cost savings through improved forecast accuracy and alerts on the mis-specifying of forecasting models. It reflects that appropriate planning horizons can provide a robust framework for evaluating forecast error impacts and demand uncertainty on lot sizing decisions.

This literature review shows the interdependency of both components to ensure fulfilment process efficiency. However, the simplified two-level MRP system may not be a good indicator of real-world manufacturing especially for semiconductor with often has multi-level BOMs and intricate processes. Focusing on only service levels and unit costs overlooks other critical metrics like lead time and production efficiency.

3. Methods

Three-Step Approach

This study takes a novel three-step approach on how lot-sizing integration into an ERP system for Company A can help to improve its overall fulfilment process (Table 2). The three-step approach will use both qualitative and quantitative data to supplement and enhance the analysis. Qualitative insights will provide context for better understanding while the quantitative data will offer measurable evidence to support findings (McGillvary, 2023).

Table 2. Data Collection Sources

Source	Type of data
Survey	Qualitative and Qualitative
Market Research	Qualitative
Company A's Lot-Sizing File	Quantitative

Survey

Firstly, field research will be conducted through a survey sent to employees in Company A to understand their experiences and gather their thoughts on the integration initiative. Understanding the end-user's perspective is essential to ensuring the improvements benefit them and drive overall supply chain efficiency. This will also provide greater statistical power, allowing for better validation of the study (Jones et al., 2013).

Descriptive analysis will be performed on the data collected such as Likert Scale as a form of quantitative to evaluate the emotions of the surveyed by ranking them in numerical order, with the highest often being the best (Sullivan & Artino, 2013). Additionally, open-ended questions will also be presented as a form of qualitative data to understand additional comments they might have(Table 3).

Table 3. Examples of use of Likert Scale in Survey

Section 2: Current Lot Sizing Simulation Activity		
Question #	Question	Options
1	How satisfied are you with the current lot sizing simulation process? (Including communication, collaboration, speed and etc)	- 5: Very Satisfied - 4: Satisfied - 3: Neutral - 2: Dissatisfied - 1: Very Dissatisfied
2	How would you rate the effectiveness of the current lot-sizing simulation process in regards to the next year's ordering pattern?	- 5: Very Effective - 4: Effective - 3: Neutral - 2: Ineffective - 1: Very Ineffective
Section 3: Integration of Lot-Sizing and ERP System		
Question #	Question	Options

4	How do you feel about the integration of the current lot-sizing activity into the current ERP system?	- 5: Very Positive - 4: Positive - 3: Neutral - 2: Negative - 1: Very Negative
5	How important is user-friendliness of the integration to you?	- 5: Very Important - 4: Important - 3: Neutral - 2: Not Important - 1: Very Not Important

Measures of central tendency, such as the mean, median, and mode, will be applied to summarize respondents' sentiments (Yusoff & Janor, 2014). The mean reflects the average response to gauge overall sentiment, the median shows the middle value when responses are ranked, and the mode highlights the most common response. Additionally, correlation analysis through cross-tabulation will identify relationships between responses, such as satisfaction with the current process and receptiveness to ERP integration, and concerns about ERP integration(Table 4).

Table 4. Purpose of Central Tendency Measures

Central Tendency Measure	Purpose
Mean	- Average response of each question to gauge overall sentiments
Median	- Middle value when all responses are arranged from lowest to highest
Mode	- Most re-occurring response, indicating a common opinion

Market Research

Secondly, we will explore various ways to integrate the lot-size simulation into an ERP system by examining current market data. This includes understanding whether existing ERP systems offer built-in lot-size functions or simulations. At the same time, this analysis will help inform any necessary amendments to better meet end-user needs (Kantar, 2023).

To evaluate the feasibility and advantages of this integration, a SWOT analysis will be conducted. This will highlight the benefits and risks, enabling the development of strategies for leveraging strengths and mitigating threats (Bigelow et al., n.d.). A feature integration analysis will also be performed to identify ERP systems with in-built lot-sizing features and assess their functionality and usability. Additionally, if different integration methods are used in the market, an analysis of their pros and cons will be conducted. Finally, a cost-benefit analysis will be performed by creating a cost matrix for various integration scenarios, helping Company A visualize the financial investment and system requirements for each approach (Stobierski, 2019).

Lot-Sizing Integration Analysis

Thirdly, multiple analytical approaches will be implemented to assess how the integration of the lot-sizing simulation into the ERP system enhances lot-sizing activities and ultimately improves the fulfillment process for Company A. A sample blueprint will be created to illustrate the logic and data flow of the lot-sizing and ERP system integration, incorporating insights from market research of different ERP systems. The blueprint will include a revamped lot-size simulation logic flow, as well as "Best-In-Class" aspects from systems that Company A can adopt.

Monte Carlo simulation and Non-Linear Programming (NLP) will be used for preliminary assessments of the integration. Performance metrics will evaluate the outcomes to determine improvements while accounting for limitations. These simulations allow different scenarios of uncertainty and variability to be considered in forecasting and planning based on the lot-sizes used by Company A (Hussain, 2023). NLP will be applied to optimize the objectives of the integration, with constraints such as MRP demand and BOM inventory (Wright, 2024). The outcome will be optimized lot-sizes, improving fulfillment processes according to set metrics.

4. Data Collection

Survey

A survey in the form of a Google Forms will be sent out to the key stakeholders of the lot-sizing activity in Company A. This includes directors, managers, data analysts and buyers. This is to maximise the effectiveness and credibility of the survey where due to company privacy restrictions, the survey is only limited to 10 people. By narrowing down to these individuals, the survey can better capture critical insights and experiences from those with direct influence in decision-making.

Market Research

Secondly, market research will be done via multiple channels such as reputable online sources and employees in Company A to review the various ERP systems to understand their capabilities and functions for a better understanding of integration processes and benefits. This is to allow for comparison for the possible features and approach that Company A can adopt.

Company A's Lot-Sizing File

The current lot-sizing excel simulation file was obtained from the company with their approval. The data consists of the company's masked 17 months' worth of direct material purchases. While the organisation has a lot of lot-sizing types, the purchasing department has a standard practice of only using pre-set lot sizes (Table 5). These lot-sizes will be implemented into analytical tools, including the MRP and BOM.

Table 5. List of Standardised Lot-Sizing for Usage

Lot Sizes Indicator	Description
TB	Daily Lot Size
WB	Weekly Lot Size
ZW	Bi-Weekly Lot Size
MB	Monthly lot size
ZM	Bi-Monthly Lot Size
Z3	3 Month Lot Size
Z6	6 Month Lot Size

However, as the BOM and MRP data are confidential, dummy data will be used for this study. Company A's multi-level BOM will be simplified for MRP with a 6-month period, considering level 0 and level 1 materials from the BOM, their lead times, and quantities.

5. Results and Discussion

5.1 Numerical Results

User Satisfaction and System Effectiveness

The user satisfaction's descriptive statistics reflects a mean satisfaction score of 3.1 (Table 6). This reflects that users are mostly neutral with the current lot-sizing approach though there are rooms for improvements. Additionally, users also rated the current effectiveness of the current lot-sizing approach, receiving a mean score of 2.8 (Table 7). This reflects that although the current approach does help in forecasting, adjustments are required to make it more affective. Moreover, users do feel that the current lot-sizing simulation aligns with the overall supply chain strategy in Company A (Table 8). However, the neutral ratings reflect their lack of trust due to the lack of standardisation and accuracy.

Table 6. Descriptive Statistics on User Satisfaction

How satisfied are you with the current lot-sizing simulation process?	
Mean	3.1
Median	3
Mode	3
Standard Deviation	0.567646212

Table 7. Descriptive Statistics on Effectiveness on Current Lot-Sizing

How would you rate the effectiveness of the current lot-sizing simulation process?	
Mean	2.8
Median	3
Mode	3
Standard Deviation	0.918936583

Table 8. Descriptive Statistics on Supply Chain Alignment

How well do you think the current lot-sizing simulation activity aligns with the company's overall supply chain strategy?	
Mean	3.1
Median	3
Mode	3
Standard Deviation	0.737864787

This is supported by the correlation matrix where there is positive correlation between "satisfaction with lot-sizing: and "effectiveness of the current process" at 0.68 (Figure 3). This implies that when users perceive the approach as being effective, their satisfaction increases proportionally. However, the current effectiveness score suggests that there are frequent negative issues.

The information mentioned above are important as how users perceive the lot-sizing approach can affect its effectiveness and usability in their supply chain strategy. Where if users feel that it does not provide valuable or accurate data, there will be less inclination to adjust or ensure data input is correct which can lead to inaccuracies in the results (Yu et al., 2016). A well-executed integration can enhance both satisfaction and effectiveness by providing accurate, real-time data and automating routine tasks. When users experience reliable outputs, it makes them more proactive in solving any errors that they find, leading to better process adherence (Dong & Rekatsinas, 2018).

Encountered Discrepancies and Forecasting Accuracy

The discrepancies of forecasted and actual ordering patterns reflect a mean score of 2.2 (Table 9). This reflects that users often experience discrepancies between the forecasted ordering patterns provided in the lot-sizing simulation and actual ordering patterns. Inconsistency is a major source of inaccuracy in lot-sizing results due to the lack of BOM and MRP integration to provide more accurate initial inputs.

Table 9. Descriptive Statistics on Discrepancies on Current Lot-Sizing

From past lot-sizing simulation activities, how often do you encounter discrepancies between the forecasted and actual ordering patterns?	
Mean	2.2
Median	2
Mode	3
Standard Deviation	0.788810638

This further highlights the user dissatisfaction where the correlation matrix reflects an inverse relationship correlation of -0.20 between satisfaction and encountered discrepancies (Figure 3). Furthermore, the negative correlation between encountered discrepancies and effectiveness of -0.52 further echoes that discrepancies affects the approach's effectiveness. An integrated approach can help this with the use of more advanced forecasting tools in the ERP system to reduce discrepancies, provide more precise forecasts and data synchronization in the form of BOM and MRP as they are handled by different departments. This can help to minimize gaps between forecasted and actual results, leading to more accurate outcomes.

A robust integration can help to address these issues through data centralization and automation, improving flexibility and reduces human errors. With the data synchronization and advanced forecasting tools integration, it would improve responsiveness to demand fluctuations and align forecasts accordingly. In return, this can improve overall accuracy which improves user satisfaction and fulfilment process.

Training and Support for Adoption and Utilization

While users are currently quite positive about the integration with a mean of 4.1 (Table 10), it is also important to ensure user-friendliness of the integration, which they have highlighted to be important with a mean of 4.7 (Table 11. Complicated processes and lack of training can affect acceptance rate over time. ome examples includes SAP where they have the SAP Learning Hub and PartnerEdge to assist with transition and other ERP companies that provides tailored support (SAP, 2021). With structured training sessions and support, employee can utilize the integrated simulation tools efficiently. With proper training and guidance, it will make users more confident in using the integration.

Table 10. Descriptive Statistics on Integration Perceptions

How do you feel about the integration of the current lot-sizing activity into the current ERP system?	
Mean	4.1
Median	4
Mode	5
Standard Deviation	0.875595036

Table 11. Descriptive Statistics on User-Friendliness

How important is user-friendliness of the integration to you?	
Mean	4.7
Median	5
Mode	5
Standard Deviation	0.483045892

Cost Evaluation

With all the possibilities that the integration can provide, it is also important to evaluate the cost that Company A might incur. The approach for the possible cost is a conservative approach, to allow Company A more room to work with for a cost-effective approach. The cost of retraining employees, At an average, is USD $1,252 per employee (Markovic & Markovic, 2020).

Additionally, if Company A continues to use their current ERP system with their provider, licensing, subscription and maintenance, except for simulation maintenance, of the ERP system cost are not included. Thus, the focus will only be based on integrating the lot-sizing simulation and ERP system.

Table 12 shows the possible cost that Company A might incur based on the features suggested in in RQ2. The cost range are based on external market research.

Table 12. Possible Cost for Integration

Integration Scenario	Range (USD)
Basic Integration	\$10,000 - \$50,000
Moderate Integration with API Support	\$50,000 to \$150,000
Advanced Integration with Predictive Analytics	\$150,000 to \$300,000
Full Customization with Modular Enhancements	\$300,000 to \$1,000,000

In summary, integrating Company A's lot-sizing simulation with an ERP system can be optimized by adopting similar features and approaches found in advanced ERP systems. With a clear cost breakdown, Company A can better design an integration strategy that enhances their fulfilment process and decision-making while managing expenses effectively.

5.2 Graphical Results

In consideration with RQ1, coupled with additional market research and survey answers, a fishbone diagram has been created to identify the causes of the inaccuracies of the lot-sizing simulation (Figure 3). In summary, it highlights the six main causes of lot-sizing inaccuracies and the antecedents of said causes.

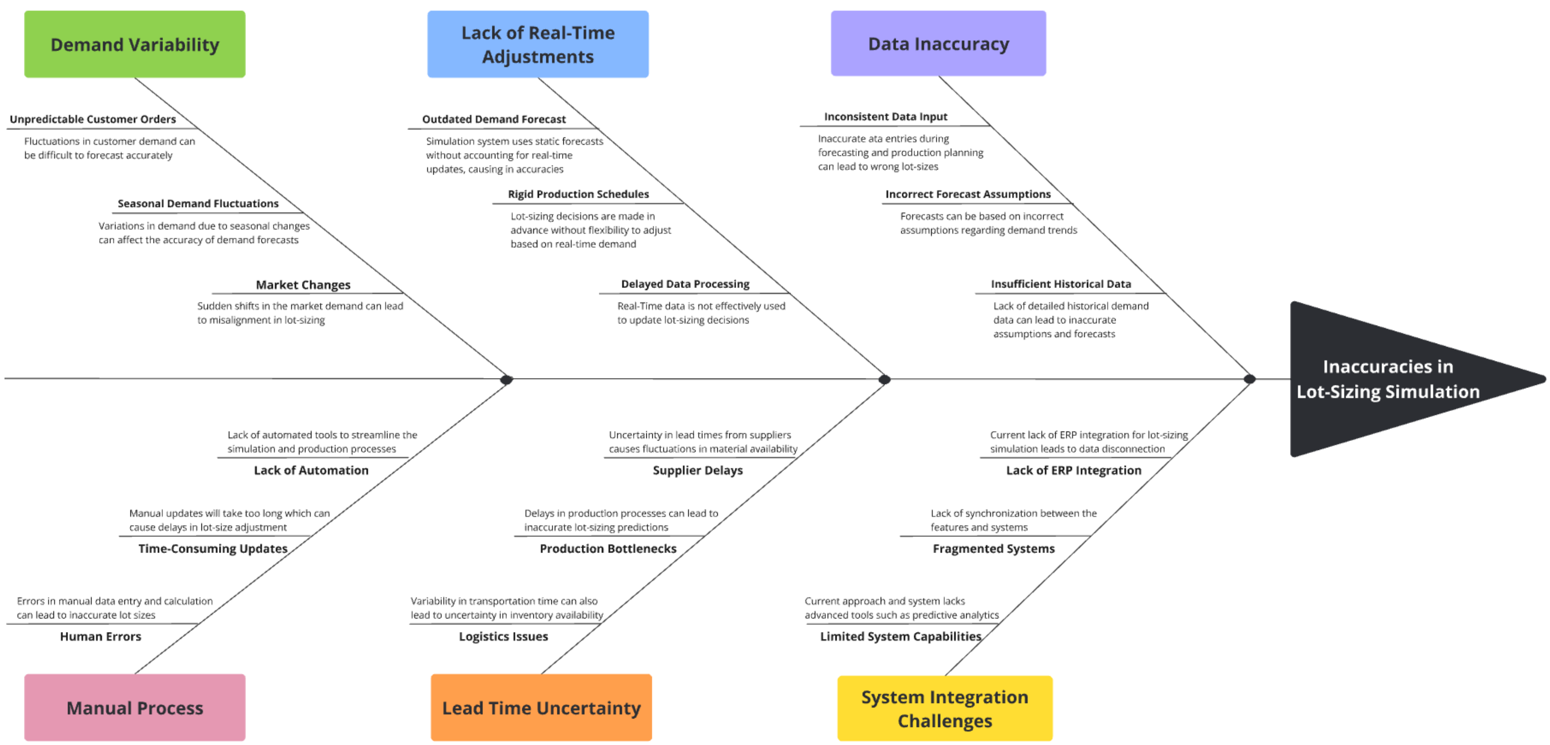

Figure 3. Fishbone Diagram

<u>Data Synchronization and Real-Time Data Needs</u>

With unsynchronized data, it creates discrepancies and infectiveness of the approach which is highlighted by the strong negative correlation of process effectiveness and data discrepancies in the correlation matrix of -0.52 (Figure 4). The lack of latest information reduces the usefulness of outcomes from the lot-sizing simulation.

As the ERP system contains the latest information and able to provide it in real-time, it reduces the time lag between data collection, update and analysis, providing a more accurate basis for simulation and decision-making. In return, it enhances overall outcome reliability.

<u>Demand Variability and Supplier Reliability</u>

The correlation matrix shows a negative correlation between encountered discrepancies and current process effectiveness with a value of -0.52 (Figure 4). This suggests that users felt that high variability in demand reduces the perceived effectiveness of the current lot-sizing approach. Such discrepancies are due to the lack of real-time data adjustments in response to the ever-fluctuating demand, leading to fulfilment process inefficiencies.

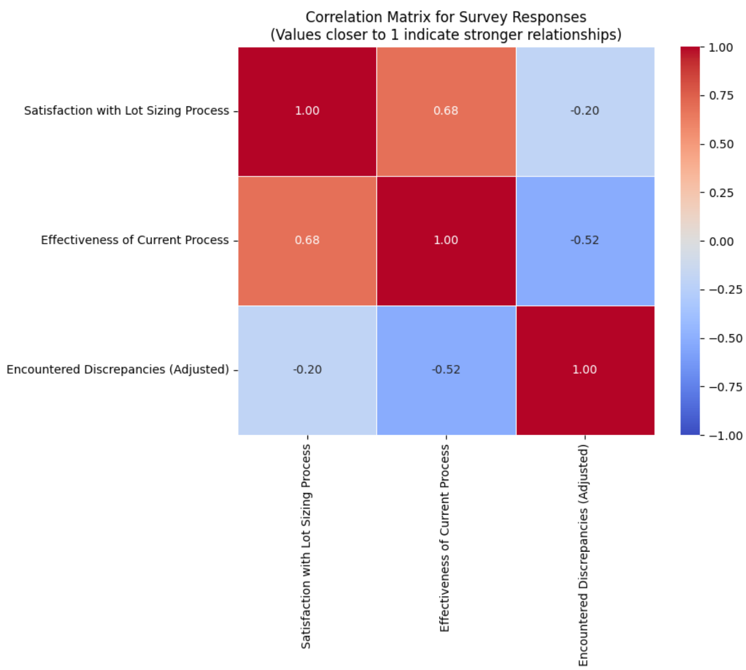

Figure 4. Correlation Matrix of Survey Responses on Current Lot-Sizing

Through integration with data analytics and demand forecasting capabilities, Company A can better manage demand variability and potentially have more ability to improve supplier coordination. Real-time insights can allow for more proactive adjustments, reducing discrepancies between forecasted and actual ordering patterns. Moreover, there is also a positive correlation between user-friendliness and positive reception towards ERP integration as seen in the correlation matrix of 0.60 (Figure 5). Emphasizing the need for an easy-to-use integrated system and simulation.

Figure 5. Correlation Matrix of Survey Responses on Integration

5.3 Proposed Improvements

Logic Flow and Data Flow Blueprint

The blueprint provides an end-to-end integration that aims to strengthen the fulfilment process of Company A through minimizing errors in lot-sizing, improving cost efficiency, and enhancing decision-making capabilities through data-driven insights within the ERP system framework.

Key focus of the blueprint:

- Data Preparation
  The process begins with the ERP system pulling data. The data undergoes verification to ensure consistency based on internal settings, including checks on BOM, before being transferred to MRP for alignment, and sales data accuracy. Any discrepancies will prompt updates from relevant departments, establishing a solid foundation for simulation inputs.

- Simulation Set-Up and Execution
  Then, the ERP system runs micro-simulations, assessing different lot-sizing parameters based on historical trends and set performance metrics. This step includes internal fine-tuning where the system will optimize to achieve the best possible results. Multiple lot-sizing configurations are tested to evaluate inventory costs and optimize demand fulfilment and meet set parameters and metrics.

- User Evaluation and Final Implementation
  Results are then reviewed by the purchasing department, who assess cost-effectiveness and alignment with current demand and parameters of all the proposed lot-sizes. If simulations meet the criteria, they move forward to implementation, with logs maintained inside the system for future reference, allowing continuous improvement and adaptability in the lot-sizing approach. If the results are not satisfactory, they can manually select the desired lot-sizing to see the potential outcome (Figure 6).

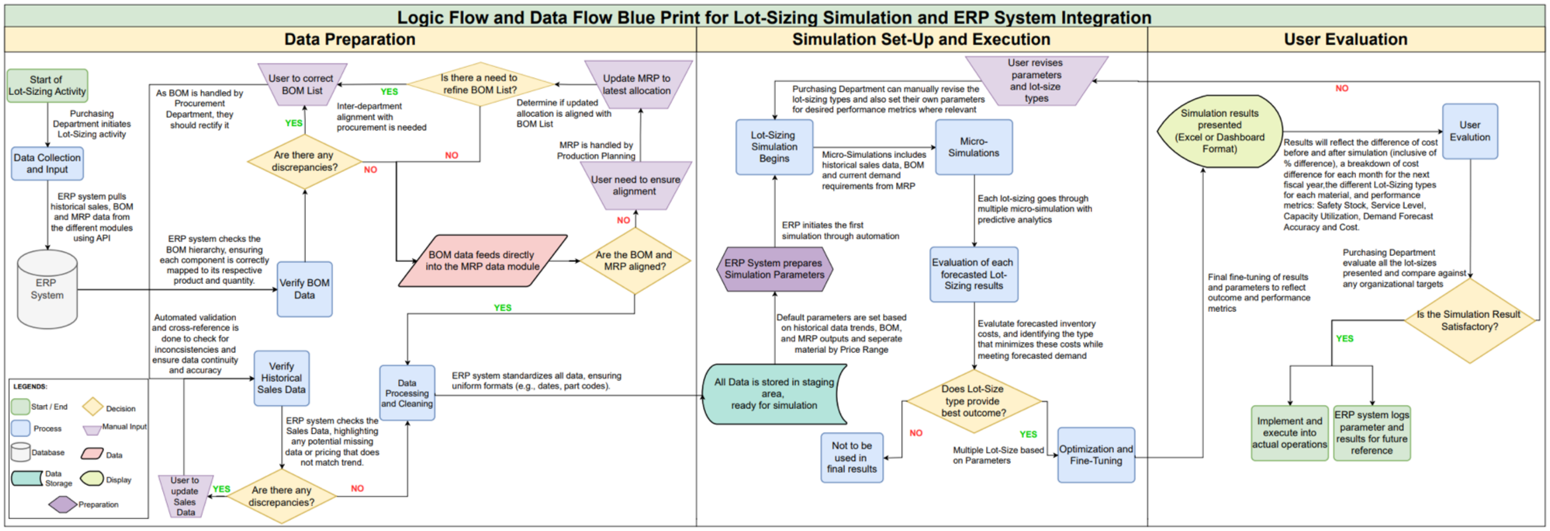

Figure 6. Blueprint of Logic Flow and Data Flow

<u>SWOT Analysis</u>
Before deep-diving into the possible features and other aspects for adoption into their ERP system, it is important for Company A to understand the Strengths, Weaknesses, Opportunities and Threats of the integration.
In a nutshell, these are the important factors for Company A's consideration:

- Strengths and Opportunities
  The integration can help to streamline dataflow, improve inventory management and enable predictive analytics (Voss et al., 2022). This can be through the use of scenario planning to enhance production planning. Decision-making benefits from real-time data, allowing Company A to respond dynamically to demand fluctuations and production constraints.

- Weaknesses and Threats
  A significant up-front capital may be needed due to high implementation cost. The reliance of technical expertise for integrations and possible integration complexity can present substantial challenges. Over-reliance on automation can also lead to inaccuracies due to outdated parameters (Ahmoye et al., 2023). Potential downtimes and technical user resistance for adoption poses as threats in integration success.

<u>Feature and Integrations Analysis</u>
This section aims to show the key features that Company A can adopt into their ERP system to enable integration, feature enhancement and user acceptability.

- API Capabilities for Real-Time Integration
  It will be useful if Company A's current ERP system has API capabilities such as SAP S/4 HANA, Oracle and Epicor. APIs allows for real-time data flow and integration allowing real-time data sharing between the different ERP modules (Homs, 2022). This helps inventory and production plans to adjust accordingly to demand changes. This also can allow the ERP system to be a centralized data source, streamlining information flow, which reduces inconsistent data input and reduces data inaccuracy (Wang, 2024).

- Enhancement with Predictive Analytics
  Company A can also consider enhancing their ERP System with advanced analytical tools such as predictive analytics which can support the lot-sizing activity. Similar to Azure Machine Learning in Microsoft Dynamics 365 and Infor Cloudsite using IBM Cognos as a third party analytics tool, Company A can create their own or integrate from an existing software (Infor, n.d.). With predictive analytics, Company A can use better forecasting

models to predict demand variability and help optimize lot-sizing strategies to improve inventory and efficiency (Biçer, 2022).

- Customizability and Modular Enhancement to Reduce Complexity
  Should Company A's ERP system supports modular addition, the lot-sizing simulation can be made as a custom module. Similar to Oracle's Advanced Supply Chain Planning (ASCP) which is modular and supports customization to include simulations, which allows tailored solutions to the company's operational requirements (Oracle, n.d.). Though it introduces additional cost, it allows the ERP to accommodate for more nuanced simulations that accounts for more variables, allowing for more accurate forecasts.

- Incremental Add-Ons for a more Cost-Effective Integration
  Adding on to APIs and modular additions, Company A can also adopt a phased approach. This helps to reduce and split upfront cost and ease the users into the change. This allows for constant reviews of new additions like add-ons and minor customizations can be made at different times instead of a complete overhaul. Acumatica adopts a similar approach with phased add-ones while NetSuite and Infor supports third party add-ons (Carignan, 2024; 2024a). Through phased add-ons, this helps to reduce redundant functions within the integration allowing for cost optimization.

- Data Accuracy and Security
  With any ERP integration or digital systems, data accuracy and security remain paramount. Such updates can create new exploits within the system that cause confidential data to be leaked. Oracle, SAP and IFS have robust security frameworks and validation features and, do regular audits to ensure data integrity and system safety. Company A should then adopt such implementations by having data validation procedures and a robust cybersecurity measure to protect themselves. Although this means increases cost, it is lesser as compared to data breaches and inaccurate data leading to loss of potential profits (Choi et al., 2017).

5.4 Validation

Lot-Sizing Simulation using Monte Carlo and Non-Linear Programming

To validate the proposed improvements, a preliminary version of the lot-sizing simulation has been created for evaluation. It will provide a simplified outcome for the new lot-sizing simulation, using Microsoft Excel, integrated with Monte Carlo and Non-Linear Programming. While it lacks certain aspects such as predictive analysis and data validation, it sets a precedence on how the integrated simulation will work with the dummy BOM and MRP included.

The following section highlights the application and purpose of the Monte Carlo simulation in the lot-sizing process. By generating multiple scenarios and making it real-time, it allows the simulation to evaluate various potential outcomes, reflecting the unpredictable nature of real-life supply chain environments. The randomization process involved generating random variables to model uncertainties such as demand fluctuations and lead time variations. Each simulation run will produce a unique scenario by randomly varying these input factors, enabling the lot-sizing simulation to capture a wide range of possible outcomes. This stochastic approach provided a more realistic and robust assessment of inventory management strategies, supporting more informed decision-making under dynamic operating conditions.

Demand Forecasting

The simulation uses probabilistic formulas to generate demand for deposition equipment. It employs random values combined with a normal distribution (NORM.INV) to simulate varying demand based on expected values and deviations.

For each period (month) t,

$$\boldsymbol{Demand_{t,i} = Round(Rand() \cdot C + ABS(NORM.INV(RAND(), \mu_i, \sigma_i)))}$$

Inventory Calculation

For each item, the simulation calculates simulated demand for each period using a probabilistic model. For the required inventory of each month, formulas determine how much inventory is needed after accounting for on-hand inventory and demand forecast.

For item i in month t,

$$\boldsymbol{Required\ Inventory_{t,i} = max(0, Demand_{t,i} -\ On - Hand\ Inventory_{t,i})}$$

For subsequent months,

$$\boldsymbol{Required\ Inventory_{t+1,i} = max(0, Demand_{t,i} -\ On - Hand\ Inventory_{t+1,i})}$$

Lead Time and BOM Quantities

Each component has a specific lead time based on the MRP and BOM quantity, which impacts the demand and replenishment schedule based on the BOM. Not all materials in the BOM will need to be purchased due to in-house assembly, only a selected number of materials will be simulated to be bought.

For item i,

$$\boldsymbol{Lead\ Time\ Demand_{t,i} \sum_{t=1}^{Lead\ Time_i} Demand_{t,i}\ \cdot\ BOM\ Quantity_i\ )}$$

Demand Fulfillment and Backlog

Required inventory for each month is calculated adjusting the requirements based on each period's cumulative demand and previous month's inventory in a six month timeframe. The logic incorporates backlogs when demand exceeds the available inventory, creating a cascading effect on future months' requirements.

Let $Backlog_{t,i}$ be the backlog for item i in end of month i,

$$\boldsymbol{Backlog_{t,i} = max(0, Demand_{t,i} -\ On - Hand\ Inventory_{t,i}\ -\ Incoming\ Inventory_{t,i}\ )}$$

$$\boldsymbol{Required\ Inventory_{t+1,i} = Backlog_{t,i} + Demand_{t,i}}$$

Standard Deviation (Variability)

For each component, standard deviation calculations track variability across periods, providing insights into demand stability or fluctuations. This is useful for assessing risk and adjusting safety stock levels.

For each material i over a period of T months,

$$\boldsymbol{\sigma_i = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(Demand_{t,i} - \mu_i)^2}}$$

Below are the main formulas used for the Non-Linear Programming Model where each metric will independently determine optimal lot sizes for user selection. These parameters collectively capture essential aspects of inventory control, operational efficiency, and service effectiveness, providing a comprehensive framework to evaluate and select lot sizes that balance cost, resource utilization, and demand fulfillment.

Safety Stock calculation:

$$\boldsymbol{SS_{ij} = Z \cdot \sigma_{demand,i} \cdot LT_i}$$

Where $\sigma_{demand,i}$ is recalculated for each adjusted forecast demand based in the lot-size type. Users can then chose the lot sizes j for each material i where SS_{ij} is minimized.

Cost calculation:

$$\boldsymbol{Total\ Cost_{ij} = Cost_{ij} \cdot Forecast\ Demad_{ij}}$$

Users can choose the lot sizes j for each material i where $Cost_{ij}$ is lowest.

Capacity Utilization calculation:

$$\boldsymbol{Capacity\ Utilization_{ij} = \frac{|Average\ Forecast\ Capacity_{ij} - Average\ Max\ Capacity_i|}{Average\ Max\ Capacity_i} \cdot 100}$$

Users can choose the lot sizes j for each material i where $Capacity\ Utilization_{ij}$ is minimized, where bigger negative results are better.

Demand Forecast Accuracy Calculation:

$$\boldsymbol{Demand\ Forecast\ Accuracy_{ij} = \frac{|Forecast\ Demand_{ij} - Actual\ Demand_i|}{Actual\ Demand_i} \cdot 100}$$

Users can choose the lot sizes j for each material i where $Demand\ Forecast\ Accuracy_{ij}$ is minimized, where values closer to 0 is better

Service Level calculation:

$$\boldsymbol{Service\ Level_{ij}} = \frac{\boldsymbol{Forecast\ Demand_{ij}}}{\boldsymbol{Total\ Demand_{i}}} \cdot \mathbf{100}$$

Users can choose the lot sizes j for each material i where $Service\ Level_{ij}$ is maximized.

Simulation Performance Evaluation

With the Monte Carlo and Lot-Sizing simulation in place, we can execute the simulation to get a sense of how the integration will work. 10 simulations was ran to see the outcome of the performance metrics and what are the lot-sizes that will be suggested. It is important to highlight as not all historical data from Company A is provided, the comparison will be on baselines created within the simulation that will randomize every time a simulation is ran to reflect variability and imitate the demand volatility that Company A experience, to allow for performance comparisons. To see the in-depth breakdown of each simulation. Below, we review the results of the 10 simulations by taking the average percentages differences of each metrics outcomes for each material(Table 13).

Table 13. Average Simulation Results

		Safety Stock	Cost	Capacity Usage	Demand Forecast	Service Level	
Material Number	Material	Average % Difference from 10 Lot-Size Simulations	Average % Difference from 10 Lot-Size Simulations	Average % Difference from 10 Lot-Size Simulations	Average % Difference from 10 Lot-Size Simulations	Average % Difference from 10 Lot-Size Simulations	Most Common Lot-Size(s) from 10 simulations
Mat 09	Screws	1%	4%	-2%	-4%	97%	TB, MB, Z3
Mat 10	Mounting Brackets	19%	31%	-6%	-24%	75%	TB, Z3
Mat 12	Cables	7%	15%	-4%	-13%	88%	TB, ZM
Mat 13	Fan	47%	73%	-11%	-56%	40%	TB, ZM
Mat 15	Sensors (Control System)	16%	30%	-5%	-25%	78%	TB, ZM
Mat 16	UI Panel	59%	75%	-10%	-56%	40%	ZW
Mat 18	Sealing Components	13%	25%	-5%	-22%	79%	TB, ZM
Mat 19	Internal Fittings	11%	27%	-6%	-23%	78%	TB
Mat 21	Valves	15%	25%	-5%	-23%	78%	TB, ZM
Mat 22	Regulators	17%	34%	-4%	-29%	73%	TB
Mat 24	Coolant Lines	15%	32%	-5%	-30%	71%	TB, Z3
Mat 25	Heat Exchange	56%	80%	-7%	-54%	39%	TB
Mat 27	Vacuum Cables	18%	39%	-5%	-33%	70%	TB, Z3
Mat 28	Sensors (Vacumm System)	31%	58%	-7%	-47%	52%	TB
Mat 30	Support Beams	12%	39%	-5%	-33%	67%	TB, ZW, MB, Z6
Mat 33	Capacitors	10%	26%	-4%	-21%	77%	TB, Z3
Mat 36	Connection Wires	14%	33%	-5%	-24%	72%	TB, Z3
Mat 40	Connectors	10%	15%	-3%	-13%	87%	TB
Mat 44	Pump Housing	45%	75%	-7%	-58%	41%	TB, Z3
Mat 45	Sheets	2%	6%	-7%	-6%	95%	TB, Z3
Mat 46	Surface Coating Films	2%	6%	-9%	-5%	95%	TB, WB, ZM, Z3
Mat 47	Windings	26%	54%	-6%	-45%	55%	TB, Z3
Mat 48	Transformer Parts	58%	74%	-6%	-49%	42%	TB
Mat 49	Diodes	12%	26%	-5%	-23%	78%	Z6
Mat 50	Heat Sink	54%	76%	-7%	-58%	39%	TB, MB
Mat 51	Processing Chip	64%	78%	-8%	-67%	32%	TB
Mat 52	Memory Chip	59%	76%	-8%	-59%	36%	Z3
Mat 53	PCB	54%	79%	-7%	-64%	34%	ZW
Mat 54	Metal Plates	20%	33%	-5%	-31%	70%	Z3
Mat 55	Protactive Coat	48%	82%	-8%	-66%	32%	TB
Mat 56	Insulation Layer (Desposition Chamber)	51%	78%	-7%	-64%	35%	TB, WB, Z3
Mat 57	Insulation Layer (Gas Delivery System)	5%	16%	-3%	-13%	86%	TB, Z3
Mat 58	Protative Coating	9%	16%	-3%	-14%	87%	TB
Mat 59	Motor	58%	80%	-6%	-59%	38%	TB, WB
Mat 60	Housing	60%	79%	-8%	-61%	36%	TB, Z3
Mat 61	Coils	53%	79%	-8%	-60%	38%	TB
Mat 62	Fins	58%	83%	-9%	-65%	33%	TB, WB
Mat 63	Rotor	58%	78%	-7%	-62%	37%	TB
Mat 64	Windings	60%	80%	-8%	-62%	35%	WB

Through these simulations, we can see the performance metrics of each material and what are the most common lot-sizes that appeared for in each metrics for each material. This allows better clarity on how the lot-sizes will perform. For deep-diving, the purchasing team can then look further to understand the numbers and calculations before they deem the simulation to be acceptable. For comparison, while the current lot-sizing simulation only reflects cost-savings, this simulation enables user to see improvements through a supply chain lens, enabling better decision-making

6. Conclusion

This study successfully demonstrated that optimizing lot-sizing strategies and integrating them with Company A's ERP system can substantially improve the fulfillment process. All research objectives were met, answering key research questions as follows:

1. **What are the factors contributing to inaccuracies in the current lot-sizing simulation?** The study identified three key themes: lack of cross-functional data integration, reliance on manual extraction, and limited real-time visibility, which all contributed to inaccuracies in the current imulation outcomes.

2. **How can ERP systems be leveraged to optimize lot-sizing strategies?** The research proposed a hybrid strategy that integrates predictive analytics within the ERP system. This approach involves automating data extraction, verifying data accuracy, and running micro-simulations to identify optimal lot-sizing configurations.

3. **What are the impacts of optimized lot-sizing strategies on key performance metrics?** Through extensive simulation analysis, this study highlighted improvements in service levels and demand variability coverage, showing a clear positive impact on operational efficiency and demand fulfillment.

The unique contribution of this research lies in its hybrid strategy recommendation and data-driven approach, which provide a scalable solution for inventory management challenges. These findings emphasize the importance of moving away from the current simulation method toward a more agile and data-driven approach. Despite some limitations, such as potential system compatibility issues and the need for user training, the research underscores the strategic advantage of a well-integrated ERP-based solution. Coupled with system enhancements and user feedback, this approach equips Company A with a more agile, precise, and cost-effective fulfillment process, capable of handling dynamic market demands while supporting the company's long-term organizational goals. Future research could explore further system integration possibilities and the use of machine learning algorithms to enhance prediction accuracy and decision-making capabilities.

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Biographies

Muhammad Syahiran Bin Sulong Khairudin is a full-time student with Supply Chain and Logistics programme under the School of Business at Social Sciences. He has a strong passion for optimizing supply chain operations, leveraging analytics, and integrating AI-driven solutions into enterprise systems. His interest in lot-sizing simulations stems from his experience in procurement and purchasing, where he saw the challenges of balancing efficiency and cost-effectiveness in large-scale supply chain operations. He has gained extensive experience through various industry roles, including his internship at ASM, where he led cost-saving initiatives, developed lot-sizing simulations, and improved workflow efficiencies, earning the ASM Rapid Award. Recently, he ended his stint as a Procurement Intern at Unilever, focusing on digitalization and procurement strategy optimization. Beyond his professional experience, Syahiran has demonstrated leadership in the supply chain field. As the External Liaison Director of the SUSS Supply Chain Interest Group (SCIG), he led industry collaborations, organized seminars, and connected students with key supply chain partners. His achievements include securing 1st Runner-Up positions in both the MaritimeONE Digital Challenge 2023 (PIL Case Study) and the Infineon Supply Chain Case Challenge 2024, reflecting his analytical and problem-solving abilities in real-world supply chain challenges. With a strong foundation in analytics, business optimization, and supply chain management, Syahiran continues to seek opportunities to drive innovation and efficiency in the supply chain industry.

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Tan Yan Weng is an Associate Professor in the School of Business at the Singapore University of Social Sciences (SUSS) where he heads the Logistics and Supply Chain Management programme. He works with the Singapore Logistics Association (SLA), SkillsFuture Singapore (SSG), Singapore Economic Development Board (EDB) and private-sector organisations to curate and develop training programmes for fresh school leavers and working adults. He works with SLA to co-organise the annual Supply Chain Challenge, Singapore's largest case competition for pre-university students. He serves as International Scientific Committee Member of the International Conference on Logistics and Transport as well as Chairman of SLA's Training Advisory Committee. He has published widely on transport and logistics matters, served on several conference and industry committees, and provided consultancy services for public and private sector organisations in Singapore. His current research interests include employment and skills as well as workplace safety and health in the logistics sector. Prior to joining SUSS, he taught transport planning and traffic engineering at Nanyang Technological University for 20 years and worked as a civil/transport engineer in a private consulting firm for five years. He obtained his MEngSc (transport) and BE (Civil engineering) degrees from Monash University. He was awarded Supply Chain Educator of the Year 2015 by Supply Chain Asia.