Distribution and Replenishment Optimization between
Locations of High and Low Real Estate cost

by

Denton He

B.E.(Hons), B.S., University of Melbourne, 2008

Submitted to the MIT Department of Mechanical Engineering and MIT Sloan
School of Management

in partial fulfillment of the requirements for the degrees of

Master of Science in Mechanical Engineering

and

Master of Business Administration

in conjunction with the Leaders for Global Operations Program

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Author .................................................................
MIT Department of Mechanical Engineering and MIT Sloan School of Management
May 8, 2020

Certified by ............................................................
Hermano Igo Krebs, Thesis Supervisor
Principal Research Scientist and Lecturer, MIT Department of Mechanical
Engineering

Certified by ............................................................
Jónas Oddur Jónasson, Thesis Supervisor
Assistant Professor, MIT Sloan School of Management

Accepted by ............................................................
Nicolas Hadjiconstantinou, Chair, Mechanical Engineering Committee on Graduate
Students
Professor, MIT Department of Mechanical Engineering

Accepted by ............................................................
Maura Herson, Assistant Dean, MBA Program
MIT Sloan School of Management
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Abstract

As companies expand and innovate, it is sometimes prudent to be conservative when incorporating new products and technologies. Instead of constructing buildings to store new products, firms may look to optimize re-allocation of space within existing facilities to fit more products and save on one-time capital outlay.

In this research, the Distribution Center (which also picks and packs products according to incoming orders) is looking to optimize utilization of offsite storage (and transportation) costs in the face of growing product demand. The DC is situated in a region of High Real Estate cost, and there is potential to increase utilization of offsite leased storage at Low Real Estate cost areas. To investigate potential changes, research will be divided into two parts:

Part One looks to optimize product storage within the current Distribution Center and Offsite Warehouse network, by developing a model that incorporates product demand, product sizes and replenishment frequency.

Part Two utilizes the built model to investigate alternative offsite solutions, taking into consideration Real Estate costs, transportation frequency and other factors.

Previous research papers have looked at the two parts separately, whilst this research aims to link the two parts together.

Finally, a simple and easy to use decision-support tool was developed that allows users to periodically review and adjust product allocation based on product information, demand and Real Estate costs.

Thesis Supervisor: Hermano Igo Krebs
Title: Principal Research Scientist and Lecturer, MIT Department of Mechanical Engineering

Thesis Supervisor: Jónas Oddur Jónasson
Title: Assistant Professor, Operations Management, MIT Sloan School of Management
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Further, I would like to thank my fellow students within the LGO and Sloan programs for providing the support network that I constantly relied upon. Specifically, my LGO Summer team (Aaron Baskerville-Bridges, Dante Montgomery, Devin Zhang, Hannah Phillips and Lea Daigle) and my Sloan Core team (Chloe Orphanides, Felipe Angel, Genevieve Dukes, Gerardo Guadiana, Lara Mitra and Trey Wilder). I know I can always reach out to you all when I need help in all aspects of life, and I could not have wished for better teammates and friends.

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1. Introduction

This study aims to develop a decision support tool that optimizes product storage between a Centralized Distribution Center (Central) and an Offsite Storage Location (Offsite). This chapter outlines the motivation behind the project, the problems it aims to solve as well as its scope and limitations. The chapter ends with an outline of the entire thesis.

1.1. Project Motivation

As of December 2019, the Distribution Center (DC) at Boston Scientific Arden Hills facility receives, manages and distributes more than 3,000 pieces of individual product per day. The product mix consists of more than 1,000 distinct Stock Keeping Units (SKUs) with an onsite monthly inventory value upward of $30m. By the end of 2020, in the space of 12 months, both the product mix and volume are projected to double\(^1\). In the face of such growth, the DC team needs to prepare its people and processes to be able to handle such growth without impacting Customer Service Level. In a broader context, due to the location of Boston Scientific Arden Hills in Minnesota, it has Real Estate cost advantages compared to other areas such as Boston or San Jose. The model and decision tool described in this study aims to incorporate the main supply features as well as Real Estate factors to support the team to make effective short and long-term Supply decisions. Specifically, the model will focus on:

- **Space Utilization**: to accommodate products ranging in volume from six parts per standard pallet\(^2\) to more than 30,000 parts per standard pallet. Some products are also stored in smaller quantities (totes) and may be placed in different ‘zones’ depending on their utilization. The quantity of products, the type of storage and the hardware used will all affect total space utilized.

- **Replenishment**: to take into consideration the location of the DC and Offsite facilities, the distance between them, as well as the mode and frequency of transportation.

- **Total Supply Cost**: in addition to cost of space and replenishment, other costs (such as handling) will have an impact on the Total Supply Cost (and therefore indirectly the product price). Whilst handling

---

\(^1\) BSC Internal statistics and projections

\(^2\) Standard Pallet Size: 48in x 40in x 48in (LxWxH)
costs may be cheaper in an Offsite Warehouse managed by a third party, replenishment costs will be lower in a self-managed Offsite Warehouse. The relationship between these costs are further explored in this paper.

1.2. Problem Statement

The goal of this study is to develop a model that simulates and optimizes the relationship between product, space utilization, replenishment and supply cost. The Decision Support Tool will consist of a Graphical User Interface (GUI) that will allow users to interact with the model to simulate and predict future states and support strategic decisions in choosing future facilities.

In development of the model, this thesis will answer the following questions:

- Given future product portfolio and forecast demand, how much space will be required both at the Central (DC) and Offsite locations?
- In preparation to support this future state, how many times per month is replenishment required (from Offsite to Central)?
- What is the projected spend for Offsite storage and transportation?
- Is it justifiable (either operationally or financially) to change the current management model of the Offsite Warehouse (from being managed by Third Party to self-managed by Boston Scientific)? If not, then given current forecasts, when should the team start to look at alternative offsite options?

1.3. Scope and Limitations

As outlined in previous sections, the scope of this thesis is focused on developing a model that best represents a future state of the supply linking the Centralized DC and its Offsite Storage location. It is within the scope of this model to consider all potential products that may be stored at or distributed from the Arden Hills DC. This includes product information such as size and demand. The model should also be capable of supporting all potential Real Estate alternatives that may be considered as potential Offsite Storage locations.
The model also has the following limitations (which will be further discussed in Chapter 6):

- **Product information**: the model relies on the availability and accuracy of product dimensions and demand which are acquired from various sources. Where both are not available or cannot be estimated for a given SKU, the model cannot include that SKU in the optimization.

- **Transportation Mode**: the replenishment assumes products are transferred from the Offsite location to the Central DC location by a vehicle of set capacity and costed according to distance travelled. If the key factors are not as distinctly provided, then they need to be estimated (by the user) before inputting into the model.

- **Two distinct locations**: the model as introduced in Chapter 4 is specific to Boston Scientific Arden Hills and considers two distinct facilities (Central/DC and Offsite) with their own handling and storage rates. Whilst the model presented in Chapter 4 can be applied to multiple Central and Warehouse locations, Chapter 5 outlines the implementation on a single Central DC and Offsite Warehouse pair.

- **Technology considerations**: factors such as automation of rack hardware and handling can only be incorporated manually into the model (by adjusting the storage and handling rates accordingly). They are not on their own adjustable variables in the current version of the model.

1.4. Thesis Overview

The following thesis is comprised of seven chapters:

Chapter 2 provides further background of the Medical Devices industry and specifically the history and current state of Boston Scientific. This chapter also maps out both the current and ideal future states of the DC in relation to its key processes. The chapter then ends by providing a brief overview of the Real Estate market in Minnesota and outlines key differences between areas of High Real Estate cost and Low Real Estate cost.
Chapter 3 reviews existing research conducted in areas relevant to the model. Specifically, subject areas such as Supply Chain and Warehouse optimization, Storage Allocation and Replenishment. Within each section will be a summary of elements that were incorporated into the model outlined in this thesis, as well as gaps that the proposed model aims to fulfill.

Chapter 4 introduces the model, including its development from key elements such as storage, handling and transportation. Once a generalized version of the model is conceptualized, it is then customized to meet the requirements and information available from the Boston Scientific Arden Hills DC team.

Chapter 5 shows the transformation of the model into a Decision Support Tool, whereby the model is implemented in R, with a Graphical User Interface built using the ‘Shiny’ library. The key inputs, variables and outputs are reviewed and linked to those from the model.

Chapter 6 presents key results and findings from using the Decision Model to simulate current state as well as its potential to predict future states. This chapter also applies the model and Decision Support Tool to an actual Case Study and shares the business and financial implications of its analysis. This chapter also discusses further the key limitations of the model.

Chapter 7 concludes this thesis by summarizing the key findings and suggests potential areas of future development.
2. Background

Chapter 2 introduces the Medical Devices industry, and one of its key players in Boston Scientific (also known as Boston Scientific Corporation, or BSC). A brief history of BSC is presented, followed by its current and future product portfolios. The role of the Materials Management team within Boston Scientific Arden Hills is introduced as well as one of its key groups, the Distribution Center (DC). The current and potential future states of the Arden Hills DC is then discussed. Finally, an overview of the Real Estate sector within Minnesota and other regions are compared in relation to Offsite Warehouse opportunities.

2.1. Healthcare and Medical Devices

Healthcare spending in the United States almost topped 18% of GDP in 2019. In a country where healthcare spending is already highest as a percentage of GDP (Figure 2.1.1) and is projected to only increase in the foreseeable future (Figure 2.1.2). Within Healthcare spending, Medical Devices is estimated to ‘account for roughly 4 to 6 percent of total spend’.

![Figure 2.1.1 Projected US Healthcare spend as percentage of GDP](https://www.fda.gov/about-fda/fda-organization-charts/fda-overview-organization-chart)

---

3 As highlighted by the FDA in their Organization Chart (https://www.fda.gov/about-fda/fda-organization-charts/fda-overview-organization-chart)
5 Patton (2019)
As defined by the US Food & Drug Administration (FDA), a medical device is ‘an instrument, apparatus... machine, intended for use in the diagnosis of disease or other conditions, or in the cure, mitigation, treatment, or prevent of disease, in man or other animals... which does not achieve its primary intended purposes through chemical action within or on the body of man or other animals’.

### Figure 2.1.2 Healthcare Spending as Percentage of GDP

Within Medical Devices, key sectors include Drug Delivery Devices, Urology and Renal, Cardiovascular and Devices and Endoscopy. Boston Scientific’s major product portfolio within each of these key sectors is outlined in Table 2.2.1. As classified by the FDA, most of the devices/products in BSC’s portfolio fall under Class III Devices, meaning that they are ‘the riskiest devices used to support or sustain life... and any malfunction can cause or create risk of illness or injury’. As such the quality and subsequently the cost of these products, including their manufacturing and supply, play a key part in their final pricing.

The research in this study aims to consider key factors in the storage and distribution of these products with the aim of supporting the company’s goal to reduce costs whilst maintaining quality to customers.

---

6 As outlined by the FDA (https://www.fda.gov/industry/regulated-products/medical-device-overview)
7 Wang (2013)
8 Laxmi (2018) – Page 48
9 Laxmi (2018) – Page 19
2.2. Boston Scientific

Boston Scientific was founded in 1979 in Watertown, MA, as a holding company for medical products. The company went public through an IPO in May 1992 and in 2003, its first major product the Taxus Stent (a drug-releasing stent that is surgically implanted within a human artery to prevent clogging) was released\(^\text{10}\). Since then, BSC have conducted several acquisitions, and as of 2018, employs approximately 32,000 people worldwide\(^\text{11}\).

Boston Scientific’s current major product segments are outlined in Table 2.2.1\(^\text{12}\):

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cardiovascular</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interventional Cardiology</td>
<td>2.6</td>
<td>+7</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Peripheral Interventions</td>
<td>1.2</td>
<td>+9</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td><strong>Rhythm &amp; Neuro</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardiac Rhythm Management</td>
<td>2.0</td>
<td>+2</td>
<td>9.6</td>
<td>2</td>
</tr>
<tr>
<td>Neurmodulation</td>
<td>0.8</td>
<td>+22</td>
<td>3.5</td>
<td>1 (in US)</td>
</tr>
<tr>
<td>Electrophysiology (EP)</td>
<td>0.3</td>
<td>+11</td>
<td>4.9</td>
<td>4</td>
</tr>
<tr>
<td><strong>Medical Surgery</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Endoscopy</td>
<td>1.8</td>
<td>+8</td>
<td>5.0</td>
<td>1</td>
</tr>
<tr>
<td>Urology and Pelvic Health</td>
<td>1.2</td>
<td>+11</td>
<td>3.3</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.2.1 Boston Scientific main product categories, revenue and growth

In the 3 years prior to 2018, BSC made 5 major acquisitions including American Medical Systems, Cosman, Distal Access, Symetis and Apama Medical Incl. In the 3 years since 2018, the company has made, and plans to make 10 additional major acquisitions\(^\text{13}\), including EMcision, nVision Medical, NxThera, Securus Medical, Cryterion, Veniti, Augmenix, Claret Medical, Millipede and Vertiflex. This expansion in product portfolio adds complexity to the supply chain, and combined with the increase in

\(^\text{10}\) Boston Scientific website, “Our History”
\(^\text{13}\) Crunchbase (2020)
sales volume, are key reasons why the ability to simulate and Distribution (and react accordingly) is so important.

2.3. Arden Hills Distribution

The Materials Management team (which falls within BSC Operations) is responsible for ‘sourcing, planning operations, and delivering quality materials and services, on time for customers’\(^{14}\). Specifically, the Arden Hills Distribution Center, which is part of the Arden Hills Materials Management team is responsible for receiving all Finished Goods (FG) from suppliers (including other BSC Manufacturing Sites), storing them appropriately, and then distributing them to customers according to incoming orders. Arden Hill’s customers of FG include other BSC plants in Clonmel (Ireland) and Dorado (Costa Rica) as well as all individual customers (such as patients, hospitals) within the United States. The Arden Hills Distribution Center is also the sole distributor for Cardiac Rhythm Management (CRM) and Neuromodulation (NeuroMod) products for BSC within the United States, shipping approximately 60,000 pieces (valued at approximately USD 20m) monthly.

Figure 2.3.1 highlights the current process whereby the Arden Hills DC receives, packs and sends out Finished Goods to customers. Due to space constraints within BSC’s facility, space at an Offsite Warehouse has been leased (from a third-party vendor) to store inventory. Currently, all products to customers must be shipped from the Centralized Distribution Center.

In this process, the Offsite Warehouse is managed by a third-party company who is only responsible for transporting and storing product from the Centralized DC. When product from offsite is required to replenish onsite inventory, the third-party provider transports entire pallets of product back to the DC, where BSC-staff extracts the exact quantity required off the pallets, before the pallet with remaining product is sent back to the offsite warehouse. As such, there is significant ‘wasted’ double handling of the same product being transported between the DC and Offsite Warehouse.

---

\(^{14}\) Boston Scientific Internal Website (Materials Management Team mission)
Figure 2.3.1 Arden Hills DC, Current process

New Order

If there is free space allocated to given product on shelf

Receive Incoming Finished Goods

Stock in Onsite DC

Pick Part(s) according to incoming Order

Place all Part(s) into Parcel

Place Parcel in area ready for delivery to customer

Customer

By 3PL (Third Party Logistics company)

Finished Goods come to Onsite DC

If there is no more free space, product is kept on pallet

Transport to Offsite Warehouse

Stock in Offsite Warehouse

Offsite Warehouse

If product stock is running ‘low’ in DC, pallet(s) of that product will be ‘called’ from Offsite Warehouse back to DC
Figure 2.3.2 presents a potential future state process, where the Offsite Warehouse is owned by a Third Party but operated by BSC-staff. Firstly, all incoming products are directed to the offsite facility for receiving and storage, thereby saving valuable space in the DC and docking area. Then, when replenishment to the DC is required, BSC staff in the offsite warehouse will pick the exact quantity required, removing the need to return pallets which would then need to be re-stocked on the shelves of the Offsite Warehouse (as shown by Figure 2.3.3). This process is an ideal future state that the DC team would like to move towards, as it will significantly reduce double handling of material. The model outlined in Chapter 4 will ultimately follow the process outlined by the future process.
Figure 2.3.2 Arden Hills DC, Future process

Onsite DC

Customer

New Order

Receive Incoming Finished Goods

Stock in Internal DC

Pick Part(s) according to incoming Order

Place all Part(s) into Parcel

Place Parcel in area ready for delivery to customer

By 3PL

If there is free space allocated to given product in Onsite DC, the exact quantity required will be transferred

Finished Goods come to Offsite Warehouse

Remaining product, not transferred to Onsite DC

Offsite Warehouse

If product stock is running ‘low’ in Onsite DC, the exact quantity required will be ‘called’ from Offsite Warehouse to DC

Receive Incoming Finished Goods

Keep in Offsite Warehouse

Stock in Offsite Warehouse

Finished Goods come to Offsite Warehouse

NEW ORDER

By 3PL

Customer
Figure 2.3.3 Receiving process, Current and Future
2.4. Warehousing and Real Estate

Utilization of third party, offsite Warehouse and storage facilities can be a major component of a company’s supply strategy. Costs of utilization (including storage, handling and sometimes transportation) are generally cheaper and it also allows those companies to utilize often constrained on-site space for other ‘core’ capabilities such as R&D and manufacturing. Companies historically have also located their manufacturing and distribution centers in the mid-west due to both location as well as cost considerations. Recent research published by Colliers\textsuperscript{15}, however, show that ‘record low vacancy rates and increasing rental rates have become a national trend’. A trend that is affecting areas of High Real Estate cost (such as Boston and San Jose) as well as Low Real Estate cost regions such as Minnesota. Most recently in 2019 Q3, vacancy rates of Industrial Real Estate (including Warehouses) have declined to 6.91\% (from more than 11\% in 2015 Q1), which is in line with the rise of average quoted rates rising from 5.35\% to 9.49\%. On the other hand, absorption rate of Bulk Warehouse in Minneapolis North, close to Boston Scientific Arden Hills is almost -90k square feet, which also indicates that there are plentiful storage warehouses in that area.

Table 2.4.1\textsuperscript{16} compares the vacancy rate of the various cities, which shows that the area surrounding Minneapolis is competitive compared to Boston and San Jose.

<table>
<thead>
<tr>
<th>City</th>
<th>Vacancy Rate of Industrial Buildings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minneapolis</td>
<td>6.7</td>
</tr>
<tr>
<td>Boston\textsuperscript{17}</td>
<td>7.4 – 7.7</td>
</tr>
<tr>
<td>San Jose</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Table 2.4.1 Vacancy Rate across High and Low real estate cities

For Boston Scientific Arden Hills, within the current offsite warehouse, BSC products are stored in their own pallets, but are stored on racks where neighboring products may not be BSC products. In the idea future state outlined in Chapter 4, BSC staff the offsite warehouse which stores only BSC products. In this scenario, the offsite warehouse will need to be wholly leased by Boston Scientific, not sharing space within with non-BSC products.

\textsuperscript{15} Brick (2019)
\textsuperscript{16} Brick (2019), Sorrentino (2019), Tutko (2019)
\textsuperscript{17} Not including Boston South
In order to verify the feasibility of the future state, eligible facilities (those that can be leased in its entirety) in proximity to the Arden Hills DC were investigated. This is presented in the Case Study in Chapter 6, as well as the results and recommendations.

2.5. Summary

In summary, given the increase in capacity that the Arden Hills DC will need to manage (due to increase in acquisitions and organic sales growth), there may be a time in the future where it will be more cost efficient for the Arden Hills DC team to lease a standalone offsite warehouse facility which will be staffed by BSC personnel. Chapter 4 outlines how an optimization model can be constructed for such a scenario, before the model is used on actual data in Chapter 6 to show the results of the investigation.
3. Literature Review

Chapter 3 provides a summary of existing literature that looks at various tools and techniques that have been employed to design, model and optimize similar distribution processes. Research was conducted first by looking at a general overview of Optimization in Supply Chain, followed by in-depth reviews of Storage Location, Warehouse Space Optimization and Replenishment between Multiple Warehouses.

3.1. Optimization in Supply Chain

Recent research in the use of modelling and optimization to solve supply and manufacturing related problems have been well summarized. Cormier et al. (1992) reviewed models for optimizing warehouse capacity and storage, and more recently Gu et al. (2010) conducted a survey of research on warehouse design and performance evaluation. The use of mathematical programming models to optimize for capacity was also investigated by Martinez-Costa et al. (2014), who summarized that recent models focus on either minimizing total cost incurred or maximizing Net Present Value as their objective function. Similarly, there was a general trend where models employed either Linear Programming (LP) or Mixed Integer Linear Programming (MILP) due to simplicity. Non-Linear Programming (NLP) was only observed to be used occasionally for similar problems as it is still difficult to automate them using commonly used tools. Martinez-Costa also propose a conceptual framework (based on review of existing studies) to support the design and development of future models. Kocaoğlu et al. (2018) reviewed 77 works published between 1993 and 2016 that focused on Supply Chain Optimization, finding that only 10 reviewed works looked at operational issues such as short-term planning of products and only 2 involved Facility/Depot Location determination.

This paper aims to address the gaps in this field, whilst the model aims to find feasible solutions by minimizing total supply cost (including storage, handling and transportation). Similarly, MILP will be utilized due to ease of implementation.
3.2. Storage Location Assignment

Berg et al. (1999) presents a classification of warehouse management models and various support decision making tools. The paper reviews Storage Location Assignment Problems (SLAP) using class-based storage, randomized storage and dedicated storage. Building upon this, the model as described in Section 4 looks to consider storage groups that take into consideration the characteristics of different storage zones and handling costs. Hübner et al. (2017) explains the concept of optimizing assortment and assignment on limited shelf space, including stock ‘facings’ and stock per facing. Whilst that paper was able to incorporate such information into the final model, the approach outlined later in Chapter 4 does not take stock facing into consideration. Products at the Boston Scientific Distribution Center are stored in dedicated totes and pallets (to ensure similar products are not erroneously picked). The maximum quantity of a given product in a tote is known and fixed, therefore the quantity of product in a tote is used rather than product ‘facing’. However, the tote size (and therefore how many different product totes can be placed in a given shelf space) is an important factor in the model and will be discussed further in Chapter 5.

3.3. Warehouse Space Optimization

Models have also been introduced specifically for optimizing warehouse space design and product allocation. S.S.H et al. (2005) makes use of ‘dwell’ time to calculate Optimal Order Quantity, where the dwell time for each product is assumed to be known by the warehouse manager in advance. Whilst the model in this paper does not employ ‘dwell’ time in the same manner, the idea of ‘dwell’ time partly inspired the final model where the relationship between space allocation and replenishment frequency is taken into consideration. Another research paper Fumi et al. (2013) uses the Vertex Color Problem (VCP) to optimize location and utilization of storage space. The objective function introduced aims to minimize space (by representing different product slots with colors) utilized whilst reducing internal handling times in a dedicated storage policy warehouse. Inspiration was taken from this paper in an initial approach to visualize the network, however, ultimately VCP was not used as the emphasis of minimizing space (no. of colors) does not fit the needs of this paper, which is to minimize cost.
3.4. Replenishment between Multiple Warehouses

Two papers specifically approached the problem of replenishment between two warehouses. Hariga (2011) proposes an inventory model that considers multiple warehouses that vary between fixed and flexible leasing contracts. Key to the model’s assumption is that the Leased warehouse also has limited space, and that any additional storage required would need to be placed in a third ‘flexible’ location. Wutthisirisart et al. (2015) proposed four variations of a model that supports the allocation of material to an owned warehouse and a leased warehouse whilst minimizing storage and transportation costs. The model proposed in this paper builds upon the ‘Material Level Flexible Storage Policy’ introduced by Wutthisirisart et al. as this guarantees that product is always available in the DC – a key requirement by Boston Scientific to ensure high customer service levels are met.

3.5. Summary

In summary, there is significant existing research on supply chain optimization and replenishment, most of the research have utilized minimization of total supply chain cost using either LP or MILP. However, to our knowledge, this paper is the first work that aims to use MILP to minimize supply cost, whilst considering replenishment frequency between a Central DC and Offsite Warehouse, especially with consideration to Real Estate costs. Therefore, the research outlined in this paper is partly driven to fulfil this gap and to provide a basis for future research.
4. Distribution and Replenishment Optimization Model

Chapter 4 outlines how the distribution and replenishment process between the Arden Hills DC and offsite warehouse is modelled. An overview of the methodology to create the general model using Mixed Integer Linear Programming (MILP) is provided, followed by a detail analysis of the key components including DC costs, warehouse costs and transportation costs. Lastly, a customized optimization model specific to BSC in Arden Hills is introduced.

4.1. Overview

Based on literature reviewed in Chapter 3, the distribution, storage and replenishment processes can be modelled as a network optimization problem using MILP, where the objective function seeks to find the minimum monthly supply cost, taking into consideration costs at the Arden Hills DC (Central), the Warehouse Location as well as Transportation Costs.

The generalized objective function is a summation of the various costs, which are functions of the decision variables:

\[
\text{monthly supply cost}^{18} \text{ (to minimize)} = \sum_i \text{Central Costs}, f(x_{i,c1}, x_{i,c2}) + \sum_i \text{Warehouse Costs}, f(x_{i,c2}, x_{i,w}) + \sum_i \text{Transportation Costs}, f(x_{i,c2})
\]

Equation 4.1.1

where:

\(x_{i,c1}, x_{i,c2}, x_{i,w}\) – decision variables represent the quantity of product \(i\) to be stored in Central for DIOH and for DIIN, and quantity of product \(i\) to be stored in Warehouse location for DIIN

---

18 Each of Central, Warehouse and Transportation Costs will be further explored in Chapters 4.2, 4.3 and 4.4, respectively.
\( i \) - Set of all distinct products (SKU/UPN); \( i \in I = \{1, \ldots, I\} \)

\( c1 \) - Index of DC (central) storage location for Days Inventory on Hand (DIOH) stock

\( c2 \) – Index of DC (central) storage location for Days Inventory In Network (DIIN) stock

\( w \) – Index of Offsite (warehouse) storage location for DIIN stock

\( D_i \) – monthly demand of product \( i \) (key input parameter)

DIOH\(^{19}\) (Days Inventory on Hand) – no. of days’ stock stored in DC (central) storage location

DIIN (Days Inventory in Network) – total no. of days’ stock stored in both DC (central) and Offsite (warehouse) storage locations

It is worthwhile to note here that the objective function does not take into consideration Inventory Cost. Whilst cost of inventory is important, Boston Scientific places service level (and the ability to deliver quality products as quickly as possible to patients) above the cost of inventory.

The decision variables \( x_{ic1}, x_{ic2} \) and \( x_{iw} \) determine the quantity of products to be stored at both the Central Location (DC) and Warehouse Location. Their specific constraints are outlined in Chapter 4.5, which include:

- that there must always be at least the exact quantity of product \( i \) required by DIOH in the Central Location, as this is considered a minimum stock level that must be met for ‘immediate’ shipping out of Central Location (Equation 4.5.2).
- a lower bound on the total quantity of a given product at both Central and Warehouse locations, and that it must satisfy the monthly demand of DIIN for product \( i \) (Equation 4.5.3).
- given that inventory for DIIN includes allocation for DIOH inventory, the combined inventory for product \( i \) at Central and Warehouse locations must be greater than allocated DIIN inventory (not including DIOH) (Equation 4.5.4).
- only positive quantities are allowed (Equation 4.5.5).

Finally, the objective function outlined in Equation 4.1.1 will be further discussed in the following sections. The model assumes that a single time-period is measured in months, and as such all constraints and variables in the following sections will be monthly.

\(^{19}\) Refer to Appendix A for a graphical explanation of DIOH and DIIN, and their relationship with other parameters.
4.2. Central Costs

\[ \sum_i \text{Central Costs} = \sum_z \left( \sum_i \text{Central Storage Costs} + \sum_i \text{Central Handling Costs} \right) \]

Equation 4.2.1

Where:

\[ \sum_i \text{Central Storage Costs} = \sum_i \left( R_{c,z} S_{i,c} x_{i,c,1} + R_{c,z} S_{i,c} x_{i,c,2} \right) = R_{c,z} \sum_i (S_{i,c} x_{i,c,1} + S_{i,c} x_{i,c,2}) \]

Equation 4.2.2

\[ \sum_i \text{Central Handling Costs} = \sum_i H_{c,z} DIOH_{r} \left( \frac{x_{i,c,1}}{P_i} \right) + \sum_i H_{c,z} DIIN_{r} \left( \frac{x_{i,c,2}}{P_i} \right) \]

\[ = H_{c,z} \sum_i \left( DIOH_{r} \left( \frac{x_{i,c,1}}{P_i} \right) + DIIN_{r} \left( \frac{x_{i,c,2}}{P_i} \right) \right) \]

Equation 4.2.3

Therefore:

\[ \sum_i \text{Central Costs} = \sum_z \left( R_{c,z} \sum_i (S_{i,c} x_{i,c,1} + S_{i,c} x_{i,c,2}) + H_{c,z} \sum_i \left( DIOH_{r} \left( \frac{x_{i,c,1}}{P_i} \right) + DIIN_{r} \left( \frac{x_{i,c,2}}{P_i} \right) \right) \right) \]

Equation 4.2.4

Sets and Indices:

\( z \) - Set of all distinct zones within Central location; \( z \in Z = \{1, ..., Z_c\} \)

\( A_{c,z} \) – maximum space available within zone \( z \) at Central location

\[ \left[ \frac{x_{i,c,1}}{P_i} \right], \left[ \frac{x_{i,c,2}}{P_i} \right] \] – no. of ‘moves’ required to fulfill \( x_{i,c,1} \) and \( x_{i,c,2} \) (see below)
Constraints:

\[
\sum_{z} \sum_{i} (S_{i,c}x_{i,c1} + S_{i,c}x_{i,c2}) \leq A_{c,z}
\]

*Equation 4.2.5*

Where input parameters are:

- \(S_{i,c}\) – space taken up by product \(i\) in Central location (sqft)
- \(R_{c,z}\) – cost of storage at zone \(z\) of Central location ($/sqft)
- \(H_{c,z}\) – cost of handling at zone \(z\) of Central location ($/pallet)
- \(DIOH_{r}\) – frequency of replenishment required to meet DIOH
- \(DIIN_{r}\) – frequency of replenishment required to meet DIIN
- \(P_{i}\) – quantity of product \(i\) in a standard pallet

\[
\left\lceil \frac{x_{i,c1}}{P_{i}} \right\rceil \left\lceil \frac{x_{i,c2}}{P_{i}} \right\rceil
\]

determine the number of moves that is required to transport \(x_{i,c1}\) and \(x_{i,c2}\). Given that products \(i\) are stored on pallets, and that in the current state, an entire pallet has to be moved whenever any quantity of \(i\) is required, \(\left\lceil \frac{x_{i,c1}}{P_{i}} \right\rceil \left\lceil \frac{x_{i,c2}}{P_{i}} \right\rceil\) produces an upper bound result that is always a whole number factor of pallets required\(^\text{20}\).

It is common in most warehouses to have different zones within a given facility. In this model, zones are differentiated by product family as well as cost of handling (however, it can also be differentiated by infrastructure).

Specifically, equations 4.2.2 and 4.2.3 describe the cost of storage and handling at Central Location. For the storage cost, a uniform rate is applied across the specific zone. It is assumed that any facility and utility costs (such as HVAC, lighting and internet) are embedded into this rate. Whilst the handling cost at Central Location is the cost of Boston Scientific employees who are responsible for receiving and re-stocking incoming products to their final location. Equation 4.2.4 states that the total space utilized within Zone \(z\) for storage must be less than the maximum available space in that zone. However (as stated earlier), Boston Scientific places services level above cost of space utilization within the Central

\(^{20}\) The use of the upper bound notation in the equation transforms it into a non-linear equation. In actual implementation (Chapter 5), the upper bound was removed to estimate/linearize the equation: \(\left\lceil \frac{x_{i,c1}}{P_{i}} \right\rceil \approx \frac{x_{i,c1}}{P_{i}}\).
DC, therefore in implementation, all space within Central DC is required to be utilized
\( \sum_{x} \sum_{l} \left( S_{l,c}x_{i,c1} + S_{l,c}x_{i,c2} \right) = A_{c,z} \)

\textit{DIOH}_r \text{ and } \textit{DIIN}_r \text{ are described in Appendix A, and are calculated as follows:}

\[
\text{DIOH}_r = \frac{\text{no. of working days per month}}{\text{DIOH}}
\]

\textit{and}

\[
\text{DIIN}_r = \frac{\text{no. of working days per month}}{\text{DIIN}_{DC}}
\]

where:

\[
\text{DIIN}_{DC} = \frac{\text{space available in DC for DIIN}}{\text{total space required for one days' inventory}}
= \sum_{z} \frac{A_{c,z} - \sum_{l} \left( S_{l,c}x_{i,c1} + S_{l,c}x_{i,c2} \right) \times \text{DIOH}}{\sum_{l} \left( S_{l,c}x_{i,c1} + S_{l,c}x_{i,c2} \right)}
\]

\text{4.3. Warehouse Costs}

\[
\sum_{i} \text{Warehouse Costs} = \sum_{z} \left( \sum_{l} \text{Warehouse Storage Costs} + \sum_{l} \text{Warehouse Handling Costs} \right)
\]

\text{Where:}

\[
\sum_{l} \text{Warehouse Storage Costs} = \sum_{l} R_{w,z}S_{i,w}x_{i,w} = R_{w,z} \sum_{l} S_{i,w}x_{i,w}
\]


\[
\sum_i \text{Warehouse Handling Costs} = \sum_i \left( H_{w,x} x_{i,w} + H_{w,x} DII \frac{X_{i,c2}}{P_i} \right) \\
= H_{w,x} \sum_i \left( x_{i,w} + DII \frac{X_{i,c2}}{P_i} \right)
\]

Equation 4.3.3

Therefore:

\[
\sum_i \text{Warehouse Costs} = \sum_z \left\{ R_{w,z} \sum_i S_{i,w} x_{i,w} + H_{w,x} \sum_i \left( x_{i,w} + DII \frac{X_{i,c2}}{P_i} \right) \right\}
\]

Equation 4.3.4

**Sets and Indices:**

\( z \) - Set of all distinct zones within Warehouse location; \( z \in Z = \{1, ..., Z_w\} \)

\( A_{w,z} \) – maximum space available within zone \( z \) at Warehouse location

**Constraints:**

\[
\sum_z \sum_i S_{i,w} x_{i,w} \leq A_{w,z}
\]

Equation 4.3.5

Where input parameters are:

\( S_{i,w} \) – space taken up by product \( i \) in Warehouse location (sqft)

\( R_{w,z} \) – cost of storage at zone \( z \) of Warehouse location ($/month per sqft)

\( H_{w,z} \) – cost of handling at zone \( z \) of Warehouse location ($)

Equations 4.3.2 and 4.3.3 are the equations for storage and handling costs within the Warehouse location. They are also similarly derived as those for the Central location and are finally combined to form equation 4.3.1.
4.4. Transportation Costs

The last major component of the optimization model is the Transportation Costs, which is governed by the frequency of replenishment from the Warehouse location to the Central (DC) location.

\[
\sum \text{Transportation Costs} = \text{Fuel Cost} \times \text{Distance} \times \text{Frequency} = F \times L_w \times \frac{DIIN_r}{T_r} \sum_i S_{i,c}x_{i,c2}
\]

*Equation 4.4.1*

Where input parameters are:
- \(F\) – fuel and resource cost (ie. driver) ($/mi)
- \(L_w\) – distance between Warehouse and Central (DC) location (mi)
- \(DIIN_r\) – frequency of replenishment required to meet DIIN (refer to Equation 4.2.7)
- \(T_r\) – size of transportation vehicle (sqft)
- \(S_{i,c}\) – space taken up by product \(i\) in Central location (sqft)
4.5. Final Objective Function

The final generalized objective function of the optimization model representing Boston Scientific Arden Hills’ DC and Offsite Warehouse can therefore be written as:

\[
\text{monthly supply cost (to minimize)}
= \sum_{z} \left\{ R_{c,z} \sum_{i} (S_{i,c} x_{i,c1} + S_{i,c} x_{i,c2}) + H_{c,z} \sum_{i} \left[ DIOH_{r} \left( \frac{x_{i,c1}}{P_{i}} \right) + DIIN_{r} \left( \frac{x_{i,c2}}{P_{i}} \right) \right] \right\} \\
+ \sum_{z} \left\{ R_{w,z} \sum_{i} S_{i,w} x_{i,w} + H_{w,z} \sum_{i} \left[ x_{i,w} + DIIN_{r} \left( \frac{x_{i,c2}}{P_{i}} \right) \right] \right\} \\
+ FL_{w} \frac{DIIN_{r}}{T_{r}} \sum_{i} S_{i,c} x_{i,c2}
\]

Equation 4.5.1

Sets and Indices:

- \( i \) - Set of all distinct products (SKU/UPN); \( i \in I = \{1, \ldots, I\} \)
- \( c1 \) - Index of DC (central) storage location for Days Inventory on Hand (DIOH) stock
- \( c2 \) – Index of DC (central) storage location for Days Inventory In Network (DIIN) stock
- \( w \) – Index of offsite/warehouse storage location for DIIN stock
- \( z \) - Set of all distinct zones within Central and Warehouse locations; \( z \in Z = \{1, \ldots, Z_c\} \)

Decision Variables:

- \( x_{i,c1}, x_{i,c2}, x_{i,w} \) - quantity of product \( i \) to be stored in Central for DIOH, for DIIN and Warehouse location for DIIN

Constraints:

\[
x_{i,c1} \geq DIOH \times D_{i}^{21}
\]

Equation 4.5.2

\[
x_{i,c1} + x_{i,c2} + x_{i,w} \geq DIIN \times D_{i}
\]

Equation 4.5.3

\[
x_{i,c2} + x_{i,w} \geq (DIIN - DIOH) \times D_{i}
\]

Equation 4.5.4

\( ^{21} \) In the actual implementation of the model, \( x_{i,c1} \) is set to equal \( DIOH \times D_{i} \)
\[ x_{i,c1}, x_{i,c2}, x_{i,w} \geq 0 \]

\[ \sum_{z} \sum_{i} (S_{i,c} x_{i,c1} + S_{i,c} x_{i,c2}) \leq A_{c,z} \]

\[ \sum_{z} \sum_{i} S_{i,w} x_{i,w} \leq A_{w,z} \]

**Input Parameters:**

- \( D_{i} \) – monthly demand of product \( i \)
- \( S_{i,c} \) – space taken up by product \( i \) in Central location (sqft)
- \( R_{c,z} \) – cost of storage at zone \( z \) of Central location ($/sqft)
- \( H_{c,z} \) – cost of handling at zone \( z \) of Central location ($/pallet)
- \( A_{c,z} \) – maximum space available within zone \( z \) at Central location
- \( A_{w,z} \) – maximum space available within zone \( z \) at Warehouse location
- \( DIOH_{r} \) – frequency of replenishment required to meet DIOH
- \( DIIN_{r} \) – frequency of replenishment required to meet DIIN
- \( P_{i} \) – quantity of product \( i \) in a standard pallet
- \( S_{i,w} \) – space taken up by product \( i \) in Warehouse location (sqft)
- \( R_{w,z} \) – cost of storage at zone \( z \) of Warehouse location ($/month per sqft)
- \( H_{w,z} \) – cost of handling at zone \( z \) of Warehouse location ($)
- \( F \) – fuel and resource cost (ie. driver) ($/mi)
- \( L_{w} \) – distance between Warehouse and Central (DC) location (mi)
- \( T_{r} \) – size of transportation vehicle (sqft)
5. Implementation of Decision Support Tool

This chapter outlines the implementation of the Decision Tool, taking the Optimization Model outlined in the previous chapter with its set of equations, transforming it into a dynamic tool with a graphical user interface that provides outputs based on user inputs. Various programming language/software environments are compared, before a final selection was decided upon. Different optimization packages are also reviewed. The relationship between the inputs to the Decision Tool and the parameters and decision variables in the model is outlined as well as sample outputs shown in the end of the chapter.

5.1. Decision Tool using R

In planning for implementation of the Decision Tool, several important features were considered. The tool should be user friendly, be able to handle large amounts of data and preferably complete the optimization and show a result in a short amount of time. It should also be able to be executed standalone without significant supporting software/hardware, or if other software required, cost should be minimal. The table below summarizes how major programming environments and software such as MATLAB, Python, R and Excel met the key considerations.

<table>
<thead>
<tr>
<th>Feature</th>
<th>MATLAB</th>
<th>Python</th>
<th>R</th>
<th>Excel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low cost</td>
<td>$50-$1000 per license (not currently used at BSC)</td>
<td>FREE (Open Source)</td>
<td>FREE (Open Source)</td>
<td>FREE (Already part of BSC computers)</td>
</tr>
<tr>
<td>Currently used by BSC Materials Management team</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>Ability to handle large amounts of data</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Speed of execution</td>
<td>Fastest</td>
<td>Fast</td>
<td>Medium</td>
<td>Slow</td>
</tr>
<tr>
<td>User friendly interface/environment for programming</td>
<td>Y</td>
<td>Y (iPython notebook)</td>
<td>Y (RStudio)</td>
<td>Y</td>
</tr>
<tr>
<td>Additional libraries easily acceptable for optimization</td>
<td>N (Most libraries require additional cost)</td>
<td>Y</td>
<td>Y</td>
<td>N (XLMiner/Frontline addon require additional cost)</td>
</tr>
<tr>
<td>Concise code to implement optimization functionality</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
</tr>
</tbody>
</table>

Table 5.1.1 Major programming environments compared
As a result of the analysis, R was chosen as the programming environment to create the Decision Support tool. From its website\(^{22}\), ‘R is a programming language and free software environment for statistical computing. R and its libraries implement a wide variety of statistical and graphical techniques, including linear and nonlinear modelling’.

R was also chosen due to its broad range of libraries (many developed by other users) which support Mixed Integer Linear Programming as required by the optimization model outlined in Chapter 4. Two such libraries that meet the requirement are ‘linprog’\(^{23}\) and ‘ompr’\(^{24}\), the major difference being how optimization equations are presented. In ‘ompr’, equations can be written algebraically (see Figure 5.1.1), whereas in ‘linprog’, equations need to be setup in matrix notation. For ease of interpretation, ‘ompr’ was finally chosen.

The following shows how the objective function (Equation 4.5.1) was written in ‘R’ using the ‘ompr’ library. The notation is like that of the mathematical form and allows easy comprehension as well as modification.

Pre-set Constants
Product Information
Decision Variable

```r
set_objective(r_c * sum_expr(product$space[i]*x_c1[i], i = 1:p)
+ r_c * sum_expr(product$space[i]*x_c2[i], i = 1:p)
+ h_c * dioh_rep * sum_expr(product$service[i]*x_c1[i]/product$pallet_qty[i], i = 1:p)
+ r_w * sum_expr(product$space[i]*x_w[i], i = 1:p)
+ (h_c+h_w) * diin_rep * sum_expr(x_c2[i]/product$pallet_qty[i],i = 1:p)
+ h_w * sum_expr(x_w[i]/product$pallet_qty[i], i = 1:p)
+ (f_l*diin_rep/truck_size) * sum_expr(product$space[i]* x_c2[i], i = 1:p)
, "min" )
```

*Figure 5.1.1 Objective Function represented in R/ompr*

Finally, the optimization model (as well as various input manipulation functions) were then written in R (using ompr as the optimization library).

---

\(^{22}\) R Project for Statistical Computing. Available at https://www.r-project.org/

\(^{23}\) Linprog: Linear Programming / Optimization. Available at https://cran.r-project.org/web/packages/linprog/

\(^{24}\) OMPR: Mixed integer linear programming in R. Available at https://dirkschumacher.github.io/ompr/
5.2. User Interface using Shiny

Shiny\textsuperscript{25} is a R library/addon which adds the functionality of having a dynamic interface. A user-friendly interface to upload input data, adjust parameters and view the output ‘live’ is important to enhance wider user adoption of the tool. The graphical user interface also allowed ease of collaboration with the user team. For example, initially, all units related to space was measured in square feet, but this wasn’t intuitive to the users, and after discussion, units of totes and pallets were included.

The ability to visually see the conversion directly in the user interface (between pallets and square feet) was added in the interface (as shown in Figure 5.2.1), but subsequently converted to square feet for use in the optimization program. This was done through an optional setting where users could change the default conversion between totes, pallets and square feet.

The following section outlines the interface, its adjustable parameters and how they relate to the equations outlined in Chapter 4.

\textsuperscript{25} R Shiny. Available at https://shiny.rstudio.com/
In the Main Page, under Step 1, the user is prompted first to upload the relevant Demand and Usage/Data Files. The Demand File contains forecast of future demand where the Usage/Data File contains specific product information such as default quantity per tote/pallet (which is then converted for space calculations). The inputs here contain information on $D_i$ (demand), $S_{i,c}$ and $S_{i,w}$ (space per product), $P_i$ (quantity of product in a pallet).

In Step 2, the user is prompted to input variables related to Capacity and Handling. These cover the variables $R_{c,z}$ and $R_{w,z}$ (storage cost), $A_{c,z}$ and $A_{w,z}$ (space capacity), $H_{c,z}$ and $H_{w,z}$ (handling cost).

In Step 3, the user is prompted to adjust variables for working days per month, $DIOH$ and $DIIN$. 

Figure 5.2.3 Decision Tool interface, Main Page with Inputs, Constraints and Outputs
Following the input and variables in the Main page, the user may also choose to adjust additional Optional Constraints.

Here, in Step 1, the user can adjust parameters that determine the relationship between space (sqft), tote size and pallet size. Then in Step 2, the user can choose to activate Zones, where separate zones have separate capacities and are dedicated to different product types. In this example, there are three Zones (PRM, PRS, SSS), and all products in the Input file from the Main page belong to one of these zones.

Lastly, in Step 3, the user sets variables for $T_r$ (transportation size), $F$ (fuel cost) and $L_w$ (distance between Central and Warehouse).
The following table connects inputs to the model with real-life data:

<table>
<thead>
<tr>
<th>Input/Variable</th>
<th>Real-Life Data Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{i,c1}$</td>
<td>Decision Variable / Output</td>
<td></td>
</tr>
<tr>
<td>$x_{i,c2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x_{i,w}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_i$</td>
<td>Input - Product Monthly Demand</td>
<td>Input data known by user</td>
</tr>
<tr>
<td>$S_{i,c}$, $S_{i,w}$</td>
<td>Input – Size of Product</td>
<td>Input data known by user (either from square feet per product or quantity of product per tote/pallet)</td>
</tr>
<tr>
<td>$R_{c,z}$, $R_{w,z}$</td>
<td>Variable – Storage Rate</td>
<td>Variable set by user (based on Real Estate, utility and infrastructure costs)</td>
</tr>
<tr>
<td>$H_{c,z}$, $H_{w,z}$</td>
<td>Variable – Handling Rate</td>
<td>Variable set by user (based on hourly rate of handlers)</td>
</tr>
<tr>
<td>$A_{c,z}$, $A_{w,z}$</td>
<td>Variable – Maximum Capacity</td>
<td>Variable set by user (based on actual data)</td>
</tr>
<tr>
<td>$DIOH_{r},DIIN_{r}$</td>
<td>Variable - Days Inventory on Hand</td>
<td>Variable set by user (based on customer service level requirement)</td>
</tr>
<tr>
<td>$P_i$</td>
<td>Input – Quantity of Product per Pallet</td>
<td>Input data known by user</td>
</tr>
<tr>
<td>$F$</td>
<td>Variable – Fuel Cost</td>
<td>Variable set by user</td>
</tr>
<tr>
<td>$L_w$</td>
<td>Variable – Distance between Central (DC) and Offsite Warehouse</td>
<td>Variable set by user</td>
</tr>
<tr>
<td>$T_r$</td>
<td>Variable – Transportation Capacity</td>
<td>Variable set by user</td>
</tr>
</tbody>
</table>

Finally, once the input files have been uploaded and the parameters set, the optimization can be executed. After a successful optimization, two outputs will be provided, one is a set of charts outlining the total space, cost and inventory value of products at Central and Warehouse locations (Figure 5.2.5 below) as well as estimate of the replenishment frequency (from Warehouse to Central). The second output is a file containing quantity of each product to be placed in both Central and Warehouse locations.
Result

Output result after successful optimization.

Total Space: 17946 sqft = 1346 pallets

Total cost: $ 8767

Total inventory Cost: $ 498620627

Space Required

Estimated Supply Cost

Estimated Inventory Cost

Replenishment Frequency

DC will need to be replenished in 18 trips per month (ie. from Offsite).

<table>
<thead>
<tr>
<th>SKU</th>
<th>Onsite</th>
<th>Offsite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product A</td>
<td>358.00</td>
<td>815.00</td>
</tr>
<tr>
<td>Product B</td>
<td>961.00</td>
<td>1933.00</td>
</tr>
<tr>
<td>Product C</td>
<td>5.00</td>
<td>11.00</td>
</tr>
<tr>
<td>Product D</td>
<td>873.00</td>
<td>1991.00</td>
</tr>
<tr>
<td>Product E</td>
<td>260.00</td>
<td>589.00</td>
</tr>
<tr>
<td>Product F</td>
<td>5.00</td>
<td>11.00</td>
</tr>
</tbody>
</table>
5.3. Summary

In this chapter, the model was transformed (through R and Shiny) into an interactive Decision Tool with Graphical User Interface. Background on the selection of R and the optimization library were discussed as well as key inputs and outputs to the Decision Tool. The next chapter will show the Decision Tool when applied on real data, and review and discuss the corresponding outputs.
6. Results and Discussion

The following chapter outlines and discusses results produced by the Decision Tool described in Chapter 5. First, the Decision Tool uses historical data to optimize results of the DC’s current state and compares it to existing data, then, the Decision Tool utilizes future demand to forecast cost, space utilization and replenishment frequency in a future state. A Case Study looking at the impact of Real Estate cost on Offsite Warehouse selection is then reviewed, followed by Discussion on the Decision Tool’s current limitations as well as further works.

6.1. Model Verification

Using historical data, the Decision Tool can be used to compare the output of the Model with actual results.

6.1.1. Offsite Spend

Monthly offsite spend is the sum of the cost to store material offsite and the cost to replenish material from the Offsite Warehouse to the Central DC. Due to the billing model of Boston Scientific’s currently Offsite Warehouse, a breakdown of the exact monthly spend is not available, rather, a range can be deduced. Then using the Decision Tool, a monthly estimate can be calculated given monthly demand and actual rates of the Offsite Warehouse and Transportation Costs. Table 6.1.126 below compares the actual Offsite Spend (range) with the output of the Decision Tool.

<table>
<thead>
<tr>
<th>Month</th>
<th>Demand (Actual) (parts/month)</th>
<th>Offsite Spend (Actual) ($/month)</th>
<th>Offsite Spend (Model) ($/month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 2019</td>
<td>91075</td>
<td></td>
<td>5382</td>
</tr>
<tr>
<td>April 2019</td>
<td>116472</td>
<td>8300 - 10800</td>
<td>8529</td>
</tr>
<tr>
<td>May 2019</td>
<td>123995</td>
<td></td>
<td>9443</td>
</tr>
<tr>
<td>June 2019</td>
<td>136314</td>
<td></td>
<td>10186</td>
</tr>
<tr>
<td>July 2019</td>
<td>115312</td>
<td></td>
<td>8125</td>
</tr>
</tbody>
</table>

Table 6.1.1 Offsite Spend (Actual vs. Model)

26 In both Actual and Model spend, return trip is considered between Offsite Warehouse and Central DC.
Figure 6.1.1 Decision Tool output (based on March 2019 demand).

- Estimated Inventory Cost
- Estimated Supply Cost
- Space Required

DC will need to be replenished in 20 trips per month (e.g., from office).
From the comparison, it can be observed that the output of the Model is consistently lower than the actual spend. A key factor of this discrepancy is due to the different replenishment method as outlined in Chapter 3 (Figures 2.3.1, 2.3.2, 2.3.3). In the Current State, when a part is required, the entire pallet of that material is transported from the Offsite Warehouse to the Central DC, the required quantity of the part is removed from the pallet, and then the remaining product returned to the Offsite facility. In the Future State simulated by the Model, the exact quantity is retrieved from the Offsite Warehouse and transported directly to the Central DC.

Table 6.1.1 also shows the order of magnitude of the potential savings if the optimized Future State was employed rather than the Current State process.

6.2. Model Optimization

6.2.1. Current Central DC/Offsite Warehouse Utilization

In current state, the ‘real’ cost of DC, including space utilization and handling are set to zero. This is since the DC team do not have to ‘pay’ for space and personnel. The Decision Tool, however, can accept the ‘real’ costs as input and provide an optimization for space and cost. Table 6.2.1 and Figure 6.2.1 below shows a comparison when associated space and handling costs are considered.

<table>
<thead>
<tr>
<th></th>
<th>Current State (DC @ Zero Cost)</th>
<th>Current State (DC @ Real Cost)</th>
<th>Optimized State (DC @ Real Cost)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Storage Cost ($/pallet/mth)</td>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>DC Handling Cost ($/pallet)</td>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Offsite Storage Cost ($/pallet/mth)</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Offsite Handling Cost ($/pallet)</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Transportation Cost</td>
<td>$10 per mi @ 5 miles per trip</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(based on March 2019 Demand)

<table>
<thead>
<tr>
<th></th>
<th>Current State (DC @ Zero Cost)</th>
<th>Current State (DC @ Real Cost)</th>
<th>Optimized State (DC @ Real Cost)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Space Used (pallets)</td>
<td>638</td>
<td>638</td>
<td>186</td>
</tr>
<tr>
<td>Offsite Space Used (pallets)</td>
<td>198</td>
<td>198</td>
<td>650</td>
</tr>
<tr>
<td>Monthly Supply Cost ($ / month)</td>
<td>5382</td>
<td>14561</td>
<td>9828</td>
</tr>
</tbody>
</table>

Table 6.2.1 Analysis of Optimal Space Utilization
Figure 6.1 Decision Tool output (March 2019 - optimized)
The above analysis shows that even though the DC team spend $5,382 to meet the supply requirements for March 2019, the ‘real’ cost to Boston Scientific is approximately $14.5k. Then taking the real costs into consideration and optimizing, the lowest possible supply cost to meet the demand is $9.8k, and this is achieved by placing 186 pallets of material in the DC and 650 pallets in the Offsite Warehouse (as shown in Figure 6.2.2 below).

This saving of 32% based on ‘real’ costs does not take into consideration the risk of delay in shipping an order to the customer. As Boston Scientific places service level above cost, this potential saving in supply cost is outweighed by storing more material at the Central DC location to ensure orders are met on time. The savings also represent a quantifiable opportunity cost of utilizing the space for other purposes (ie. manufacturing, R&D, etc.). The alternative use could be considered more financially beneficial if it is able to generate income ‘value’ to the business greater than $4,733 per month ($14.5k - $9.8k).
6.2.2. Future Volume Growth

Another feature of the Decision Tool is the ability to forecast future space requirement, supply cost and replenishment frequency. Figure 6.2.3 shows what impact growth of 10%, 20% and 30% (of monthly product volume) has on Storage Space, Monthly Offsite Spend and Replenishment Frequency. Whilst it may be intuitive that 10% volume growth may lead to 10% increase in total storage space required (a 1:1 relationship), the model shows that a 10% increase in volume actually causes a 20% increase in monthly offsite spend but also a 10% increase in replenishment frequency (based on current product characteristics such as size and demand).

In this case, the tool aims to help the DC team prepare for the increased growth by looking to increase head count and/or alternative offsite storage solutions that would closer mimic a future state.

![Impact of Product Demand Growth on other Factors](image)

*Figure 6.2.3 Impact of Future Volume Growth*

It is important to note here that the Product Demand Growth assumptions are based on current products. If future products differ in size, then this could influence the replenishment frequency and therefore the linear relationship between Growth of Product Demand and Growth of Other Factors. These additional factors are further explored in Chapter 6.6.
6.3. Case Study – New Offsite Warehouse

With the increase of demand projected for coming years, the Decision Tool was used to support a review of the current Offsite Warehouse location. The figure below outlines the features of the current offsite warehouse and a potential new facility:

<table>
<thead>
<tr>
<th></th>
<th>Current Offsite Warehouse</th>
<th>Future Offsite Warehouse</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owner</td>
<td>Third Party</td>
<td>Third Party</td>
<td></td>
</tr>
<tr>
<td>Managed/Operated By</td>
<td>Third Party</td>
<td>Boston Scientific</td>
<td></td>
</tr>
<tr>
<td>Cost (per month)</td>
<td>$6 / pallet</td>
<td>TBD</td>
<td></td>
</tr>
<tr>
<td>Distance from Boston Sci (mi)</td>
<td>~ 5</td>
<td>TBD</td>
<td></td>
</tr>
<tr>
<td>Maximum Capacity (k sqft)</td>
<td>80</td>
<td>TBD</td>
<td></td>
</tr>
<tr>
<td>Temp Control/Humidity Monitoring</td>
<td>N</td>
<td>Y</td>
<td>Future facility will be able to store all products (incl. temp/humidity sensitive products)</td>
</tr>
</tbody>
</table>

Table 6.3.1 Impact of Future Volume Growth

From Table 6.3.1, the main short-term features of the Future Offsite Warehouse (operated by Boston Scientific personnel) is the ability to replenish the Central DC with exact quantities of the products required. This would reduce the replenishment frequency between Central and Offsite as well as the associated cost. A longer-term feature of the Future Offsite Warehouse would be the addition of functionality such as receiving stock directly from manufacturers (reducing traffic to the Central DC) as well as being able to pack and ship directly to customers.

A survey was conducted of nearby vacant Offsite Warehouses, and the associated cost/distance data inputted into the Decision Tool.
6.4. Case Study – Results

Figure 6.4.1 below shows vacant Offsite Warehouse locations that meet Boston Scientific’s basic criterion (cleanliness, owner reputation, etc.). The table outlines the associated Distance, Rate and Capacity. Using the information from Figure 6.4.1 and future product demand as inputs to the Decision Tool, an estimate of the Monthly Supply Cost can be forecasted. Table 6.4.1 compares the forecast cost of various locations. For comparison purposes, the demand from March 2019 was used to analyze all locations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Distance from Boston Sci (mi)</th>
<th>Rate ($ per sqft per year)</th>
<th>Max Capacity (k sqft)</th>
<th>Distance from airport (mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4.7</td>
<td>8.1</td>
<td>82</td>
<td>22</td>
</tr>
<tr>
<td>B</td>
<td>7.6</td>
<td>9.8</td>
<td>80</td>
<td>19</td>
</tr>
<tr>
<td>C</td>
<td>5.3</td>
<td>8.3</td>
<td>172</td>
<td>19</td>
</tr>
<tr>
<td>D</td>
<td>8.1</td>
<td>8.3</td>
<td>168</td>
<td>17</td>
</tr>
</tbody>
</table>

*Figure 6.4.1 New Offsite Warehouses – survey*
<table>
<thead>
<tr>
<th>Location</th>
<th>Distance from Boston Sci (mi)</th>
<th>Rate ($ per sqft per year)</th>
<th>Rate ($ per pallet per month)$^	ext{27}$</th>
<th>Storage</th>
<th>Transport</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>5</td>
<td>6</td>
<td></td>
<td>3915</td>
<td>1466</td>
<td>5382</td>
</tr>
<tr>
<td>A</td>
<td>4.7</td>
<td>8.1</td>
<td>2.2</td>
<td>3117</td>
<td>1378</td>
<td>4495</td>
</tr>
<tr>
<td>B</td>
<td>7.6</td>
<td>9.8</td>
<td>2.7</td>
<td>3215</td>
<td>2228</td>
<td>5444</td>
</tr>
<tr>
<td>C</td>
<td>5.3</td>
<td>8.3</td>
<td>2.3</td>
<td>3136</td>
<td>1554</td>
<td>4691</td>
</tr>
<tr>
<td>D</td>
<td>8.1</td>
<td>8.3</td>
<td>2.3</td>
<td>3136</td>
<td>2375</td>
<td>5512</td>
</tr>
</tbody>
</table>

Table 6.4.1 New Offsite Warehouses - forecast costs (March 2019 demand)

Results from Table 6.4.1 show the projected operational costs of utilizing locations A-D compared to the current Offsite Warehouse is comparable. The table does not include the one-off costs associated with refitting a new Offsite Warehouse. Nor does it consider the potential savings and opportunities that a Boston Scientific-managed Warehouse would be capable of. However, it does show how the Decision Tool may be used as an input to support such an analysis.

6.5. Impact due to Real Estate Cost and Location

Whilst Minnesota may be considered a major US city with lower Real Estate cost, the model can be similarly applied to other major US cities with higher Real Estate cost. For the purposes of comparison, similar Offsite Warehouses in Boston and San Jose were reviewed, with similar proximity to their respective airports as well as to the Boston Scientific facility in those cities.

$^	ext{27}$ Conversion from square feet to pallets is based on a pallet size of 48” x 40” = 1920 sq. inch per pallet = 13.3 square feet per pallet. It is assumed that each New Offsite Warehouse can store pallets up to 4 levels.
The results show what the potential supply cost could be, if a similar sized Offsite Warehouse was utilized in a city of High Real Estate cost. Not only is the availability of vacant warehouse locations (in proximity to both Boston Scientific facility and a local airport) scarce, there are only a few that could potentially meet the requirements in terms of total space.

Plotting the data from Table 6.5.1, the Monthly Supply Cost due to Transportation (distance between Central and Offsite Warehouse) is almost linear in relationship (as seen in Figure 6.5.2a). The more important factor is the Storage Rate of the facility (Figure 6.5.2b), which shows that even with a 3x increase from the Low Real Estate cost region to the High Real Estate cost region, the Monthly Supply Cost only increased by ~1.5x. This shows how the model and the Decision Tool may be used to help companies determine the location of their Offsite Warehouses in terms of location and distance from DC.

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28 Prices in the figures do not include Real Estate Tax and Common Area Maintenance costs, to ensure consistency with results in earlier chapters, a 45% RE Tax/CAM is added.
Figure 6.5.2 Monthly Supply Cost (of Future State) in different Real Estate regions: a) Due to Transportation and b) Due to Storage Rate
Two caveats of the above result are that personnel costs (including handling costs) have been set to zero and that transportation costs are set to that of the Low real estate area. It could be argued that in areas of High real estate cost, personnel costs are likely to be higher than Low real estate costs, and therefore the total Monthly Supply Costs are likely to be higher as a result. Similarly, transportation costs (including fuel costs) are also likely to be higher in areas of High real estate costs. The example above isolates these factors to show only the influence of distance and real estate.

Figure 6.5.3 below further shows the two main components of Monthly Supply Cost (Storage and Transportation) and their change as the distance between Central DC and Warehouse increases. The results here include Offsite facilities (A-I) from both High and Low real estate cost areas. It can be observed that the Storage Cost of across different regions and different distances are generally within the $3,000 to $4,000 per month, however the cost of transportation increases linearly with distance, and ranges between ½x to 2x monthly storage cost. From this information, it would be advisable for companies with similar product profiles to focus on distance rather than storage cost when considering new offsite storage facilities.

![Components of Supply Cost vs. Distance from DC](image)

*Figure 6.5.3 Components of Supply Cost vs. Distance from DC*
6.6. Impact due to Other Factors

In addition to the influence of Real Estate Cost and Location, the following factors were reviewed to analyze their impact on Monthly Cost. Baseline demand input from Chapter 6.2 (March 2019) is used for all following cases.

6.6.1. Transport Vehicle Size

The size of the Transport Vehicle that replenishes product between the Offsite Warehouse and Central DC Storage locations will impact the replenishment frequency and therefore the Monthly Supply Cost. Figure 6.6.1 shows that as the Transport Vehicle capacity increases from 9 to 18 pallets, the Monthly Supply Cost reduces by 16%, however, the replenishment frequency per month reduces by 50%. Depending on how much Boston Scientific ‘values’ low replenishment frequency, the tool can be used to help decide the optimal transport vehicle capacity to be employed.

![Impact of Transport Vehicle Capacity](image)

*Figure 6.6.1 Impact of Transport Vehicle Capacity*
6.6.2. Days Inventory on Hand & Days Inventory in Network

Figure 6.6.2a shows the impact of varying Days Inventory on Hand (DIOH) on Supply Cost and Replenishment Frequency whilst Days Inventory in Network is maintained constant at DIIN = 45. It can be seen that adjusting DIOH between DIOH = 3 and DIOH = 10 has minimal impact on Monthly Supply Cost and no impact on Replenishment Frequency.

On the other hand, Figure 6.6.2b shows the impact of varying Days Inventory in Network (DIIN) whilst Days Inventory on Hand is maintained constant at DIOH = 10.

A number of observations can be made:

- **DIIN has significant impact on Supply Cost** - when DIIN is increased three-fold (from DIIN = 15 to DIIN = 45), Monthly Supply Cost increases by more than 5x. Companies like Boston Scientific may not be comfortable with maintaining DIIN stock level as low as DIIN = 15, and the tool is able to show the cost tradeoff to support any decision making.

- **DIIN has significant impact on Replenishment Frequency** – replenishment frequency increases linearly with DIIN, and plateaus at replenishment frequency = 30 times per month. Here the tool is suggesting that for DIIN ≥ 35, replenishment every calendar day is required to fulfill the conditions in this scenario.

The above scenarios show that DIIN has a much greater impact on Monthly Cost and Replenishment Frequency than DIOH (when all other factors are held constant). However, the comparison does not consider impact on other features such as the amount of storage space required at Central DC.

One of the benefits of the tools is its ability to incorporate multiple factors simultaneously to produce an optimized output. Whilst it is useful to know which factors have more influence on Supply Cost and Replenishment Frequency, users should consider (and apply) all factors before deciding on the most suitable set of inputs for their unique situation.
Figure 6.6.2 Impact of a) Days Inventory on Hand (DIOH) and b) Days Inventory in Network (DIIN)
6.7. Limitations of the Model

The Decision Tool models a future state which is different to the process of the current state. The major differences and its limitations are outlined below.

6.7.1. Inventory on Hand

In the Decision Tool, one of the variables set by the user is the Days Inventory on Hand (DIOH) and Days Inventory in Network (DIIN). These variables govern the amount of stock (multiple of estimated demand) that should be available on hand (in the Central DC) or within the network (in the Central DC or at the Offsite Warehouse). The Decision Tool accepts a distinct number for each DIOH and DIIN and applies across all products. In the Current State, Boston Supply Chain’s Global Supply Chain group sets the amount of inventory that the DC must hold on hand, and the value is calculated based on other inputs and factors. Figure 6.6.1 below shows a snapshot of the actual forecast daily demand and the required days inventory on hand for a set of products.

![Actual Demand (Daily) vs. Days Inventory on Hand (Dec 2019)](image)

*Figure 6.7.1 Inventory requirement of Top Products*
A future iteration of the model and Decision Tool could potentially implement Days Inventory on Hand as a dynamic input which the user can set. Whilst this would closer resemble the current state of the supply chain, it further complicates the model. Boston Scientific’s Arden Hills DC team also believed that this was not a key feature of the Decision Tool and that they wanted the option to set their own DIOH/DIIN, and as such it was not implemented in the current version. For the purposes of testing the Decision Tool, an average DIOH = 10 days and DIIN = 45 days were utilized, and this was accepted by the user team.

6.7.2. Replenishment from Offsite

As mentioned in Chapter 6.1.1, another major difference between Current State and the Decision Tool is replenishment from Offsite Warehouse to Central DC. In the current state, when a product is required from Offsite, the entire pallet of that product is brought to the Central DC regardless of the quantity required. Whereas in the state outlined in the Model, the exact quantity required is replenished from the Offsite facility. The DC team are working on projects that would enable the future state process to become a reality, thereby reducing waste in the replenishment process. As a result, the model was not created to mimic the current state. However, this feature could be realized if the quantity at the Offsite Warehouse of each product was known and could be provided as an input. The model could then determine the ‘pallet moves’ required.

6.7.3. Setting up Zones

Another limitation of the Decision Tool is the creation and configuration of Zones. As part of the Optional Constraints outlined in Chapter 3, the user has the option to enable Zones, where the product is allocated to pre-set Zones in the input file, and the model can then optimize allocation accordingly.
In the current version of the Decision Tool, the cost of Zones is all the same, but the space available for storage is different (and measure differently). This closely represents the current state of the Central DC. A future iteration of the Decision Tool could allow for the number and cost of different Zones to be set within the tool, and then product allocation optimized accordingly. This would be especially useful if there was different cost of equipment such as racking or environmental conditions within different Zones which the supply cost would need to take into consideration.

### 6.8. Summary

This chapter presented the results when the Decision Tool was applied to actual data, specifically that total monthly offsite spend is estimated to grow twice as quickly as increase in product demand. When applied to the Case Study of searching for a new Offsite Warehouse, the Decision Tool showed that the current Offsite Warehouse leased is similar in cost to potential new options, however, the efficiency gains in replenishment frequency had not been included. When applied to High Real Estate cost regions such as Boston and San Jose, the Decision Tool helped to show the supply cost savings of placing a Warehouse in a Low Real Estate cost region such as Minnesota. Lastly, various factors were analyzed individually to determine their impact on Supply Cost and Replenishment Frequency.
7. Conclusion and Future Works

This study presented an optimization model that helps users determine how much inventory to store at a Centralized DC and an Offsite Warehouse based on a variety of factors. Given input information such as demand and product size, the user can adjust various parameters and the Decision Tool will assist in producing an optimal output that minimizes Monthly Supply Cost. The tool can also be used to help users make informed decisions on the placement of Offsite Warehouse/Storage Locations to support the overall Supply Strategy. This chapter summarizes the key results and findings, as well as recommendations for future work.

7.1. Summary of Results

This paper described the development of an optimization model that determines the minimum monthly spend on product storage and transportation between a Centralized Distribution Center and an Offsite Warehouse. The model was then implemented using R, and a Graphical User Interface added with Shiny.

When applied to real data, the Model/Decision Tool was able to provide the following results:

Cost Comparison: the model was able to show the difference in costs between the actual cost of supply for Boston Scientific Arden Hills DC in its Current State, and what the optimized cost would be in a Future State. The results obtained (Figure 6.1.1) show that savings of up to 35% may be possible through transformation to the Future State represented by the optimization model.

Comparison of internal costs: the Decision Tool was also able to compare the utilization of the Offsite Warehouse with and without consideration of resource costs at the Central DC. It was discovered that when taking those costs into consideration, the user team were spending 23% extra to store product closer to the shipping point. This is useful information that quantifies the ‘risk’ of not meeting customer service level.

Future volume growth: projecting future volume and demand growth, the Decision Tool estimated a 2x increase in offsite spend and almost a 1.5x increase in replenishment frequency with the growth of current products. With further information on new product demand and sizing, any future analysis will be much more accurate.
New Offsite Warehouse: the Decision Tool was also used to support the selection of a new Offsite Warehouse that would contain only BSC products and staffed by BSC personnel. The results obtained in Figure 6.4.2 show that when only considering normal operational costs, the current Offsite Warehouse setup is neither the most expensive, nor the cheapest option. There are two potential locations which may produce 15% and 13% monthly savings, respectively.

7.2. Future Works

The model and Decision Tool introduced in this study has been customized for the scenario as faced by Boston Scientific Arden Hills DC team. However, there are several features that can be added to help generalized the model for use in other situations.

- **Dynamic inventory level**: one limitation of the current model is the fixed inventory level (DIOH and DIIN) that is applied to all products. Future iterations of the model could apply different inventory settings to different product/product families depending on requirement.

- **Post process update comparison**: as the BSC DC team is looking to move to a BSC-managed Offsite Warehouse that will support the new replenishment process as outlined in Figure 2.3.2, it will be useful to use the Decision Tool to further compare results with actual spend and replenishment to verify the validity of the tool and to adjust as required.

- **Multiple locations**: the current model as outlined in Equation 4.5.1 is suited for one Central DC and one Offsite Warehouse that can include different ‘zones’ within each facility. It can be further expanded to include features for multiple DC/Warehouse locations, to emulate a more complex Network Supply Chain.

- **Use of Technology**: whilst the current model takes into consideration Handling Costs of personnel (wages), one area that has not been explored is the use of automation is the picking and relocating process. The cost of technology implementation can be embedded into the Equations in Chapter 4 through modifying the Handling Cost and/or the Storage Cost.
- **Pick Process**: in the current picking process, operators travel to the bin location of the desired product and retrieves the quantity as per customer order. A potential future process state would be to mimic the pick process similar to that utilized in large Amazon fulfillment centers whereby robots bring required products to the human operator\(^{29}\). Results show an 80% reduction in cycle time and 50% reduction in inventory space required.

- **Resource cost**: Another area that is not explored in this paper is the different cost of personnel between High and Low real estate cost areas. People in areas of higher cost of living is likely to command higher wages, and therefore cost of transportation and pallet movement will also increase. These factors are likely to change the result of any optimization and should be considered in the future.

\(^{29}\) Kim (2016)
Bibliography


Appendix A

As outlined in Chapter 4.1, constraints for the general form of the Optimization Model is given below:

Sets and Indices:

- $i$ - Set of all distinct products (SKU/UPN); $i \in I = \{1, ..., I\}$
- $c1$ - Index of DC (central) storage location for Days Inventory on Hand (DIOH) stock
- $c2$ – Index of DC (central) storage location for Days Inventory In Network (DIIN) stock
- $w$ – Index of offsite/warehouse storage location for DIIN stock

Decision Variables:

- $x_{i,c1}, x_{i,c2}, x_{i,w}$ – quantity of product $i$ to be stored in Central for DIOH, for DIIN and Warehouse location for DIIN

Constraints:

- $x_{i,c1} \geq DIOH \times D_i$\(^{30}\)
- $x_{i,c1} + x_{i,c2} + x_{i,w} \geq DIIN \times D_i$
- $x_{i,c2} + x_{i,w} \geq (DIIN - DIOH) \times D_i$
- $x_{i,c1}, x_{i,c2}, x_{i,w} \geq 0$

The following examples aim to illustrate how the constraints are applied, and how variables such as DIOH, and DIIN, and calculated

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\(^{30}\) In the actual implementation of the model, $x_{i,c1}$ is set to equal $DIOH \times D_i$
Scenario A:

Given:

Working Days per month (days): 20
Available Space in DC (units): 16 units
Available Space in Offsite (units): 30 units

Set by User:

Days Inventory on Hand (DIOH): 8 days
Days Inventory in Network (DIIN): 28 days

In this scenario, there are 20 working days per month and there is space for a total of 16 units available in the Central DC. The user sets DIOH and DIIN to 8 and 28 respectively.

First, space in the DC is allocated for DIOH, thereby taking up 8 units in total, with space for 8 units (= 16 − 8) remaining.

Then, assuming the cost of storage and replenishment is cheaper at the Central DC than the cost of storage, replenishment and transportation at the Offsite Warehouse, the remaining space in the DC will be allocated to DIIN (8 units). The remaining DIIN units are then allocated to the Offsite Warehouse (28 − 8 = 20 units) to satisfy user requirements.

The replenishment frequency at the DC is calculated based on how many times per month DIOH need to be replenished (DIOH). In this case, as DIOH = 8 units, DIOH would need to be replenished every 8 days. Given that there are 20 working days per month, the replenishment would happen 2.5 (= 20 / 8) times
per month. Similarly, replenishment frequency of DIIN in Central DC by DIIN in Offsite Warehouse (DIIN,) is required every 8 days and occurs 2.5 times per month.

Total cost of supply (storage, handling and transportation) is then calculated by apply storage space, replenishment frequency and other constants to equations in Section 4.

Note that the replenishment cost of DIIN at Offsite Warehouse (by upstream supplier) is not included in the scope of this optimization equation. It is assumed that inventory there is always readily available when required.

**Scenario B:**

Given:

- Working Days per month (days): 20
- Available Space in DC (units): 16 units
- Available Space in Offsite (units): 30 units

Set by User:

- Days Inventory on Hand (DIOH): 4 days
- Days Inventory in Network (DIIN): 32 days

In this scenario, there are 20 working days per month and there is also space for a total of 16 units available in the Central DC. The user sets DIOH and DIIN to 4 and 32 respectively.

First, space in the DC is allocated for DIOH, thereby taking up 4 units in total, with space for 12 units (= 16 – 4) remaining.
Then, assuming the cost of storage and replenishment is cheaper at the Central DC than the cost of storage, replenishment and transportation at the Offsite Warehouse, the remaining space in the DC will be allocated to DIIN (12 units). The remaining DIIN units are then allocated to the Offsite Warehouse (32 \(-12 = 20\) units) to satisfy user requirements.

The replenishment frequency at the DC is calculated based on how many times per month DIOH need to be replenished. In this case, as DIOH = 4 units, DIOH would need to be replenished every 4 days. Given that there are 20 working days per month, the replenishment would happen \(5 = 20 / 4\) times per month. Similarly, replenishment frequency of DIIN in Central DC by DIIN in Offsite Warehouse is required every 12 days and occurs 1.7 times per month.