Long Range Planning of Manufacturing Footprint

by

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Submitted to the MIT Sloan School of Management and the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degrees of

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and
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Abstract

Firms developing an Operations Strategy need to make decisions across a wide spectrum. Within the field of operations strategy, common practice defines the stratification of these decisions into structural and infrastructural elements. Structural decisions relating to the amount of capacity and facilities a firm deploys can impact a firm's cost competitiveness if implemented incorrectly because of the large capital expenditures and time horizons involved.

Boston Scientific, a medical device manufacturer, recognizes the importance of operations strategy in achieving competitive success and continually seeks tools that assist in the creation of strategy as it pursues growth. This thesis discusses the development of a scenario planning tool that is focused on estimation of manufacturing footprint requirements for the company's internal manufacturing network. The tool we develop takes a demand forecast as an input and converts it to a physical space requirement in square feet. Additionally, the tool exhibits significant flexibility in being able to develop multiple scenarios, especially given the ability to modify parameters ranging from growth rates to improvement factors within facilities. The tool also offers a deeper level of detail than previously available, with the critical decision unit being the value stream, rather than an aggregation of data to only present factory or network level results.

Whilst this work is applied to the context of a medical device manufacturer, the methodology is easily transferable to a range of industries. The work can be applied to any manufacturing setting where investment decisions for new facilities take significant time and capital. Our research of the literature on this topic identified a gap, and the development of the tool is a positive addition to the field of estimation of manufacturing footprint.

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To the Operations Strategy team at Boston Scientific, thank you for the openness with which you embraced me and for making me feel a part of the team. Each of you went above and beyond to help me accomplish what is detailed in the following pages.

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1. Introduction

1.1. Background

Strategic capacity planning plays an important role within organizations that conduct a significant amount of manufacturing activity. Decisions about how much and where to invest in facilities play a central role in defining the organization's cost structure and ability to serve customers with the right products at the right time at an acceptable cost. These decisions typically take a long period to enact and come with significant requests for capital allocation. It is in the interest of firms to develop sound planning processes to ensure the decisions made are best for the company. Within the broader spectrum of strategic capacity planning considerations, this thesis focuses specifically on manufacturing footprint and develops a tool to help evaluate a firm's future needs in this regard.

Manufacturing footprint is defined as an overhead cost, and based on cost accounting principles, needs to be allocated to the cost of products. An overhead cost, by definition, is one which does not change from period to period or with a change in output. Examples of overhead cost include rent and insurance expenses for a facility. By extension, underutilized footprint can be deemed as having a negative impact on the cost structure of a firm's products. Therefore, careful planning is required to ensure facilities are well utilized, and especially so when planning for investment in new facilities, since the firm risks introducing long term costs into its cost structure.

This thesis is the result of a 6-month research internship at Boston Scientific (BSCI), as part of MIT's Leaders for Global Operations Program. It is the result of collaboration across a wide spectrum of the company's teams and functions and has helped the company further their strategic planning capability.

1.2. Problem Statement

Initial investigations into the planning process reveal that the topic of manufacturing footprint is a key agenda item for senior leadership within the company. This manifests itself in the significant amount of time senior leadership and the facilities group spends in the area of improving the utilization of space. Across multiple tiers of the organization, from the factory floor to corporate offices, meetings and reviews are dedicated to discussing the issue of space and how it can be better utilized. The primary reason for this focus is to ultimately keep overhead costs attributed to facilities under control.

Although this focus is positive, much of the activity can be classified as short term and localized in nature. Specifically, within manufacturing plants, individual factories within BSCI's internal manufacturing network actively pursue space improvements, and these activities in the many individual lines and value streams that make up the facility are aggregated to a facility level for reporting. However, there is currently no overarching strategic plan that drives what improvements should be made and what targets are required to meet the company's objectives. The factories are improving, but what strategic goal is driving their improvement?

Further assessment reveals that there is not currently a tool that allows for centralized/network level footprint scenario planning. A tool of this nature could be used to develop a strategic plan that drives specific targets for each of the factories in the network.

1.3. Thesis Goals, Contributions and Scope

Given the problem highlighted in the preceding section, we have sought to develop a tool that meets a few objectives. The tool should be able to:

- Forecast manufacturing footprint requirements at a value stream level based on a demand forecast
- Aggregate information up to a network level view
- Quickly allow for generation of scenarios to assist in building strategic plans
- Allow for specific improvement goals to be established once a strategic plan has been identified

In addition to these goals, it is also desired that the tool is developed in a program/format that is easily accessible to and useable by the BSCI Operations Strategy team and is scoped to include only internal BSCI manufacturing facilities.

1.4. Thesis Overview

This thesis is structured in 8 chapters, brief details of which are described here. In Chapter 1, we set out to introduce the work before delving into specifics of the company in Chapter 2 where we give the reader some background into the company, its history, organization, competitive landscape and rationale for requesting this work. In Chapter 3, we present the results of a literature review, with an aim of defining this works contribution to the field of operations strategy.

In chapter 4, we detail the methodology for development of the tool. Within this chapter, we introduce basic concepts relating to capacity and footprint as well as some company specific considerations. Following this, we discuss and present the core elements of the. In Chapter 5, we detail the results gathered from the tool, in addition to discussing validation of the tool. We discuss future work required to further develop the tool in Chapter 6 and conclude the thesis in Chapter 7.

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2. Company background and Problem Statement

2.1. Company Growth

BSCI are a developer, manufacturer and marketer of medical devices. The company was founded in 1979 [1], and over the course of 38 years has grown to become a $8bn revenue company. The company currently serves 24 million patients across 100 countries [1].

The company's products cover a range of medical specialties, and the company's organizational structure reflects these different markets. The company is composed of seven divisions, each responsible for the development and sales of a suite of products. Figure 2-1 details the divisions and broadly highlights the relative size of each with respect to company sales and market growth potential.

	IC	SH	PI	RM	NM	UroPH	Endo
'16 Revenue	$2.3B	$0.2B	$1.0B	$2.1B	$0.5B	$1.0B	$1.4B
'16* Market Size	$7.5B	$3.0B	$6.0B	$14.5B	$2.5B	$3.5B	$3.0B
'20* Market Size	$8.0B	$6.0B	$7.5B	$17.0B	$3.5B	$4.5B	$3.5B
'16-'20 Market CAGR**	0-2%	20%	6-8%		8-12%	5-6%	5-6%

* Estimate ** Compound Annual Growth Rate

Figure 2-1 - Divisions and Relative Size (Adapted from [2])

BSCI has ambitions to increase revenue growth over the next 3 years [2]. In addition to increasing revenue, it is also focused on re-balancing its product portfolio to ensure its revenue mix is balanced, with 25% of revenue coming from Low Growth markets, 25% from High growth markets and 50% from moderate growth markets [2]. This desire for growth is corroborated by the overall trends in the market as highlighted in the 2020 market size estimates in Figure 2-1. Most divisions are expecting moderate year on year revenue growth. The company expects a significant portion of this growth is expected to come from both organic growth and new revenue generating products, but historically the company has also grown through strategic acquisitions. Over the 5-year period between 2012 and 2017, the company spent $1.13B on 10 acquisitions [3].

Revenue growth continues to be a focus for the company as is keeping operating costs under control to improve operating margins. From [2], the company is looking to keep its gross margin percentage relatively flat, which means focus controlling costs will be paramount over the period. The overhead cost attributable to manufacturing footprint affects gross margin. This provides some rationale for the desire within the company to answer the following question: Will growth trigger an increase in footprint that affects the cost position of the company?

	BSCI [4]	Medtronic [5]	Abbott [6, 7]
Revenue FY 2016	$8,386 M	$ 28, 833 M	$2,896 M
Sq. Ft for Manufacturing & R&D	8.8 M	14 M	[not reported]
Number of Facilities	13	[not reported]	6
Facility locations	Puerto Rico, Costa Rica, Ireland, USA	China, Mexico, Puerto Rico, Ireland, Italy, Switzerland, Japan, Dominican Republic, Canada, USA	Costa Rica, Puerto Rico, Ireland, USA

Figure 2-2 - Competitor Comparison

From a competitive perspective, BSCI's main competitors are Medtronic and Abbott. Figure 2-2 summarizes available public footprint data for Abbott and Medtronic with direct comparison to BSCI. We don't have full information across all the companies but overall, the table gives us a sense of the number of facilities and geographic spread. From this, it is possible to deduce that operating in this industry requires significant investment in manufacturing footprint. By extension, firms that can minimize this footprint as the market grows will likely be in a better position to control costs and benefit from increased margins. This is corroborated in [8] & [9], where BSCI and Medtronic make reference to savings expected from plant network optimization and/or footprint optimization.

2.2. Company Structure

In this section, we define some key concepts and terms that will be used in the thesis. We also attempt to give the reader better understanding of the scope of operations at BSCI and an appreciation for product flow through the organization. These basics directly relate to understanding the workings of the footprint estimation tool that will be discussed in subsequent chapters.

Operations at BSCI encompasses all manufacturing related activity, whether internal or external. Also within the responsibility of Operations are the intermediary activities that enable a product to flow from raw material to the customer. From an organizational perspective, the Executive Vice President of Global Operations has multiple functions reporting to him. These include Purchasing, Supply Chain, Manufacturing and Quality.

Delving into the company's operations, products can be classified as either internally or externally manufactured. In the latter case, BSCI is branding, marketing and selling products manufactured by 3rd parties. In some cases, these products are internally developed by BSCI. In other cases, they are externally developed by BSCI's partners. BSCI's internal network includes the manufacturing and distribution facilities owned or operated by BSCI. The scope of this thesis is specifically the internal manufacturing network. In the context of this thesis, a network will be defined as the interconnected set of factories, sterilizers and distribution centers represented in

Figure 2-3 below.

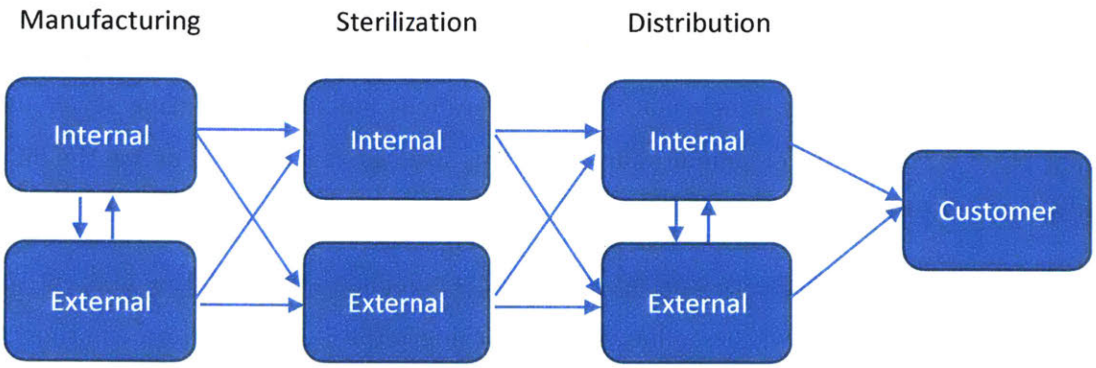


Figure 2-3 - Operations Network

Figure 2-3 generally represents the steps required for BSCI to get a product to market, with the only omission being Design and Process Development steps. In the design phase, teams of researchers, clinicians and engineers work to design products to meet specific clinical needs. These designs are then handed over to the Process Development organization that works to prepare the designs for handover to the manufacturing network, where raw materials are converted by various processes to physically manifest the designs as products. Following this, and given the importance of cleanliness for products used in medical applications, products are sterilized before onward distribution via a network of distribution and fulfillment centers across the world. The company sells products in approximately 100 countries.

In defining products as relates to this thesis, two key concepts will be introduced. Firstly, a finished product will be described as a Stock Keeping Unit (SKU). This represents a saleable product that will eventually be used by a medical professional on a patient, the ultimate customer. Secondly, the other broad category of products will be defined as intermediary products. For purpose of this thesis, this will include products that may be in a manufactured state, but are not saleable.

2.3. Strategic planning at BSC

Operations Strategy can be defined as 'the pattern of strategic decisions and actions which set the role , objectives and activities of operations' [10]. Generally speaking, some of the decisions made in the area of operations strategy include defining where to produce, what to produce and how to produce it.

In BSCI, the Operations Strategy team is responsible for development of the company's operations strategy. They are tasked with understanding the needs and constraints of the different divisions and functions and developing a strategic plan for the operations function. In thinking about the strategic planning process and the development of an operations strategy, it is useful to define the different time scales for planning decisions.

For the purpose of this thesis, long term goals will be defined as those falling in the 5-10 year time horizon. Medium term goals will be defined as those falling in the 3-5 year horizon and short term goals the 0-3 year horizon.

Given the company's goals regarding financial performance discussed in Section 2.1, strategic planning is an important factor in developing means to meet these goals. Strategic planning in this context can be defined as the process of gathering and analyzing internal and external data for the purposes of devising a strategic plan. Given the size and global nature of the organization, strategic planning involves multiple divisions, functions and regions. At a global level, each part of the organization has access to a variety of tools both unique and commonly available that help with the task of creating the company level strategic plan. In addition, there is also a structure by which information flows up to the executive levels of the organization where resource allocation decisions are signed off.

In linking to the company's broader strategic growth objectives, the operations strategy plays a key role when one considers the cost element of the strategy. Specifically, it looks to ensure that overhead costs do not grow uncontrollably with growth. To this end, a key driver of cost within operations is the cost attributed to overhead for facilities. This cost is driven largely by how many facilities the company has and by extension, how much manufacturing footprint there is in the network. The question of how much manufacturing footprint is required to adequately meet customer requirements over a given time period must be addressed by whatever strategic plan is devised by the team, and thus forms the rationale for a study on this topic.

2.4. Current State of Strategic Planning

In preparing this thesis, we collaborated with BSCI's operations strategy team. Through a variety of interviews with core team members and those that directly interface with the team, an assessment of current strategic planning tools and processes has been conducted.

BSCI is publicly listed on the New York Stock exchange, and as such has a natural cadence of reporting results on a quarterly basis. This in turn establishes an internal cadence for planning and reporting. At a higher level than the quarterly reporting sits the Annual Operating Plan (AOP). This is the budget for a fiscal year and can be considered more strategic than day to day plans, but not too strategic to be irrelevant. It is active in so far as budgets have been committed and personnel objectives are aligned to deliver the plan.

A step higher than the AOP is the 3-year strategic plan. It differs from the AOP in that budgets may not necessarily be committed, but there is strong alignment about what decisions will be prioritized. At this level, revenue forecasts are available, but the 'how' of translating revenue into units is being worked out. Beyond the 3-year strategic plan, longer term strategies exist and are primarily concerned with major strategic initiatives that are estimated to extend beyond the period of the three-year plan. This could include major restructuring programs or investments in new facilities or research and development. The operations strategy team is mainly concerned with items that fall in the 3-year plan window and longer.

We set out to evaluate the tools currently used for strategic planning. Our first finding is that whilst a previous project created a tool intended for the estimation of manufacturing footprint, the tool does not have sufficient granularity or the ability to run scenarios easily. Additionally, at a site level, factories are working on footprint reduction programs, but the tools used to estimate and plan these activities are locally owned and can't easily be aggregated to form a view of the network.

Second, we found that where tools do exist, they are often campaign-specific. They are created and /or maintained by a person (or function or team) to answer a specific question, and often might use a data source common to other team members that is modified for the specific exercise. Once the question has been answered or scenario evaluated, these one-off tools are typically retired, or retained by the creator.

An issue highlighted with campaign specific tools is that there is potential for over-proliferation of tools. This presents the risk that everyone is not using the same baseline data or assumptions. In addition, there is a real risk that access is lost when the owner is out of the office or leaves the company.

The third issue highlighted is in the area of scenario modelling. We have found that the tools that exist do not allow for quick manipulation of scenarios. Whilst these tools can offer unparalleled detail, there is often a sacrifice with respect to time required to create alternate scenarios.

The fourth issue is that the same baseline data is not often used for analyses. In some cases, this is warranted given unique nature of the analysis, however in most cases, the same core pieces of information such as annual sales quantity and product flow through the network are used regardless of the analysis. Not having a standard set of core data results in wasted time, due to duplicated effort, but also makes comparisons between analyses difficult.

Finally, we have identified deficiencies in the area of granularity. Granularity can be described in this context as the level of the decision unit in the overall product hierarchy. An example would be aggregation and use of data at a division level rather than at a product level. The product level data is described in this context as more granular. Granularity allows for more targeted prescriptions following data analysis. Some of the tools evaluated are not as granular as desired by the team, and this has traditionally meant suggestions can be too general to be acted on. In addition, the opposite problem is true, where some tools are very granular, which limits the ability to quickly generate scenarios or maintain the core data sets used to generate them.

It should be noted that progress has been made in regards to the problems highlighted above over the last few years. First, there is evidence that standardization of tools is being actively pursued, with the goal addressing the issue of campaign-specific tools and non-standard baseline data. Two recent projects have been focused on development of tools with more standardized approaches. The most recent was a network capacity model for manufacturing and distribution that acted as a foundation for the tool developed in this thesis. The team was able to develop a source for core data that has been used in this work and also introduce elements of estimating manufacturing footprint. Second, we have found there is now focus on developing a suite of tools that enable quicker initial analysis and scenario planning before more detailed studies are commissioned.

In summary, we have found that some of tools used in the current strategic planning process can be described as non-integrated, inflexible and lacking sufficient granularity. In addition, given the focus on manufacturing footprint, no means currently exists by which the company can evaluate and forecast manufacturing footprint in a fashion that overcomes the deficiencies noted. This presents the company with the problem of not being able to develop strategic plans that are reliant on manufacturing footprint as a key input.

2.5. Goals and Scope

In light of the problem statement, the goals of this thesis are to develop a tool to estimate the required manufacturing footprint in the long term and ensure it addresses some of the problems highlighted in preceding sections. A further goal is to evaluate the tool's ability to guide decision-making. In addition to the broader goals set out in Chapter 1, it is desired that the tool will have the:

- Ability to change where a product is manufactured
- Ability to modify growth rates by product, family, division or region
- Ability to introduce these changes at different points over the time horizon
- Ability to model acquisitions
- Ability to operate at a more granular level than is currently possible

The new tool is intended to improve the ability of the operations strategy team to more effectively formulate a strategic plan. Specifically, the team wants to be able to answer the question of how much manufacturing footprint will be needed at a future point in time as this relates directly to how much investment will or will not be needed in new manufacturing facilities. Knowing these answers will also help in estimating what the overhead costs attributed to footprint will be.

With respect to scope, this work is focused on strategic planning and long term decision-making. This defines to some extent what structure the tool should take. Specifically, we use aggregated data at the annual level, rather than attempting to conduct analysis on the basis of daily or weekly data. This decision results in potential loss of detail, however the time horizon over which we hope the tool will influence decisions is sufficiently long that temporal effects of using detailed data don't have as much of an impact, specifically when the additional effort required to gather and use the data is considered. In line with this, we also approach our analysis from a deterministic rather than stochastic perspective. Our primary reason for this is not being able to gather sufficient data to understand stochastic behavior of the inputs. The work also focuses specifically on the internal manufacturing footprint for a majority of BSCI's manufacturing sites.

3. Literature Review

3.1. BSCI Operations in Literature

BSCI has been a partner of the LGO program since 2014 and have sponsored 3 internships and theses. The work conducted for these theses has been wide ranging. In [11], The author worked within the Cardiac Rhythm Management division and developed a profit mapping tool to help the division assess and compare product profitability. This tool gave the division the ability to establish best practices in the sales process that would help drive revenue. In [12], the author developed a model to assess the potential opportunities that would arise from collaboration between the company and hospitals. The primary interaction within the company was within the supply chain and distribution functions. Finally, in [13] , the author focused on identifying methodologies by which an internal component manufacturing plant within BSCI could increase capacity utilization.

In assessing the work described above, each thesis gives a nuanced review of BSCI's operations. However, the disparate nature of functions, divisions and locations presented in the theses above suggest that the proposed goals of this work are unique in the context of the company. This is especially so given the wide range of topics. There is however some alignment between [13] and this work, since the author touches on capacity utilization and capacity planning. Additionally, the author works to develop a capacity planning tool to identify long-term capital requirements is aligned with this work, albeit at a factory-specific level. One can see the corollary between capital requirements and footprint, since the capital equipment needs footprint within the factory to enable production.

3.2. Broader themes in literature relevant to this case

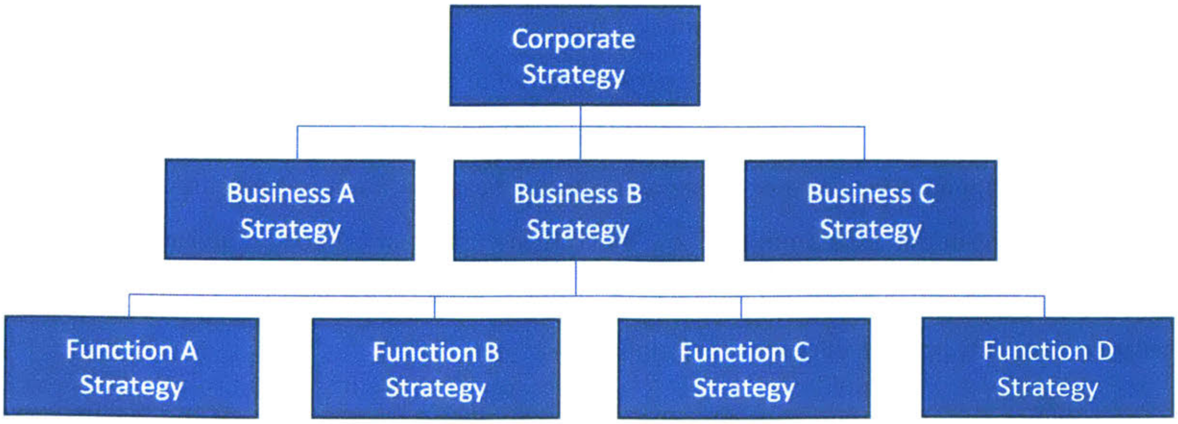


Figure 3-1 - Hierarchy of Strategy

A generally accepted hierarchy for strategy within organizations is presented in Figure 3-1 above. At the highest level, corporate strategy seeks to define the set of businesses a corporation should be in and how it wants to compete. This is then translated to strategies at both business and functional levels, with increasing detail at each level. Business strategy would be representative of the specific strategy for a business unit whilst functional strategy would be the responsibility of each of the main functions within an organization such as finance, engineering or sales. Operations strategy can be considered a functional strategy, and is primarily concerned with how the company combines its resources to serve its customers.

This works primary contribution is in the area of operations strategy. The body of research in operations strategy can trace its roots back to [14]. Within the literature there appears to be a generally acceptable demarcation between structural and infrastructural decisions that need to be addressed to formulate an operations strategy [15, 16, 17]. The general decisions that need to be made and their alignment to either the structural or infrastructural pillars are depicted below in Figure 3-2.

Structural	Capacity
	Facilities
	Technology
	Vertical Integration
Infrastructural	Workforce
	Quality
	Production planning
	Organization

Figure 3-2 - Decision Categories

This work is most closely aligned to the capacity and facilities sub-pillars. The capacity sub-pillar is concerned with questions regarding how much capacity is required, when it will be required and what type of capacity will be required. To answer the question of how much, organizations need to have a prediction regarding growth of the business as it relates to primary demand. This can then be translated into the most meaningful measure of capacity in the organization, be it output rate, physical space or otherwise. Inherent in this assessment of how much is the timing of capacity requirements. In order to fully answer the question of when, establishing the size of changes, the trigger mechanism for change and the relation to facility specific decisions is essential.

The facilities sub-pillar then considers the size, location and specialization of the facilities that are required. Under the topic of size, the company seeks to define the physical size and footprint of facilities.

This is directly related to the capacity considerations discussed earlier. Understanding size and timing of demand changes enables better planning for facility size. Within this sub-pillar, the decision of where to locate facilities is closely related to what should be made in each facility. Ultimately, the firm often seeks to optimize the cost to serve their customers, which is a balance between production costs and distribution costs. A summary of important considerations for each of these areas as described in [16] is presented in Figure 3-3 below. The primary focus of this work is the size element of the facilities sub-pillar.

Location factors	**Specialization factors**
Access to markets/distribution centers	Market focus
Access to suppliers and resources	Product focus
Community and government	Volume focus
Labor	Process focus
Taxes	Product/market focus
Transportation	Geographical focus
Utilities	

Figure 3-3 - Location and Specialization Factors

Within the literature, the facilities sub-pillar appears to be the most mature, at least from the perspective of the amount of research into tools aiming to assist with deciding optimal selections of size and location. Here, mathematical programming appears to be the most common approach. Within this field of research, there is evidence of development of these tools for strategic purposes, rather than just tactical decisions. In [18], the authors present a summary of work in this field as it relates to the strategic dimension. Specifically, it is noted that under the topic of capacity size decisions, the authors frame capacity size from the perspective of number of machines required [19] or throughput [20, 21].

In [16], the authors describes the use of critical ratios established from historic data to forecast physical space requirements. The ratios mentioned include square foot of floor space per employee, sales per employee and sales per square foot. The authors do not present a methodology or process by which this analysis can be conducted. However, the author in [22], presents an approach rooted in a similar methodology, with a model for forecasting footprint that is rooted in understanding square foot of floor space per employee. The author develops a tool to project manufacturing floor space requirements for a military electronics manufacturer that is founded on an algorithm. The algorithm that takes 6 inputs such as work force budgeted and planned straight time production and outputs floor space required in square feet. At its core, the approach is founded on having knowledge of manpower requirements. The author does not divulge specifics regarding the process of formulating and refining the model but it appears to be very specific to the industry and company.

Whilst these approaches can offer a means for quick estimation of physical space requirements, there is a risk within a firm where, even within the same facility, the unique attributes of each of the components produced in the facility mean that a blanket figure for sales per square foot can result in inaccuracies if the volume mix differs significantly from the base case/historic data. Additionally, the use of these measures can miss the important element of utilization. Specifically, use of floor space per employee results in floor space increasing where more employees are required, however it could omit the importance of being able to add people and not increase space by utilizing a second or third shift. Whilst a ratio could be corrected to include the notion of a shift-employee to ensure accuracy, this can become complicated and is also not intuitive.

A search within literature does reveal however that work exists in the development of tools and methodologies to establish physical space requirements for warehousing facilities. This is an area that can also be considered to fall within the reach of operations strategy. In [23], the author develops a forecast for capacity storage requirements based on a demand prediction in an Amazon Fulfillment Centre. In [24], the author develops a similar tool, albeit for a national defense contractor and with sensitivity and scenario analysis capability built into the tool. Finally, in [25], the author also is concerned with understanding how much warehouse space is needed at a Bio-Pharma manufacturer. Whilst warehouse footprint is his output, the work primarily revolves around the development of an inventory model to establish the storage requirements.

An evaluation of the literature leaves us to conclude that there is a gap in the literature as concerns the sizing decision, especially as pertains to understanding physical space requirements for manufacturing facilities. The lack of research in this area is the primary motivation for this work.

4. Methodology

4.1. Defining Capacity

The goal of this work is to develop a tool that outputs requirements for manufacturing footprint. It becomes evident however that this is closely linked with understanding the capacity requirements for a manufacturing operation. In this section, we define capacity and the related terms and concepts that will be used in this thesis.

Capacity utilization (C_a) in a manufacturing context can be defined as the ratio between the actual output of a manufacturing entity to the maximum that could be produced. This is represented in Equation 1. The actual output can also be called the demonstrated capacity. An alternate equation (C_b) is presented in Equation 2, where the denominator used is the effective capacity, otherwise known as the planned capacity.

$$Capacity\ Utilization, C_a = \frac{Actual\ Output}{Maximum\ Capacity}$$

Equation 1

$$Capacity\ Utilization, C_b = \frac{Actual\ Output}{Effective\ Capacity}$$

Equation 2

The concept of capacity utilization plays a central role in this thesis as it is the main criterion used to evaluate whether additional manufacturing footprint is required. The basic premise is that once a pre-defined capacity utilization threshold is crossed, there is need for additional footprint to enable demand to be met. The rationale behind this is that once a factory is 'full', or operating at the threshold, more capacity is required in order to meet additional demand. This additional capacity, be it more machines or people, needs to be housed within the factory, and as a result more space is required. In the following sections, the means by which the threshold is established and by which footprint grows will be discussed.

4.2. Manufacturing at BSCI

In section 2, we laid out some key requirements for the tool. One of the needs identified was for a tool that had sufficient granularity to enable actionable insight at a useful level within the manufacturing network. In this section, we describe the levels within the manufacturing network and also describe the structure and relationships between the data used to build the tool.

Figure 4-1 is a diagrammatic representation of the levels of the manufacturing network. It breaks down the BSC manufacturing network to its constituent elements.

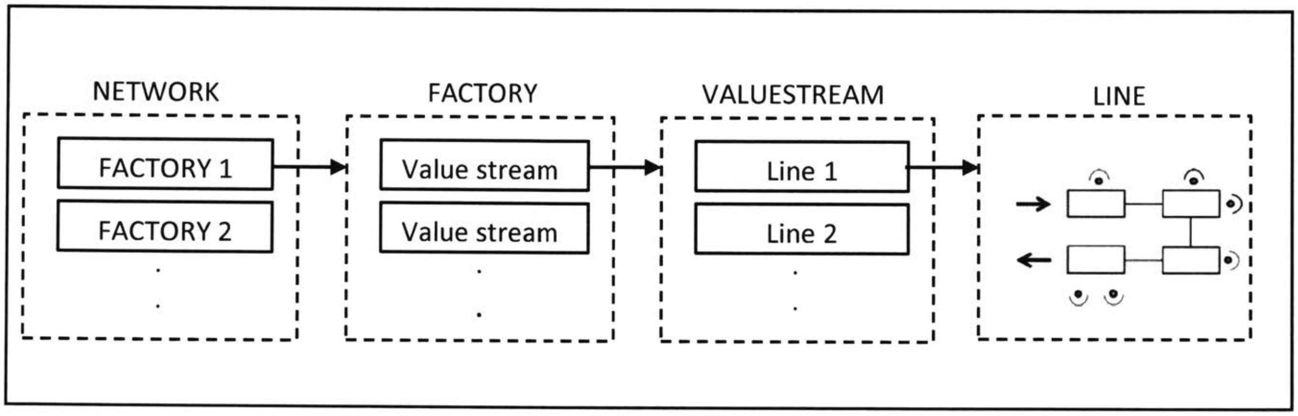


Figure 4-1 - Manufacturing Network Levels

As represented, the highest level is network itself. This level represents the collection of manufacturing plants within BSCI's internal manufacturing organization. At next level, we have the Factory level, which is an individual manufacturing facility making a variety of products. Below this level sits the value stream level. A value stream represents a collection of lines that are used to manufacture a family of products. Whilst the products might have different SKUs, they are similar in as far as underlying processes and technology used to make the product. An example would be different lengths of the same product, or slightly modified versions of the same fundamental design. Each factory is a collection of value streams. The last level that is represented is that of the line. A value stream is typically made up of multiple lines, each of which manufacture the same product, but are independent of the other lines as far as output is concerned. As an example, a value stream with two lines would have the ability to work one line, or both, depending on the required output/demand.

In discussing granularity of the tool, we could describe the tool as more granular as it traverses down the levels of the network described above, with a tool that allows output at line level being the most granular. At the facility level, analysis would simply aggregate number of products output at a facility and evaluate on this basis. This is the easiest option since current data is structured in this manner. The data in the company's Enterprise Resource Planning(ERP) system details what plant a SKU is manufactured in. The effect of a pooled view means that prescribing a targeted solution is difficult. Because of aggregation of multiple value streams, it is impossible to tell whether a specific value stream is an issue or not. Additionally, it is difficult to pass detailed insight to a plant. Rather than say, 'you have enough space', the team wants the ability to say 'you have enough space in aggregate, but you need to do work on value stream x, y and z'.

At the next level, or the value stream level, we would want to understand capacity and footprint requirements for each value stream. This would give the ability to offer detailed feedback, however a gap exists in that there is currently no link between a SKU and a specific value stream within the current data architecture of the ERP system. For the line level, we would be looking to identify capacity and footprint requirements for each piece of equipment, and detailing the interactions of personnel with the machines to manufacture products. At this level, information would be extremely detailed, with potential to offer machine specific feedback and potentially introduce concepts such as bottleneck identification, however the downside is that it would require significant amounts of time to collect data at this level across the whole network. Given the limited time period of this engagement, we have chosen to extend our analysis to the value stream level. In order to combat the issue of no linkage between the SKU and value stream, preparatory work for creation of the new tool has included creation of a survey that formed the basis of a database to enable linkage between an SKU and a value stream.

One detailed element that was captured however was that of sub-assemblies. The complexity of BSC's products means that often they are made up of sub-assemblies. Figure 4-2 illustrates an example of a sample Bill of Material (BoM) that would represent a top level assembly (SKU) and the relationship between it and its sub-components.

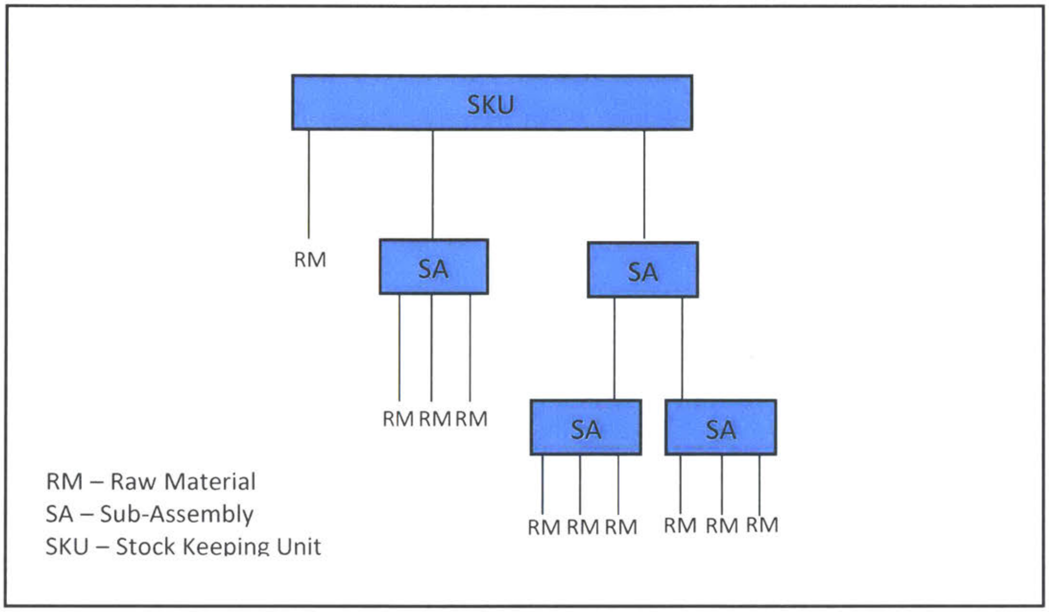


Figure 4-2 - Bill of Material example

In some cases, the sub-components that make up a SKU are raw material inputs, and in others they are sub-assemblies that have been processed and assembled from a different selection of sub-components. It is important to note that some BSC manufacturing facilities are in the business of manufacturing these sub-assemblies both for use in SKUs that are manufactured in the plant, and in some cases that are sent to other plants for further processing and assembly into SKUs. The distinction is important because manufacture of sub-assemblies constitutes a large amount of activity within certain plants and their omission from the analysis would mean a significant proportion of manufacturing footprint is not captured. To that end, the survey used to link SKUs to specific value streams also gathered information detailing relationships between top-assemblies and sub-assemblies. Details on the use of this information to evaluate space requirements at the sub-assembly level are detailed in subsequent sections.

4.3. Integrated planning tool

In order to achieve some of the objectives set out in the goals section of this thesis, such as the ability to run scenarios and operate from a single data source, a broader tool was developed. The tool in question is referred to as the scenario modeler. In this section, we will briefly discuss the workings of the scenario modeler at a high level, with a focus on defining inputs and key terminology before proceeding to a more in-depth analysis of the manufacturing tool in the next section. The stylized architecture of the integrated planning tool, and its relationship to the manufacturing specific model is represented in Figure 4-3 below.

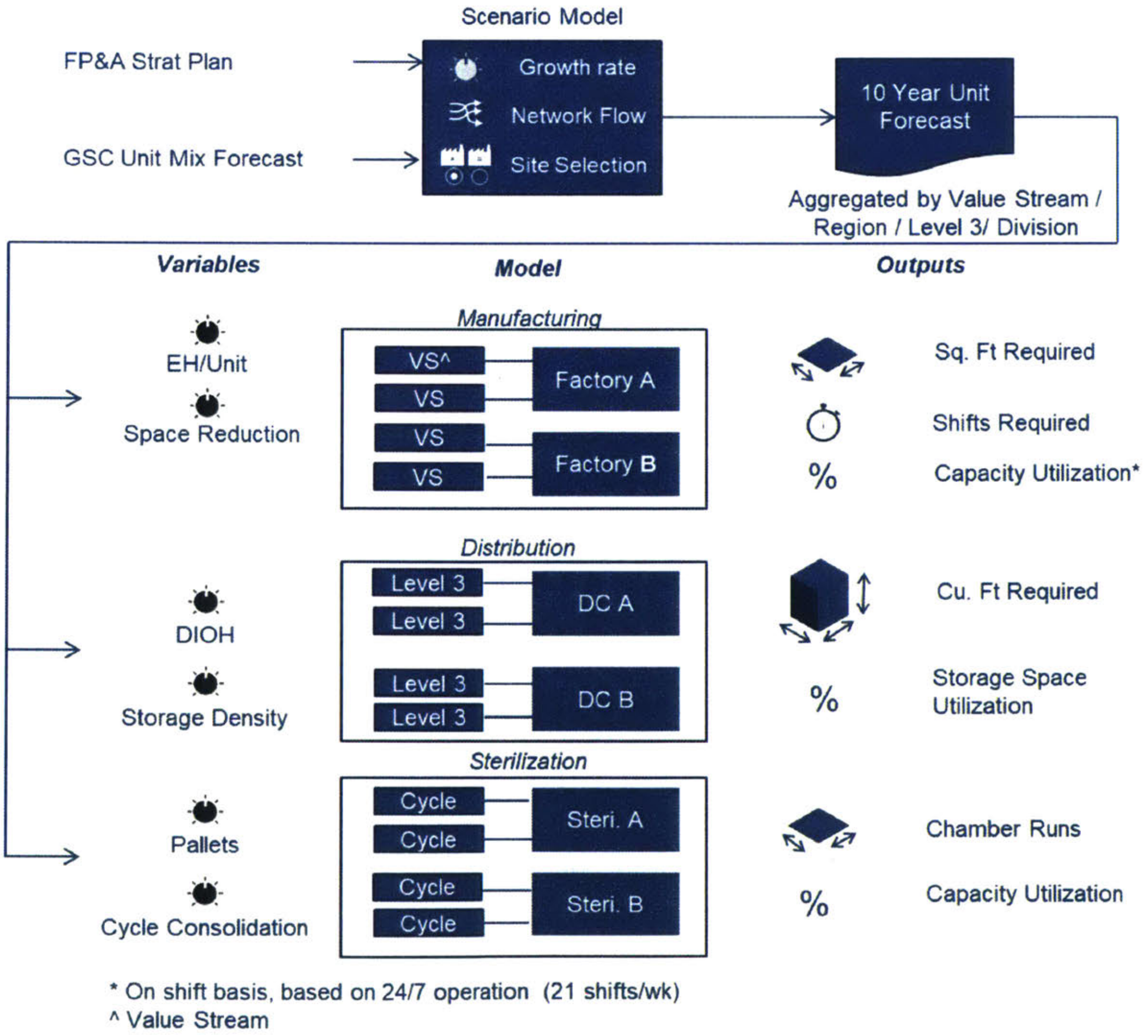


Figure 4-3 - Integrated Planning Tool

Figure 4-3 is a high-level overview of the flow of information between different sections of the overall integrated planning tool that is envisioned by BSC. The tool can be split into two main sections, the first being the scenario modeler and the second a detailed model section, which includes both manufacturing-, distribution- and sterilization- specific models.

The scenario modeler is a standalone workbook that takes a range of primary inputs, enables generation of various growth and product flow scenarios and outputs annual volumes for further analysis in the manufacturing and distribution models.

The key inputs to the scenario modeler are a unit-mix forecast and a growth rate forecast. The unit mix forecast contains a range of information for each SKU-Destination combination. Because the same product can be sold in various locations, the report has been structured this way to give as much possible detail. The key piece of information associated with each SKU-Destination combination is the forecasted sales volume for the next year, which represents the quantity of the SKU that will be sold in the given destination. It is important to note at this point that whilst it is forecast information, it is supplied from the supply chain function and represents their best/most accurate current estimate given the yearly planning cycle. At a detail level, production plans and commitments will be set on a weekly to monthly basis, but this represents the closest the company has to a yearly figure. The SKU-Destination information is aggregated to the value stream level to keep the data tidy and manageable. The downside to aggregating is that we lose ability to drill down, but we benefit by being able to work 3,000 rows vs 60,000 rows. Overall, the aggregation does not represent a significant loss in detail because the value stream is a good aggregator given the products manufactured in a value stream are similar from a manufacturing process and flow perspective.

Another key piece of information included in the unit-mix forecast is that detailing the flow of the product from source to destination. This includes information regarding which factory the product originated from, what selling distribution center will finally issue the SKU to the customer and which intermediary Tier 1 and Regional Tier 1 Distribution Centers (DCs) the product will flow through. In addition to this, the information from the manufacturing survey mentioned in Section 4.2 is appended to provide a link between the SKU and a specific value stream.

The last key piece of information is obtained from the Financial Planning and Analysis (FP&A) group, and contains revenue forecast information for different regions and product franchises as defined by the FP&A group. The data is represented on Figure 4-3 as the FP&A Strat Plan. Strat Plan is an abbreviation for the strategic plan. Because of differences in nomenclature that exist between different hierarchical product descriptors used by different functions, each SKU is linked to a FP&A growth franchise.

The growth rate forecast includes a 3-year revenue forecast by FP&A franchise and region. In addition, the department supplies information on Average Selling Price to allow for translation of the revenue growth into unit growth.

Both these files are inputted into the scenario modeler. It takes the baseline data from the unit mix file and applies growth rates that have been calculated from the growth rate forecast. Within this, functionality exists that allows user to create a range of scenarios. Specifically, there is functionality to modify the manufacturing location and product flow through the network over user defined time horizons. On the forecast side, there is an option to define specific/custom growth rates for each row of data. This enables customization of growth rates at a value stream level if so desired. It is entirely plausible that the products from one value stream end up routed through different distribution centers (hence will have a different flow), or end up sold in different regions (hence have different growth rate (because they are regionalized).

The output of these changes/inputs is then converted to give an output for manufacturing that is units per year per value stream. For Distribution, we are primarily concerned with the units that will flow through the main two DC's, although functionality exists to output data for each DC in the network. Specifically, the output in this case is units per year, but for DC, we are concerned primarily with this data for Hierarchy Level 3 parts rather than value stream, as Level 3's are assumed to be similar enough to have generic box sizes. In fact, an option exists for the user to output annual cubic foot requirements per Level 3. Level 3 is a term used to describe the product hierarchy from Level 6, which is the SKU, up to Level 1 which represents the division. It is a classification system used by the ERP system.

At this point it is important to note that changes the user makes in any of the modifiable fields are reflected directly in the outputs. This is achieved by use of formulas to manage the calculations. An alternative could have been the use of programming to achieve the same result, however a 'hard code' approach was chosen because of the direct feedback available, something that was identified as critical in the feedback. Additionally, there was a concern that a programming approach would put the tool out of use of most users. This hard code approach was used at the expense of an increase in file size, however the sheet was optimized to ensure the size did not affect performance.

As mentioned, the output of the scenario modeler is fed into either a manufacturing model or a distribution model. Both are described briefly below.

The manufacturing model is primarily developed to take a unit forecast and convert this to a footprint requirement. To do this, a baseline for how much space was currently being used within a value stream as well as overall performance was established via a survey of the facilities. The new unit growth is then compared against this baseline and a resulting space required metric is outputted on the basis of calculations that attempt to model the relationship between units and the need for footprint.

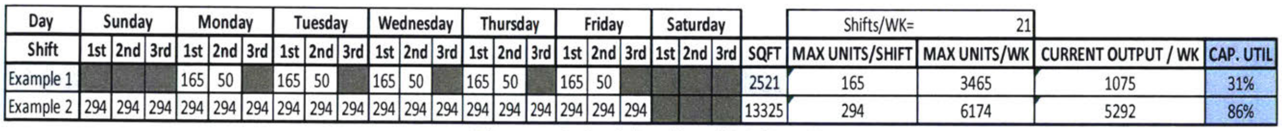
The distribution model takes the forecast of cubic volume for the annual units, and combined with data on storage utilization, days of inventory on hand (DIOH) and distribution center specific storage allocation, evaluates whether there is sufficient storage space for the volume.

Further sections of this thesis will expand on the development and evaluation of the manufacturing model. As mentioned in the literature review, previous work exists on modeling of warehouse space, but to the author's knowledge, this has not been conducted in the area of manufacturing footprint.

4.4. Manufacturing Model

The manufacturing model was briefly described in the section above. However, this section is intended to give a more thorough introduction to estimating footprint as relates to BSCIs manufacturing facilities, and the decisions that need to be made with regards to estimating footprint and how it grows (or shrinks) with associated changes in demand.

As described in the preceding section, the model's basic function is to evaluate how much footprint is required for a given level of output. A central concept in achieving this is capacity utilization as defined in Section 4.1. At 100% utilization (or at some other defined threshold), we can consider that a value stream is full, that is, no more output can be obtained with the resources that it has available. At this point, more resources would be required, and the rationale is that more space would be required to house the additional resources. It is from this logic that we use the capacity utilization as the means of triggering additional space. In expanding on this topic, it is important to specify how we calculate the capacity utilization for a given value stream. Figure 4-4 below represents two idealized value streams.



Day	Sunday			Monday			Tuesday			Wednesday			Thursday			Friday			Saturday				Shifts/WK=	21		
Shift	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	SQFT	MAX UNITS/SHIFT	MAX UNITS/WK	CURRENT OUTPUT / WK	CAP. UTIL
Example 1				165	50		165	50		165	50		165	50		165	50					2521	165	3465	1075	31%
Example 2	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294				13325	294	6174	5292	86%

Figure 4-4 - Idealized Value Streams

The figure represents the output of two idealized value streams for a week. Each day is split into three idealized 8 hour shifts, representing a total of 21 shifts over the week. In addition, the footprint occupied by the value stream, in square feet, is represented in the SQFT column. To the right of this are a variety of calculations that lead up to the final calculation of capacity utilization in the CAP. UTIL column. Focusing on the first portion of the figure, we can see that there are values filled in for each of the value streams on different days and shifts. For the Example 1 value stream, it appears that the line is running two shifts, 5 days a week, with a reduced output on the second shift. This is typical of many value streams where output in the second shift is tempered by having fewer people and lines running. The numbers represent the number of units output during the shift, that is 165 products are completed during first shift and 50 units are completed during second shift. A similar logic can be followed for the Example 2 value stream. In previous sections, mention has been made of a manufacturing survey being populated by all the sites. The survey includes collection of the data that would enable us to fill in similar information for all the value streams included in the study. Each value stream presents us with weekly output data (on a shift by shift basis) and square footage occupied. This enables us to establish a baseline.

In progressing towards a calculation for capacity utilization, we can now define some additional terms. The first is Maximum Units per Shift. This represents for a given value stream the maximum number of units that can be produced on a fully staffed shift. The information received from the facilities was aggregated/average data, that is, it was a best approximation of what they output on a weekly basis to get to their annual volumes. An alternative would have been to ask for exact output data by week for all weeks in a given year and for all value streams, however this was deemed to be too burdensome a task given the desire to capture information for most of the company's manufacturing network in a short timescale and difficulty in being able to efficiently extract the information from the information management system. These challenges are discussed further in Section 6.

Given the nature of information received, as an approximation, the maximum units per shift for a given value stream was evaluated on the basis of Equation 3 below.

$$Max\ units/shift = \max_{shift=1:21} Shift\ Output$$

Equation 3

Part of the rationale behind the approximation was that, especially in the case where multiple shifts are run, it made no sense to run a partial second shift if one could complete the output all in the first shift. We have also corroborated this through interviews with plants and confirmed many value streams are typically running full shifts on their first shift and reduced shifts on subsequent shifts. This maximum output per shift is then used to compute the theoretical maximum output per week for a given value stream, which is calculated in Equation 4 as

$$Max\ units/wk = MaxUnits/shift \times Shifts/wk$$

Equation 4

We can consider this the denominator for our Capacity Utilization calculation presented in Equation 6. For the numerator, we would simply sum the current output across all shifts, to give us the current output per week. This is presented in Equation 5 below.

$$Current\ Output/wk = \sum_{Shift=1}^{21} Shift\ Output$$

Equation 5

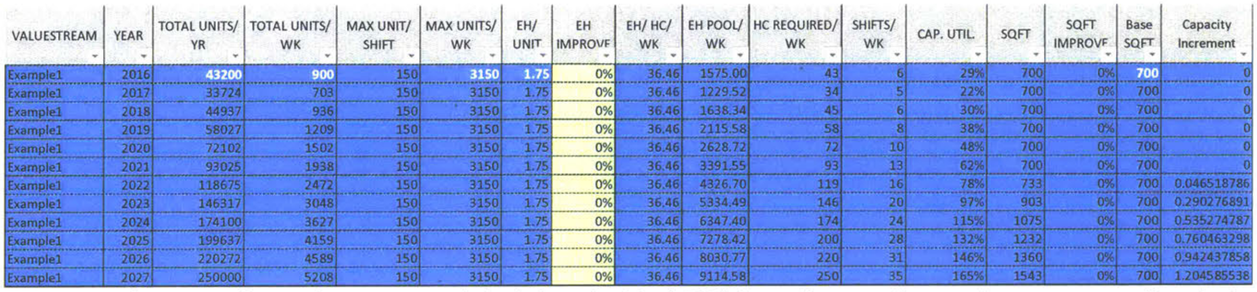
Given the above, our capacity utilization can be expressed with the following formula presented in Equation 6 below.

$$Cap.\ Util = \frac{Current\ Output/wk}{Max\ Units/wk}$$

Equation 6

In calculating the above capacity utilization, we are making the assumption that a 21 shift operation is how we choose to measure our potential capacity. This is a somewhat controversial assumption given many value streams do not work 3 shifts on any given day, so they could see this as having the effect of making their capacity utilization appear to be extremely low. This is a valid concern; however, we have chosen this denominator because our primary concern is when more space will be required. We could equally use the term theoretical capacity utilization. To that end, we make the assumption that a value stream that faces increased demand will fill shifts first, until they have a full 3rd shift, before adding space. This is under the assumption that no additional equipment is required to add a shift. Because of this mechanism for adding capacity, we want our capacity utilization figure to tell us when a value stream has filled all available time and thus truly requires more space. We will call this value of capacity utilization where more space is required the capacity utilization threshold. In the basic iteration of the model, any increase in capacity utilization above the threshold results in an equivalent increase in footprint required. That is to say, if Capacity Utilization is 1% above the threshold, 1% more space is required. This modelling decision is discussed further in chapter 5.

One could assume that a threshold of 100% would be ideal to establish when space is triggered, however we must consider that in any manufacturing setting, there are essential non-productive tasks that must take place, and effectively reduce the capacity of the line. An example of such a task is maintenance. Given these tasks, a capacity utilization threshold of less than 100% is a more realistic option, however one could start to debate what value is correct? The additional tasks could include yield losses, planned or unplanned machine downtime and human factors constraints. Depending on the value stream, country and operating policy at a specific plant, this figure for each facility could be very different.



VALUESTREAM	YEAR	TOTAL UNITS/ YR	TOTAL UNITS/ WK	MAX UNIT/ SHIFT	MAX UNITS/ WK	EH/ UNIT	EH IMPROVF	EH/ HC/ WK	EH POOL/ WK	HC REQUIRED/ WK	SHIFTS/ WK	CAP. UTIL.	SQFT	SQFT IMPROVF	Base SQFT	Capacity Increment
Example1	2016	43200	900	150	3150	1.75	0%	36.46	1575.00	43	6	29%	700	0%	700	0
Example1	2017	33724	703	150	3150	1.75	0%	36.46	1229.52	34	5	22%	700	0%	700	0
Example1	2018	44937	936	150	3150	1.75	0%	36.46	1638.34	45	6	30%	700	0%	700	0
Example1	2019	58027	1209	150	3150	1.75	0%	36.46	2115.58	58	8	38%	700	0%	700	0
Example1	2020	72102	1502	150	3150	1.75	0%	36.46	2628.72	72	10	48%	700	0%	700	0
Example1	2021	93025	1938	150	3150	1.75	0%	36.46	3391.55	93	13	62%	700	0%	700	0
Example1	2022	118675	2472	150	3150	1.75	0%	36.46	4326.70	119	16	78%	733	0%	700	0.046518786
Example1	2023	146317	3048	150	3150	1.75	0%	36.46	5334.49	146	20	97%	903	0%	700	0.290276891
Example1	2024	174100	3627	150	3150	1.75	0%	36.46	6347.40	174	24	115%	1075	0%	700	0.535274787
Example1	2025	199637	4159	150	3150	1.75	0%	36.46	7278.42	200	28	132%	1232	0%	700	0.760463298
Example1	2026	220272	4589	150	3150	1.75	0%	36.46	8030.77	220	31	146%	1360	0%	700	0.942437858
Example1	2027	250000	5208	150	3150	1.75	0%	36.46	9114.58	250	35	165%	1543	0%	700	1.204585538

As a general approach, we have set a global threshold of 75% based on an internal company policy, but made sure this parameter can be set individually for each value stream to allow for tuning of the parameter at a later stage.

Figure 4-5 - Manufacturing Model

Now that we have covered the basics of the model, we can present the tool in full. Figure 4-5 above shows the manufacturing model as implemented. When it comes to general structure, each row represents a different year. Additionally, the first row for each value stream contains baseline data. This was mostly collected from the manufacturing survey mentioned in earlier sections. There are some terms however that have not yet been introduced and a general description of what is contained in each column follows.

Value Stream – This is the name of the value stream

Year – This is the year. We are interested in evaluating this over the long term, hence the 10-year period. The reason we have 11 rows is because the first row is baseline data.

Total Units/yr – This is the annual demand for a given value stream in a given year. For the baseline year, this is simply the output stated in the manufacturing survey. For subsequent years, the data is calculated in the scenario modeler as described in section 4.3.

Total Units/wk – This is the Total units/yr divided by the number of weeks in a year

Max Units / Shift – This is calculated as detailed in Equation 3

Max Units / Wk – This is calculated as detailed in Equation 4

EH/Unit – Earned Hours (EH) is the labor content required, in hours, to complete the manufacture of a given SKU.

EH Improve – This represents the percentage improvement in EH/unit from one year to the next. This is a corollary to productivity improvement and can be specified by the user.

EH/HC/WK – This represents the number of standard/productive hours one employee can generate in a week.

EH Pool/Wk – This is a product of the Total units/wk and the EH/unit. It represents the amount of labor hours that would be required to output the quantity of parts required.

HC Require/Wk – This is simply the EH Pool/wk divided by the EH/HC/WK to give a sense of how many people would be required in a given week

Shifts /Wk – This is the Total Units/Wk divided by the Max Units/Shift. It gives us a sense of how many full shifts of work would be required to output required volume

Capacity Utilization – This is calculated as detailed in equation 6

SQFT – This represents our key output of manufacturing footprint. It is the square footage required for a given demand level for a given value stream.

SQFT Improve – Similar to EH Improve, teams consistently look at ways to reduce the footprint of given value streams and this represents the percentage reduction in space year on year. This can be specified by the user; however, functionality also exists to solve for an improvement rate on the basis of maintaining the footprint from the baseline. This is useful as it allows for useful feedback to the plants to give them an idea of how much improvement they should be making to ensure they don't generate the need for additional space. From a variety of discussions, it is interesting to find that on a day-to day basis in the plants, space improvement activities can be thought of as independent to productivity improvements. The sites are often driving to reduce footprint, even when not linked to a productivity improvement activity. As a result, the two variables have been modelled separately.

Capacity Increment – This represents how much the capacity utilization is over the threshold of 75%. This information is used to help in determining the amount of additional space.

At this point two additional parameters should be introduced, namely the space scale and the improvement tradeoff ratio. To begin with the improvement tradeoff ratio, this effectively determines, whether an improvement in EH/unit (EH improve) drives more output with the same number of people, or the same output with less people. As a default this is set to 70/30, in favor of output. This figure has been agreed on following discussions with staff at the factories and represents their perception of how they currently use gains from improvement. The space scale is effectively a means of damping how much extra space is needed when the capacity threshold is triggered. In an example where space scale is zero, being 100% above the capacity threshold drives a requirement for 100% additional space. However, in the same example, if a space scale of 0.25 is selected, being 100% above the capacity threshold drives a requirement for 75% more Square footage. This factor was added to try and allow for further adjustments to the mechanism by which the requirement for footprint grows. It is rare that a doubling of output requires double the machinery and the space scale helps us capture this consideration.

4.4.1. Dealing with sub-assemblies

In section 4.2, we introduced the concept of a sub-assembly. In this subsection, we aim to give the reader insight into how these have been modeled. It is important to note that some facilities in the BSCI network are specifically set up to manufacture sub-assemblies. In some cases, the sub-assembly output accounts for upwards of 50% of all manufacturing activity. Initially, it had been suggested that sub-assemblies could be left out of scope, but given their importance at specific facilities, it would have resulted in a large omission of productive manufacturing footprint from the model. In discussing sub-assemblies, it should be noted that they can be manufactured and used in a variety of settings that the model would need to capture. Firstly, a sub-assembly value stream can make sub-assemblies for use in a top-assembly manufactured within the same plant. Alternatively, a sub-assembly value stream can manufacture product that is consumed by a different plant in the BSC network.

The main challenge with introducing sub-assemblies into the model is a result of not being able to easily link between a top-assembly and a sub-assembly. Whilst BoM databases exist, the data structure and formatting does not allow for the linkages to be made. The databases were simply not designed with this use case in mind. Attempting to fix the databases and devising a novel extraction is an option however it is a very time consuming activity. As an alternative, the manufacturing survey used to gather a variety of baseline information is a quick way of establishing relationships.

It should be made clear that another challenge with sub-assembly value streams is that they often have differing units of output. One would reasonably expect the output of an extrusion line to be measured in feet, whilst a machining value stream would likely output in pieces. In making the decision to not use the BoM, we introduce the challenge of not being able to ascertain exact units and quantities. To combat this, we take a general approach as is outlined below.

Top Assy Value Stream	Annual Volume	Sub-Assy1	Sub-Assy2	Sub-Assy3	Sub-Assy4
TopAssy1	100	1		1	
TopAssy2	50		1		
TopAssy3	200	1	1		1

Figure 4-6 - Top Assembly/ Sub Assembly Relationship

First, we establish the linkage between a sub-assembly and a top-assembly. In establishing this relationship, we are identifying the demand drivers for a given sub-assembly value stream. Figure 4-6 above represents a survey response that is used to establish the relationship between a top-assembly and a sub-assembly. As an illustration, it can be seen that sub assembly value stream Sub-Assy1 supplies the top assembly value streams TopAssy1 and TopAssy3. The ultimate goal is to establish a growth rate for the sub-assembly that is linked to the growth rate of the top assembly as this will help us understand volume growth of the sub-assembly value stream in absence of more detailed BoM data. We compute a weighted average growth rate for the sub-assembly area on the basis of top-assembly volume. Whilst this approach allows for relatively quick linkage, we inherently assume that mix of the top-level assemblies remains constant in future years, which could potentially affect the result were the mix to change.

4.5. Summary

Over the preceding sections, we have given the reader insight into the methodology used and presented the manufacturing model. The model allows the user to evaluate what manufacturing footprint is required for a given output. It takes the output from the scenario modeler, which gives us annual output per value stream for a period of 10 years, and outputs the annual footprint requirements for each value stream over the time period. In its final state, the model computes this for upwards of 70 value streams. This is a significant improvement given that no tool currently exists for this type of analysis. A feature that is specifically useful is the ability to modify improvement rates, as this gives managers an ability to model and think of different scenarios as they establish targets for different areas. In the following chapter, some sample results from modelling activities will be presented. We will also discuss the modelling decisions made in more detail as it relates to potential accuracy of the tool. This should give the reader an appreciation of the potential pitfalls of the decisions made and insight to potential improvements that could be made in further iterations of the model.

5. Results and Discussion

In the following chapter we present results from modelling conducted with the tool. In the first sub-section, we will introduce the reader to the main results and output of the model before discussing secondary results and insights in the second sub-section. We conclude in the third sub-section with a discussion on key managerial insights.

5.1. Main Results

The model described in Chapter 4 has been populated with data for approximately 80 Top Assembly value streams and approximately 50 associated Sub Assembly value streams. The data has been modified to maintain confidentiality. The baseline data for each value stream is generated from the manufacturing survey sent to all plants. Before running any scenarios, a baseline case is developed and modelled. This scenario involves no network changes and uses default growth rates. In addition, the manufacturing model is set to default values for variables and parameters as set forth in Chapter 4. The output is Sq. Ft. Required per annum and development of this baseline allows for direct comparison to scenarios where changes are made.

The first scenario involves maintaining network flow and growth rate as in the base case, but feature modifications to the Sq. Ft. Improvement variable. In the second scenario, rather than modifying the Sq. Ft. Improvement variable, we modify the EH/Unit Improvement variable, and subsequently in the third scenario we combine both improvements. Improvement values of 2% and 5% respectively are selected for illustrative purposes. Figure 5-1 below, though disguised, is an example of the graphical output generated following the modelling activity. In each case, we compare 2017 Sq. Ft Required (the first series) to 2027 Sq. Ft. Required. On the x-axis, we display the various factories. The data for each factory is a summation of value streams assigned to that factory. On the y-axis, we display the Sq. Ft Required. Since the goal of the model is to establish whether there will be enough space in the network, the black line represents the total amount of space available in a given facility. Breaching this line is a flag that a facility will not have enough space to meet demand.

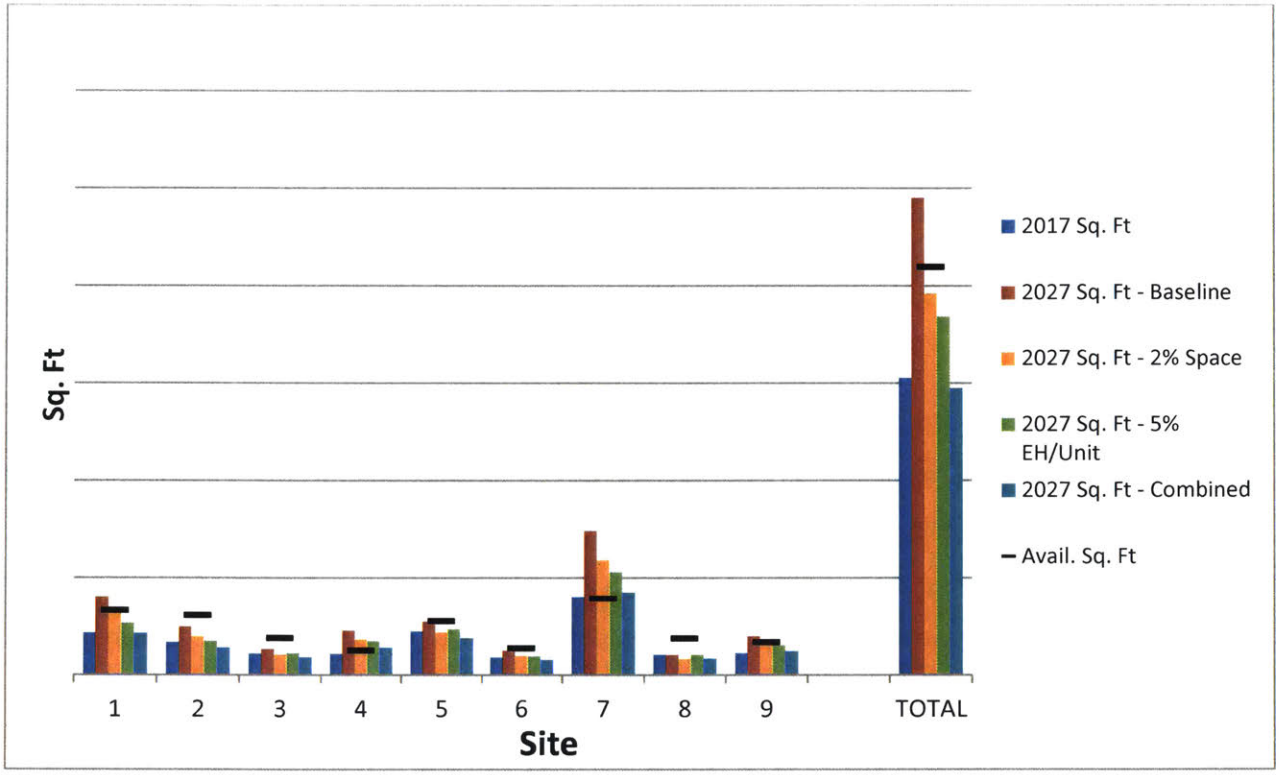


Figure 5-1 - Sample model Output

Overall, we can see that whilst most factories appear to have sufficient space to cover the projected 2027 demand, factories 1, 4, 7 and 9 will require additional space under the base case (second series). When we introduce a year on year(YoY) Sq. Ft. Improvement of 2%, only factories 4 and 7 require additional space. In a similar fashion, introduction of a YoY EH/Unit Improvement of 5% results in factories 4 and 7 requiring additional space. As modelled, the two variables discussed are independent, and a combined improvement, as presented in the 5th series, results in further reduced requirements for footprint across the network, with factories 4 and 7 still requiring additional space.

It should be noted that for the case of the Sq. Ft. Improvement, EH/Unit Improvement and combined improvement, the network appears to have sufficient footprint at an aggregate level. This could potentially prompt discussions regarding moving value streams to ensure no additional factory space is built at factories 4 and 7. The results presented are representative of the main output of the tool, and serve to illustrate the main capability of the tool. These scenarios also demonstrate the ability to model improvements and gives leadership a means to think about the strategic goals factories should be driving towards in a way that is currently not possible.

5.2. Additional Results and Insights

In addition to the results presented above, there were other criteria identified during early stages of the work that the operations strategy team considered essential. Specifically, they identified the need for the tool to be flexible, in so far as having the ability to model a variety of scenarios, and granular enough to derive actionable insight. The outcomes of this work with regards to meeting these criteria are discussed below. In addition, we have conducted sensitivity analysis on the tool and also discuss the effect of certain modelling decisions that have been made.

5.2.1. Flexibility

The discussion in the previous section gives the reader basic insight into the tool's usefulness. However, as discussed earlier, another goal of the tool is that it be flexible enough to support a wide range of scenarios in a timely manner. In addition to the Sq. Ft. and EH/Unit Improvement variables presented in the results above, there are numerous variables that can be modified to give the operations strategy team the ability to model a wide range of scenarios. For some of these, changes can be made in the scenario modeler and for others, changes can be made in the manufacturing model. In the following sub-sections, we discuss the ability to introduce custom growth-rates, modify location and introduce new products or acquisitions.

5.2.1.1. Custom growth rates

For the scenarios presented above, the growth rates used were based on default values calculated via a growth formula agreed upon within the operations strategy team. Whilst this can serve as a baseline for other comparisons, the scenario modeler allows the user to input custom growth rates to enable scenario planning. Specifically, the user can manually enter specific growth rates by FP&A franchise by region by year or create new franchises or define new regions and requisite growth rates for even more flexibility. Ultimately, this flexibility allows for potential modelling of scenarios such as:

- High/Low growth in a specific region
- High/Low growth in a specific division
- High/Low growth of a specific product

5.2.1.2. Location

In the baseline analysis presented above, location of the value streams was assumed constant. The scenario modeler allows for the movement of manufacturing location for each value stream over the time horizon. Specifically, the user is able to model scenarios such as:

- Full move of a value stream from one factory to another at a given time
- Move of a subset of products from one value stream/factory to another at a given time

5.2.1.3. New Products/ Acquisitions

Whilst the baseline information presented above was based on the current product portfolio, it is possible to model the introduction of new products due to research and development or acquisition. This is particularly important given the discussion in section 2 regarding the number of acquisitions in the industry. Acquisitions of companies with physical space is almost expected, and being able to model this gives the team a better picture of the impact of on the overall network.

5.2.2. Granularity

A key criterion established for the tool in early stages of development was for increased granularity. As mentioned, the most recently available tool only offered detail at the factory level. The new tool gives the ability for the operations strategy team to conduct their analysis at the value stream level. The power of this is evident when one considers the result presented above. Whilst the information is aggregated at the factory level, the team have the ability to go one layer deeper and offer identify specific value streams within factories that are causes for concern. This also allows for improvement factors to be established at the value stream level, which allows for targeted feedback to facilities.

5.2.3. Sensitivity

In addition to the scenarios, we pay particular interest in trying to understand the sensitivity of total network Sq. Ft. Required to Sq. Ft. Improvement and EH/Unit Improvement. The results are presented in Figure 5-2 below.

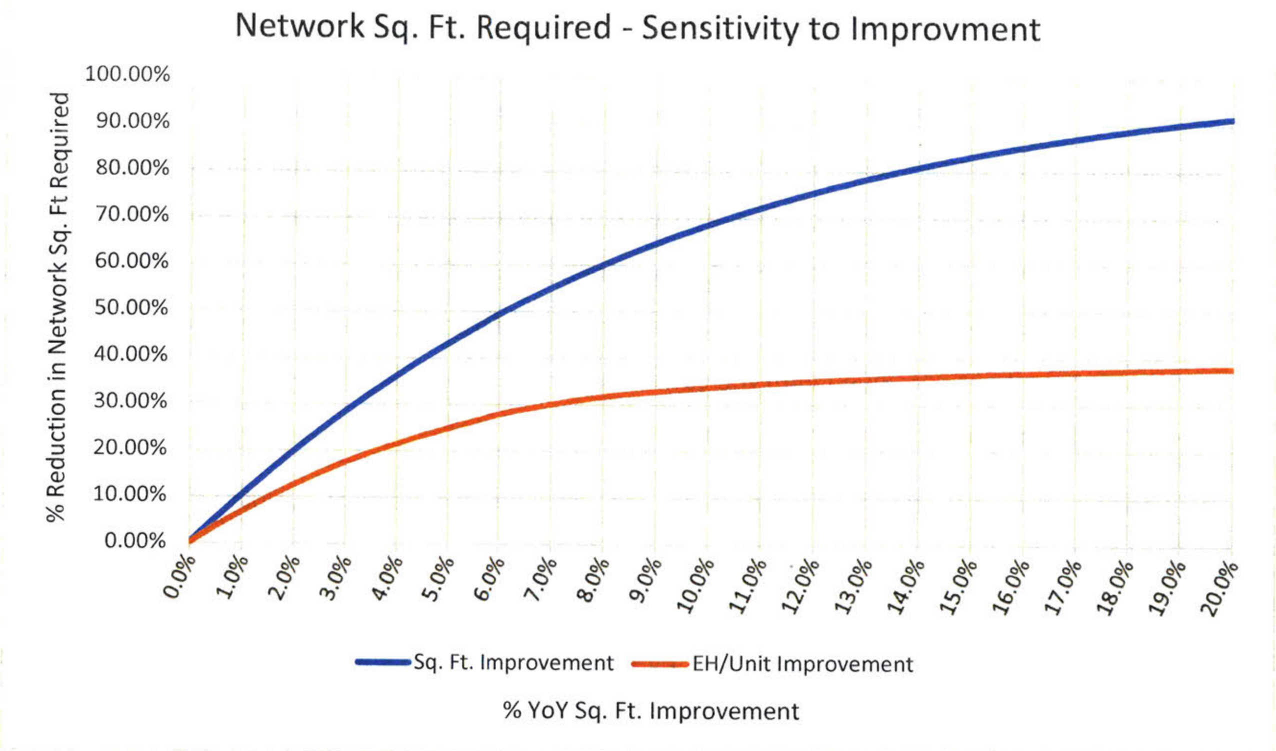


Figure 5-2 - Sq. Ft. Required Sensitivity

To generate Figure 5-2, we vary the Sq. Ft. Improvement and EH Improvement in increments of 0.1%, up to 20%. We can see from the plot above that the benefit of additional increases in the Sq. Ft. Improvement variable diminishes at higher values. This is also true for EH Improvement, however it is more pronounced. This curve is a useful management tool as it allows management to think about the potential benefit that can be accomplished from given rates of improvement. This is a useful addition to the strategic planning toolkit. It should be noted that whilst we have portrayed a Sq. Ft. Improvement in the region of 20%, sustaining an improvement rate of 20% each year for 10 years is highly improbable. A figure in the 0-10% range is deemed feasible. Equally, for EH improvement, a figure within the 0-20% range would be considered feasible. Working back from this limit can help the company understand the maximum reduction in Sq. Ft. Required that can be obtained.

5.2.4. Impact of Modelling decisions

As discussed in Chapter 3, granularity plays an important role in modelling decisions. Specifically, for the manufacturing model, it can limit the ability to model growth accurately. For our modelling, we have chosen to use the value stream as our lowest decision unit. We take the demonstrated output of the value stream and define our capacity utilization on this basis. Because we operate at this level, we lose the ability to identify whether a bottleneck exists within a value stream, be it a specific line within a value stream or a machine or process within a line. Since the bottleneck, by definition, is the rate limiting process of the value stream, we would only need to improve output at this process to improve overall output, at least until another process becomes the bottleneck. This has an effect on modelling how much additional space is required since we would only need to increment by the amount of space the expanded bottleneck area would require. For approximately 80 value streams manufacturing and approximately 400 product families, the complexity of gathering the necessary information to create a model at this level is very laborious, so we have continued with the current approach. This could however be an area in which the model could be extended on the next iteration.

Choosing the value stream as the decision unit also limits the ability to evaluate the amount of space needed for buffer inventories and storage. We currently receive a value for current sq. ft. occupied by a value stream from the survey and receive no further granularity. One would reasonably expect that this space includes physical footprint occupied by machines, but also supporting areas for items such as storage of in-process inventory. Because we do not model at the line or machine level, we also lose the ability to take into consideration the effect of changes in output at this more granular level on the amount of space needed to store buffer inventories. A potential solution to overcome this shortcoming would be development of a more detailed model in line with that described above however, the same issue of limited time and resource presents itself.

We briefly described the logic by which the model increases Sq. Ft. Required on the basis of output in Section 4. The described method is referred to as linear growth. We could equally opt for step-wise growth, where footprint increase in defined increments. This is intended to mitigate the downsides of the linear approach, namely that it is not realistic to expect that a value stream could increase space in increments as small as 1%. Equipment typically cannot be added in continuous increments, but rather in discrete blocks. To evaluate the difference between the two methods, we amend the model and make a direct comparison between the two techniques.

The comparison is based on the baseline data as presented at the beginning of the results section. For the step-wise version, we model the extreme case where Sq. Ft. Required increases in value stream- sized increments when the capacity utilization threshold is crossed. The results are displayed in Figure 5-3 below. With the most extreme step-wise case, the estimated network Sq. Ft. Required is about 26% more than the linear case. This is described as the extreme case because it is unlikely that increases in output would require duplication of the whole value stream. As alluded to in the preceding paragraphs discussing granularity, it is more realistic to expect that the actual increment is a fraction of the size of the whole value stream. This would align with adding a machine or set of machines that can only be added in a discrete block of space. To take this into consideration, we introduce a variable to scale the size of increment. As an example, we set it at 0.25, which means that growth in space occurs in increments 25% of the total value stream footprint. This 25% case is also presented in Figure 5-3. In this case, the estimated network Sq. Ft Required only increases by 5% when compared to the linear case. The presence of this variable allows each value stream and factory to tune how they grow, and represents an attainable intermediate step towards a more detailed line/machine level model.

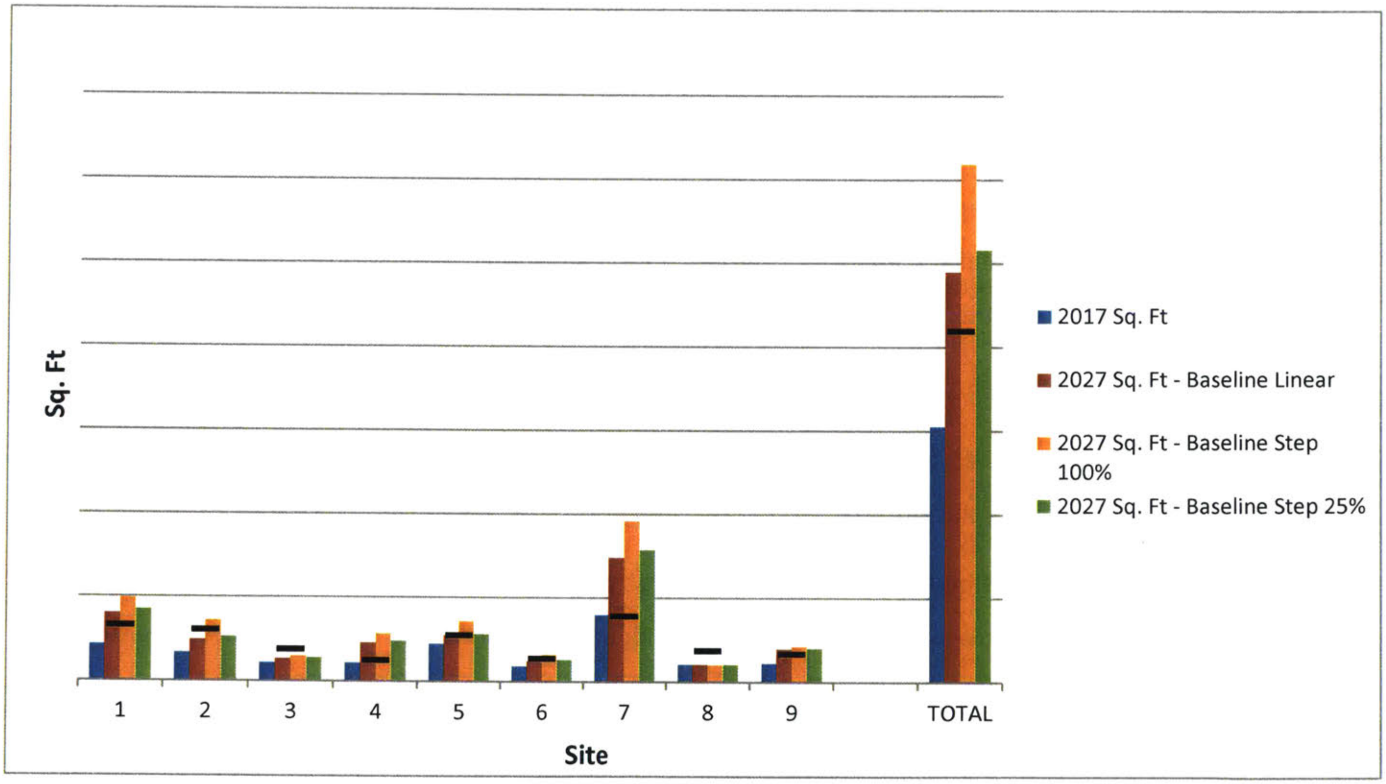


Figure 5-3 - Linear vs Step-wise Growth

5.3. Managerial Takeaways

The key managerial takeaways from the results are presented below.

5.3.1. Implied maximums on space improvement given sensitivity

The sensitivity analysis presented above allows for implied maximum square foot reductions for the network to be obtained. For example, if the maximum achievable improvement rate for Sq. Ft. Improvement is known to be 5%, the company can imply that the maximum obtainable reduction in Sq. Ft. required would be approximately 44%. If the company knows the value of this improvement in absolute square foot terms, they can evaluate whether space requirements over and above the baseline case would fit within the network. If the additional amount required is greater than the maximum obtainable reduction, the company will need to identify ways to add more space.

5.3.2. Sites for further review

From all the analysis conducted, sites 4 and 7 appear to be closest require additional space. This is evident from Figure 5-1 - Sample model OutputFigure 5-1, where the Sq. Ft. Required breaches the available capacity line for all the scenarios presented. The team should evaluate the results at the value stream level to understand the key drivers of this result.

5.3.3. Headcount constraint

One of the model outputs presented in Section 4.4 is the headcount requirement. There are two points to consider regarding this output.

First, the amount outputted represents the number of people that would be required to complete the weekly demand. This is calculated on the basis of knowing how many hours of work content are required and how many hours of work a single person can do in a shift. As presented, it does not give a sense of how the people would be arranged on different shifts.

Second, the amount of people required is considered boundless in our model. Because we are primarily concerned with footprint, we assume no constraints in the areas of adding machines or headcount. This is problematic as it does not reflect the reality often found across the world. Many companies are constrained in their ability to hire more workers. From the example in Figure 6, the company would need to increase headcount from 43 people to 250 people, an increase of 480%. Even over a period of 10 years, this would be an extremely challenging target. In practice, each factory would have a sense of their labor market constraints and this could be set as a hard capacity limit in the model, after which no further increase in output could be seen. A situation like this would likely result in the company looking for alternate locations where they can tap into excess labor capacity.

5.4. Conclusion

In this section we have presented results gathered from initial use of the tool. In addition, we discuss secondary results and additional insights that help the reader appreciate the capabilities of the tool. Overall, these results help to validate the attainment of the objectives set out in the problem definition and goals sections. In addition, we are able to present managers with key insights that may not have otherwise been identified. These insights are intended as tangible takeaways that managers will need to address as they continue to develop the operations strategy.

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6. Future Work

In this Chapter we will detail future work that we feel would enable BSC to make the most of this tool and improve the accuracy of its output further.

The first recommendation regards data acquisitions and data structures. In the course of compiling the model, large amounts of data were collected from a variety of sources. In addition, we created linkages between these data sets that had not previously been used, such as the link between a SKU and its associated value stream. Whilst the work conducted was sufficient for creation of the first iteration of the model, it is recommended that a database expert work to develop a version of the model (or core data) that is easy to update and refresh. This might entail the creation of standard forms to collect data that is not available in company systems, but also delving deeper into understanding the core sources of data used in creation of the model and extracting the data from as close to the source as possible. Taking these steps will also chart a course to help think about the practical implementation of an Industry 4.0 data solution, where large amounts of core manufacturing data is easily accessible for analysis.

Secondly, we recommend that the approach presented here for calculation of capacity utilization be established as a standard and spread throughout the company. Through various discussions with sites, it is apparent that each factory thinks about capacity utilization in a different way. Aligning the fundamental definition across all tiers of the organization would go a long way in ensuring that the language used for strategic planning is the same as that used at the factories and that all functions are pursuing the strategic plan with better alignment.

Our third recommendation regards the updating of the various parameters introduced in this model. To generate the results presented above, global values have been set for a variety of parameters. Some of these parameters, such as the capacity utilization threshold, the space scale factor, the improvement trade-off ratio and the step increment % for step-wise growth can reasonably expected to be different from value stream to value stream. We recommend that each factory take the time to establish their best estimates of these parameters to allow for more accurate modelling. They are best placed to conduct this activity given their intricate knowledge of the particulars of the value streams and products they manufacture.

Our fourth recommendation is for BSCI to introduce costs into the analysis. By design, the model does not take into account the costs associated with increasing capacity. These costs can include the amount required to buy more machines, hire construction workers or pay shift premiums. The omission of costs allows for a more focused manufacturing model with the intention that additional cost items are displayed in separate models for subsequent analysis. We believe that once the relevant cost data is collected, it would enable analysis relating to the financial impact of different scenarios. Additionally, the data would be well suited for use in large scale optimization models that could be used to optimize the network configuration.

Our final recommendation is for the update of the model to include some consideration for uncertainty in inputs and outputs of the model. In developing the first iteration of the model, we have chosen to keep the inputs and outputs as deterministic for the ease of modelling at the scale envisioned. One could reasonably expect that there will be uncertainty in most of the parameters defined. A commercial software package, such as @Risk could reasonably be used to model this uncertainty through the use of Monte Carlo Simulation. We would prioritize modelling the effect of uncertainty in each value stream's Max Units/ Shift before moving on to adding uncertainty in other parameters. The underlying distribution for the Max Units/Shift could reasonably be extracted from historical analysis of output from each value stream. Additional inputs that could be modeled include introduction of uncertainty into the annual demand values as well as the improvement parameters, for a case where the factories supply the current improvement goals they are working towards. The addition of uncertainty would help management have some sense of understanding of the risk involved with decisions made based on the tool.

7. Conclusion

We have built a manufacturing footprint model that allows for estimation of manufacturing footprint given varying annual demand. Within the context of BSCI, this represents a step forward since visibility of footprint at a network level, at this level of granularity, is not currently available in the company. In addition, the model not only allows management the ability to run multiple scenarios to assist in developing a strategic plan, but to use the improvement variables to modify solutions and use these to develop tangible and strategy-aligned goals for the manufacturing sites.

In developing the model, we have had to make decisions regarding default values for the model, granularity and the mechanism by which footprint grows. In making these decisions, a large factor for our choices has been the requirement for timely completion of the first iteration. We do however discuss and suggest alternatives and potential modelling improvements that would be suited for integration into a second iteration of the model. Engaging with individual sites to refine assumptions and establishing a method to centralize collection of data would largely address these concerns.

Whilst this work has focused on estimating footprint for BSCI, the methodology presented is equally valid across a range of industries. The general process of developing a relationship between volume, capacity utilization and footprint could be extended to a variety of industries, specifically those where controlling the overhead cost associated with footprint is critical to business success. Central to any analysis would be adequate definition of the relevant decision unit (e.g. value stream in our case) and close interaction with factories or operations teams to establish the mechanism by which footprint grows in response to increases in demand.

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References

[1] Boston Scientific, "Boston Scientific History," [Online]. Available: https://www.bostonscientific.com/en-US/about-us/history/1970-1979.html. [Accessed 15 03 2018].

[2] B. Scientific, "Investor Relations: Events and Presentations," 27 June 2017. [Online]. Available: http://investors.bostonscientific.com/~/media/Files/B/Boston-Scientific-IR/documents/events/BSX_2017_Jun27_Investor%20Day.pdf. [Accessed 18 March 2018].

[3] M. Stendahl, "Boston Business Journal," 2017. [Online]. Available: https://www.bizjournals.com/boston/news/2017/05/04/boston-scientific-is-the-2nd-biggest-dealmaker-in.html. [Accessed 16 March 2018].

[4] Boston Scientific, "Investor Relations: Filings - SEC Filings," 2016. [Online]. Available: http://otp.investis.com/clients/us/boston_scientific_corporation/SEC/sec-outline.aspx?FilingId=11206841&Cik=0000885725&PaperOnly=0&HasOriginal=1. [Accessed 18 March 2018].

[5] Medtronic, "Investor Relations: Financial Information - SEC Filings," 2016. [Online]. Available: http://services.corporate-ir.net/SEC/Document.Service?id=P3VybD1hSFlwY0RvdkwyRndhUzUwWlc1cmQybDZZWEprTG1OdmJTOWtiM2R1Ykc5aFpDNXdhSEEvWVdOMGFXOXVQVkJFUmlacGNHRm5aVDB4TVRBeE1qazJOeVp6ZFdKemFXUTlOVGM9JnR5cGU9MiZmbj1NZWR0cm9uaWNwbGNfMTBLXzlwMTYwNjI4LnBkZg==. [Accessed 18 March 2018].

[6] Abbot, "Investor Relations: Financial Reporting - SEC filings," 2016. [Online]. Available: http://services.corporate-ir.net/SEC.Enhanced/SecCapsule.aspx?c=94004&fid=14218934. [Accessed 18 March 2018].

[7] Abbott, "Investor Relations: Financial Reporting - Annual Reports," 2016. [Online]. Available: http://phx.corporate-ir.net/External.File?item=UGFyZW50SUQ9MzcwMDY1fENoaWxkSUQ9LTF8VHlwZT0z&t=1&cb=636247693000670189. [Accessed 18 March 2018].

[8] Boston Scientific, "Newsroom: News Releases," 8 June 2016. [Online]. Available: http://news.bostonscientific.com/2016-06-08-Boston-Scientific-Announces-Restructuring-Program-to-Support-Long-Term-Growth-and-Innovation. [Accessed 18 March 2018].

[9] Medtronic, "Investor Relations: Events & Presentations," 23 August 2017. [Online]. Available: file:///C:/Users/bawuondo/Desktop/2017.08.23-Parkhill-MN%20CFA%20Society_vFINAL.pdf. [Accessed 18 March 2018].

[10] N. Slack, S. Chambers and R. Johnston, Operations Management, 4th Edition ed., Harlow: Pearson Education, 2004.

[11] B. Chang, *Profitability Improvement Through Profit Mapping,* Massachusetts Institute of Technology, 2014.

[12] S. Machinani, *Uncovering Opportunities for Cost Containment and Operational Improvements via Shared Practices beetween Device Manufacturer and Hospital,* Massachusetts Institute of Technology, 2015.

[13] S. Laskowski, *Capacity Utilization and Lean Manufacturing at a Plastic Medical Device Components Manufacturer,* Massachusetts Institute of Technology, 2017.

[14] W. Skinner, "Manufacturing - Missing link in corporate strategy," *Harvard Business Review,* vol. 47, no. 3, pp. 136-145, 1969.

[15] N. Slack and M. Lewis, Operations Strategy, Pearson, 2008.

[16] R. H. Hayes and S. C. Wheelwright, Restoring Our Competitive Edge : Competing Through Manufacturing, John Wiley & Sons, 1984.

[17] M. Rudberg and J. Olhager, "Manufacturing networks and supply chains: an operations strategy perspective," *Omega,* vol. 31, no. 1, pp. 29-39, 2003.

[18] C. Martínez-Costa, M. Mas-Machuca, B. Ernest and A. Corominas, "A review of mathematical programming models for strategic capacity planning in manufacturing," *International Journal of Production Economics,* vol. 153, no. 2014, pp. 66 - 85, 2014.

[19] S. Chanda, T. McClurgb and J. Warda, "A Model for Parallel Machine Replacement with Capacity Expansion," *European Journal of Operations Research,* vol. 121, no. 3, pp. 519-531, 2000.

[20] V. Verter and C. Dincer, "An integrated evaluation of facility location, capacity acquisition, and technology selection for designing global manufacturing strategies," *European Journal of Operations Research,* vol. 60, no. 1, pp. 1-18, 1992.

[21] S. Karabuk and S. D. Wu, "Coordinating Strategic Capacity Planning in the Semiconductor Industry," *Operations Research,* vol. 51, no. 6, pp. 839-849, 2003.

[22] P. J. Andrisani, "Manufacturing Floor Space Forecasting," *Computers and Industrial Engineering,* vol. 13, pp. 92-95, 1987.

[23] M. A. Zeppieri, *Predictive Capacity Planning Modeling with Tactical and Strategic Applications,* Cambridge: Massachusetts Institute of Technology, 2004.

[24] L. B. Sutterer, *Development of a Tool for Forecasting a Warehouse Facility Footprint and Enabling Rapid Scenario Analysis,* Cambridge: Massachisetts Institute of Technology, 2010.

[25] P. Johnson, *Developing a Long Term Strategy for a Warehouse Network,* Cambridge: Massachusetts Institute of Technology, 2017.