Enabling Effective Lifecycle Management of Manufacturing Facilities with Enhanced Decision Making Processes

by

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Submitted to the Department of Mechanical Engineering and the MIT Sloan School of Management in partial fulfillment of the requirements for the degrees of
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and
Master of Business Administration
in conjunction with the Leaders for Global Operations Program at the
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Abstract

As a global manufacturing company, Company X has built up an extensive and varied portfolio of manufacturing facilities. These facilities vary greatly in capability, age, and performance. This creates difficulties in effectively managing the manufacturing portfolio to best utilize the different resources.

One approach to this issue of resource management is to analyze the manufacturing facilities as having a lifecycle. The lifecycle of manufacturing facilities is hypothesized to be a function of the people involved in the operations at the facility. This is generally captured under the term "culture." Part of the work focuses on characterizing the culture of a facility through the performance of its equipment in an effort to predict future performance, thus helping to determine the expected productive lifecycle of a facility.

A decision tree framework is developed to help aid in this lifecycle determination process. The decision tree uses a combination of existing and modified metrics in providing recommendations for reference when determining the future of the manufacturing network. Importantly, the decision tree analysis is intended to be completed on a recurrent basis and executed with a focus on process discipline. Implementation of the decision tree will lead to improved decisions for the manufacturing network and an increased understanding of how to effectively manage manufacturing facilities throughout their lifecycles.

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1 Introduction

Company X is a large manufacturing company with a global presence for both manufacturing and distributing its goods. Company X operates in a traditional industry that has been around for more than a century. The industry is currently experiencing significant shifts in the market both in terms of an increasing number of competitors taking market share from traditional market leaders and customers demanding increased customization in terms of performance and sizes. An enhanced manufacturing strategy is viewed as an opportunity to help match capacity to anticipated demand in an effective manner that gets the greatest value out of capital expenditures through a rationalized manufacturing footprint.

1.1 Project Background

As a global manufacturing company, Company X has built up a portfolio of manufacturing facilities around the world through building and acquisition. This has resulted in a diverse manufacturing portfolio with plants ranging from over a century old to relatively new. Equipment within these plants is similarly varied. These factors combine with a need to simultaneously upgrade for capability to complicate the capital investment process.

Many people have been working at Company X for decades in a variety of roles and have developed a comprehensive knowledge base regarding facility operations and related needs. Current capital investment decisions are made on a periodic basis with input from a variety of sources, including those in operations roles with manufacturing experience and those in finance projecting the financial impact of any given project. The intersection of these areas of expertise are intended to deliver the best returns for Company X by enabling the proper combination of capacity and capability with minimal investment.

Company X uses several measures to evaluate the performance of a plant both before and after investment. Particular measures include cost evaluated on product output, such as on a per unit or per weight (e.g., 100 lb.) basis. Recent investments have not always stemmed the tide of escalating costs by these measures. The cost curve of Figure 1-1 is an example of how it has become more costly over time to create products at certain plants of Company X.

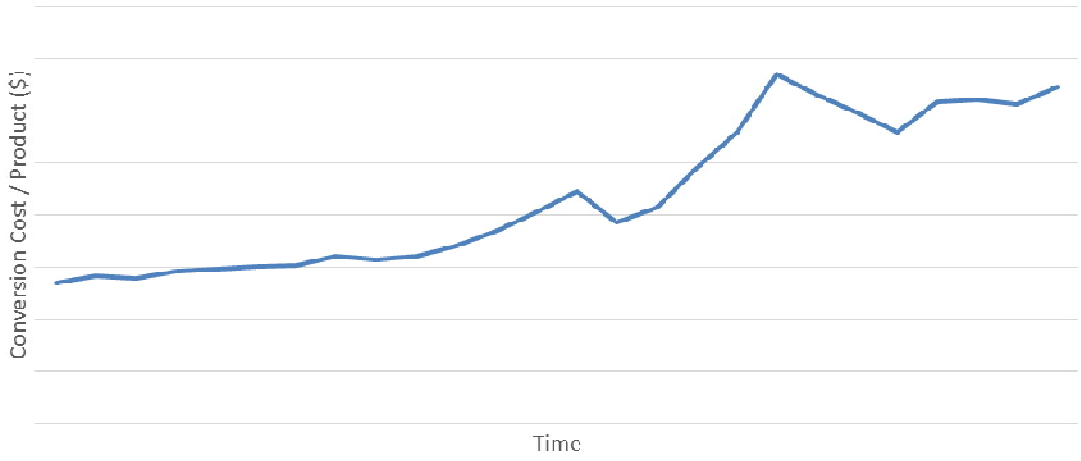

Figure 1-1: Conversion Costs Have Increased On a Per Product Basis Over Time.

This research examines opportunities to evolve the current investment process to better account for the above challenges.

1.2 Project Objectives

The primary objective of this research is to enhance the process at Company X for allocating capital expenditures and determination of manufacturing footprint to further improve the return on investment of allocated capital. Improvements are expected by taking a holistic view of manufacturing facilities as an interconnected network. An evolved process should encompass both quantitative and qualitative components that consider factors internal and external to the manufacturing network. Communicability to stakeholders of the enhanced process is essential to continued success of this initiative.

An additional objective is to provide insight into the metrics that are used to measure plant performance, and to potentially identify improved or alternative metrics to evaluate said performance. A measure for measuring the culture of a plant is a particular focus.

1.3 Methodology

The project had three different phases which overlapped and continued to be iterative, but can be broken down as follows: Research, Past Performance Analysis, and Decision Modeling.

The Research phase involved the examination of resources around the concept of plants having a lifecycle and how plant investments can be made effectively. As the project progressed, additional research was performed into plant cultures and receptiveness to new technologies. Research also included discussions with employees across the corporate organization and a visit to a plant to discuss management and culture with plant leadership and to identify what are considered to be best practices.

Past Performance Analysis helped establish a baseline understanding for the current state of the investment decision making process. Investments in a plant were observed by following plant trends in depreciation expense and examining cost and output performance following the investments. Additional analyses included comparing machine performance across company facilities, with a particular focus on performance of new technologies following implementation, and breaking down sources of operational loss (i.e., machine downtime) within different plants.

Finally, Decision Modeling was driven by an understanding of past performance within Company X and as qualitatively understood through research. The resultant decision tree framework is intended to function as a tool for aiding decisions with respect to capital investment expenditures. The model was presented to company stakeholders and left with Company X for future expansion.

1.4 Thesis Overview

A central thesis of the research is that factors contributing to successful investments in manufacturing facilities are, in many instances, quantifiable and predictable. Chief amongst these factors is expected to be the "culture" of a plant, which is hypothesized to be determinable at some level based on previous plant performance. And while no single factor is expected to be determinative of how a facility will perform following an investment, a holistic, defined framework is expected to be usable to better predict this performance. Failure to accurately understand how and where to effectively invest can lead to decreased performance with time and an enlarged manufacturing footprint that, despite its size, can be ill equipped to handle the market demand for certain products.

By extension, a closely correlated thesis is that by understanding how and where to effectively invest, a manufacturing footprint can be rationalized into an improved position. Such rationalization includes identifying manufacturing facilities that have reached the end of their effective lifespan. This effective lifespan is expected to vary for different facilities and may not be predictable in advance, but this research aims to help identify when the role of manufacturing plants should be reevaluated based in many respects on the factors related to investment.

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2 Research

The first step to establishing a baseline of knowledge in these areas is to review the literature that has already been conducted in these areas. The literature review focused on three primary areas: the lifecycle of manufacturing facilities, measuring plant performance, and plant culture.

2.1 Lifecycle of Manufacturing Facilities

At the start of the project, one of the theories was that manufacturing facilities have a natural lifecycle, beyond which point further investment will always face diminishing returns. An early example of the idea of plants having a lifecycle comes from Roger W. Schmenner's work, in an article titled *Every Factory has a Life Cycle*. [1] In this article, Schmenner sought to explain why factories die and ultimately analogized factory deaths to a slow death resulting from hardening of the arteries (as opposed to a sudden death from a massive heart attack). Schmenner attributes poor management practices to the failure of many plants and posits that good management can function as a form of preventive medicine. To Schmenner, looking at a plant as having a life cycle "enables the company to evaluate the long-term use of each of its plants and to commit itself to a plan, or charter, for that long term." A company that "contemplates how its facilities will be used and changed over the years in response to various contingencies, the better able it is to design its plants and all the accompanying manufacturing systems expressly for such contingencies." A key to longer term success is providing plants with constant attention beyond day-to-day operations to long-term roles and capabilities. In Schmenner's own words, the "usefulness [of the life cycle] concept comes from recognizing that plants are subject to all kinds of changing forces, many of which are related to age but all of which must be carefully considered and coped with."

In an ideal world, the life cycle of a plant would be integrated with a product life cycle and allow for feedback loops between both plant and product development processes. [2] However, older companies with large plant portfolios tend to have a substantial portion of their plant portfolio in what Schmenner calls the "mature years." This creates difficulties because plants cannot be optimized and developed in concert with product development, but instead new products must be fit into a constantly aging plant portfolio. This can lead to a loss of "focus," i.e. an increase of product mix. This is not uncommon, and "focus" has been the subject of a number of articles over the past several decades. While the particular impacts of loss of "focus" are not part of this research, a general understanding of the impact of product mix and the difficulty this can introduce when comparing plants is explored.

2.2 Measuring Plant Performance

Evaluating plants requires measuring their performance. The Next-Generation Manufacturing Project (NGM) started in 1995 to provide a framework for success in U.S. manufacturing. [3] Their report specifically contemplated some of the issues associated with how to measure plant performance and the challenges associated with limited and/or poorly organized analysis of production data. Specifically, the NGM recognized the following:

> *Many times the difficulty in meeting new market challenges lies not with the personnel or equipment but with the lack of useful manufacturing process knowledge. In other instances, new technologies may be needed but this determination cannot be made without a thorough understanding of a particular manufacturing operation.*

This project has a strong focus on how to improve the understanding of manufacturing processes in the context of a factory and at the individual equipment level. There are a number of ways to measure a factory, and the NGM includes a list of many of these, such as: product throughput or daily production rate; percentage of product that meets or exceeds specification; cycle time for process update or replacement; and, key for this work, tradeoff analysis among capital, operations, and total life-cycle costs for manufacturing processes. The NGM recognizes the "challenge in balancing investment needs against near-term requirements, and in evaluating the results of such efforts."

The importance of measuring performance was also acknowledged in an April 2014 report by the Manufacturing Enterprise Solutions Association. [4] One interesting aspect of this report was the correlation of financial and OEE (Overall Equipment Effectiveness) performance. OEE is a way to measure performance of equipment across a facility. An excellent explanation of how OEE works is available in *OEE for Operators - Overall Equipment Effectiveness*. [5] OEE is a measurement of several different aspects of a facility, specifically Scheduled Rate, Availability Rate, Performance Rate, and Quality Rate. Scheduled Rate is a function of the portion of total available time the equipment is expected to be running. Availability Rate relates to how long the equipment is actually running (Run Time) divided by the Scheduled Rate to determine how long equipment was actually available. Performance Rate relates to how much Actual Output is achieved relative to the Target Output based on the Availability Rate. Finally, the Quality Rate is determined by comparing the Good Output to the Actual Output. When multiplied together, typically excluding the Scheduled Rate, this represents the OEE for a facility.

There are many other metrics available, and whole reports could be written summarizing these metrics. However, for the context of this project, OEE and related metrics are sufficient until others are introduced later.

2.3 Plant Culture

While certain metrics are described above with respect to measuring plant performance, plant culture tends to be much harder to define (let alone measure). Yet culture is considered to be an essential part of the functioning of any facility. Anecdotally, many people mentioned throughout the project the importance of culture, identifying certain plants as having a "good culture" or a "bad culture." However, when details were requested, those offering the comments often could not offer specifics. Another way to approach the question of culture is to put it in the context of how it relates to strategy.

The article *Beyond World-Class: The New Manufacturing Strategy* discusses the issues with companies focusing on the form of their organizational assets as opposed to "their substance, the skills and capabilities that enable a factory to excel and make it possible for various improvement programs to achieve their desired results." [6] The authors indicate that "[c]apabilities that provide enduring sources of competitive advantage are usually built over time through a series of investments in facilities, human capital, and knowledge." Further, "solutions are viewed as a part of a longer term *path* of improvement. Individual practices are adopted not just to solve an immediate problem but also to build new skills that open up new opportunities."

In the article *How should you organize manufacturing?* the authors address how the "problems and pressures facing manufacturing companies ultimately find their way to the factory floor, where managers have to deal with them through some sort of organizational structures." [7] Thinking about culture in terms of the broader environment in which people operate, the authors suggest that the "task for manufacturing is to arrange its structure and management so as to mesh with and reinforce this strategy." The authors also recognize the challenges faced in implementing such change, identifying how "manufacturing inertia is made worse by many manufacturing managers' reluctance to change. And is further compounded by many top managers' lack of understanding of the kind of changes that are needed, as well as their unwillingness to commit the resources to effect such changes."

This research serves as a starting point for the work described below, which expands upon these concepts in different ways.

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3 Past Performance Analysis

While this research is forward looking into developing a process for enhancing future strategic manufacturing facility planning, an analysis of past performance can be useful to inform the expectations of the future. First, Company X's manufacturing process is explained at a high level to establish the environment in which the company operates. This is followed by a discussion of data collection and analysis at both a facility and equipment level. Finally, included is an analysis of how Company X's manufacturing facilities have fared with prior investment and a look at other variations in plant and machine performance.

3.1 Manufacturing Process

The manufacturing process of Company X is partitioned into several different processes. Downstream processes are highly dependent on upstream processes. Figure 3-1 is a schematic of the manufacturing process.

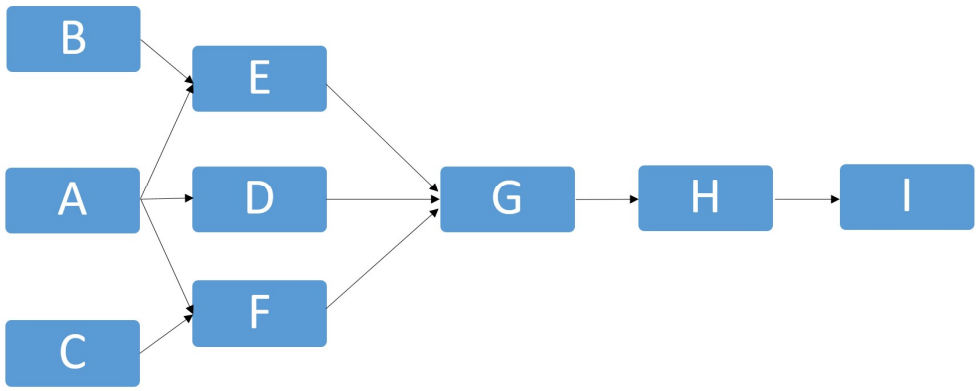

Figure 3-1: Schematic of Product Manufacturing Process. Each Block Represents a Process Type with Unique Equipment and Capacity. Material Flow is Parallel Upstream and Continuous Downstream.

The number of machines involved in each process varies significantly, with some processes relying on as few as one or two pieces of equipment (primarily the upstream processes) and others having in excess of 100 pieces of equipment (e.g., Processes G and H). Equipment of varying capabilities and capacities may be initially installed in a single process area to facilitate the manufacture of a variety of product types (e.g., variations in size, materials, and components). Over time, this equipment variation is exacerbated as the equipment mix evolves through a combination of addition and replacement.

3.2 Data Collection and Analysis

Company X tracks a significant amount of data at an aggregated facility wide level. This information is easily accessible through a standardized system and allows for comparisons between overall plant performance on a variety of metrics that are examined

below. Information on individual machine performance can also be accessed, but often requires access to plant level systems which have a much greater variance.

3.2.1.Facility Level Information

Company X has data on a vast array of metrics over an extended period of time. Table 3-1 includes a sampling of several of the metrics considered relevant by leadership of Company X.

Conversion Cost	Product Output	Tonnage Output
Internal Cost	Compensation Cost	Waste %
External Cost	Energy Cost	Bad Goods
Material Cost	Downtime Maintenance	Scrap

Table 3-1: Exemplary Facility Level Manufacturing Metrics

These measurements are available across the entire worldwide manufacturing portfolio, and are divisible into even finer measurements. For example, Internal Cost represents the sum of the quantities of the costs in Table 3-2.

Depreciation/Insurance/Taxes	Hourly Wages	Salary Wages
Engineering Materials	Hourly Benefits	Salary Benefits
Operating Supplies	Utilities	Other

Table 3-2: Components of Internal Cost

Cost is a prime focus of current manufacturing strategy. An exemplary breakdown of cost from one plant shows how Material Cost and Hourly Compensation (hourly wages plus hourly benefits) are the primary drivers of product cost in the plant in Figure 3-2.

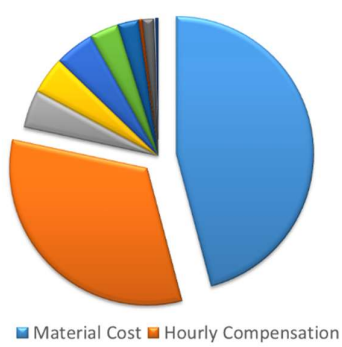

Figure 3-2: Material Cost and Hourly Compensation are Greatest Contributors to Product Cost at a Plant.

Making the assumption that material costs are largely uncontrollable, to improve gross costs at the manufacturing plant the greatest lever is hourly compensation. However, other cost components should not be ignored as they can be indicative of trends and still have an impact on profit margins. For the purposes of this research, particular attention

was paid to trends in Depreciation/Insurance/Taxes as increases over time are indicative of capital investment. Exemplary trends in these and other components of Internal Cost are depicted in Figure 3-3.

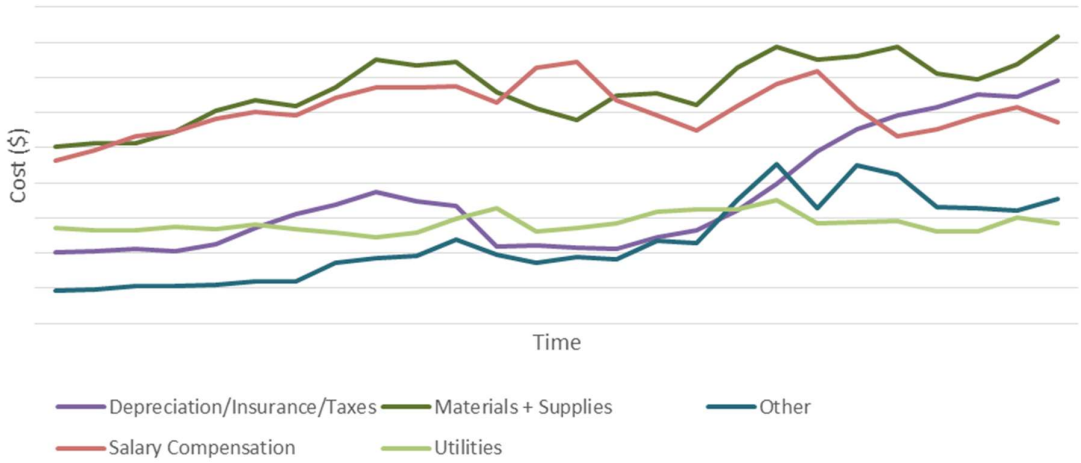

Figure 3-3: Trends in Components of Internal Cost (excluding Hourly Compensation) Over Time.

While plant level metrics provide a good overview of individual plant performance, comparisons at a gross level can be difficult given the variety of products produced and the equipment used to manufacture them. Attempts to compensate for this great variety (e.g., looking at production on a per weight production basis) can still fail to capture many of the intricacies that could lead to varying performance. It is possible to dig another level deeper beyond the overall plant metrics and into how individual pieces of equipment perform.

3.2.2. Equipment Level Information

Information on performance of equipment is available at different levels of granularity at different manufacturing facilities, and can also vary within a facility. This variation is often a function of the equipment, with newer equipment tending to be configured to collect more statistical information for analysis. Information related to production and downtime are generally captured regardless of the environment or equipment. In older environments this information is often recorded by hand. This introduces the possibility of incorrect information being captured and/or entered into a general manufacturing monitoring system. Newer environments can have more robust monitoring and reporting systems which enable real (or near real) time monitoring of the status of equipment across the entirety (or at least a section) of a manufacturing facility from anywhere in the world.

Elements of equipment performance related to OEE are of particular interest in this research. Testing the hypothesis that plant culture is reflected in the performance of certain aspects of equipment requires digging into the details for why a machine is

performing in a certain manner. It is useful to focus on some of the more modern equipment for this analysis. For one, this information is typically more accurate as in most cases it is recorded and transmitted by the equipment itself during operation. Second, it provides insight into how factories perform with newer equipment, which is directly related to another element of this research (see Section 3.3 for additional discussion about analyzing plant performance following investment). Yet another reason is because the same (or very similar) equipment may be installed in different locations and can provide a much better basis for comparison.

Reasons for why equipment is not operating (downtime) and the quantity that is produced when the equipment is running are expected to be indicative of plant cultures. This information is generally available on the equipment considered, though the number and type of downtime codes may vary. Accordingly, these codes can be associated with a more generalized downtime reason for uniform analysis across facilities and equipment. Production data is already generally tracked as number of units produced on a machine in a designated period of time. The use of this and other equipment level information is described in greater detail in Section 3.4.1.

3.3 Responsiveness to Capital Investment

One aspect that can be tracked at both a plant and equipment level is performance following a capital investment. Capital investment decision making at Company X frequently involves many parties with different perspectives, and finance plays a critical role in projecting return on investment in helping to select which projects should proceed. The return can come in many forms. This includes an increase in output and/or a reduction in costs, trends in which can be seen at the plant level. Whether a plant has been able to realize the expected benefits of an investment can be evaluated by looking at the correlation of different factors with Depreciation, which at Company X is coupled with Tax and Insurance Costs. However, significant movement in this value can be largely attributed to Depreciation as Tax and Insurance Costs are not expected to vary greatly from year to year.

An absolutely perfect investment would be one that is strongly negatively correlated with total cost and hourly compensation, while strongly positively correlated with unit output. Such a pattern would suggest that subsequent to investment in a facility (as evidenced by an increase in Depreciation, Tax, and Insurance Costs) the total costs for operating the facility along with hourly compensation were reduced while output increased. Though this ideal scenario may be rare, insight can be gained by looking at correlations of these factors at some facilities. Table 3-3 provides some exemplary correlations between depreciation and the following key components: Total Cost, Unit Output, and Hourly Compensation.

Depreciation Correlation	w/ Total Cost	w/ Unit Output	w/ Hourly Comp.
Plant A	+	+	+
Plant B	+	-	+ / -
Plant C	+	+ / -	+
Plant D	-	+ / -	-

Table 3-3: Exemplary Correlations of Depreciation with Total Cost, Output, and Hourly Compensation. Green Cells are Favorable Correlations and Red Cells are Unfavorable Correlations.

The correlation analysis reveals a variety of plant responses to changes in depreciation over a defined period. At a high level, Plants B and C appear unable to leverage capital investment into the desired responses, namely reductions in Total Cost and/or Hourly Compensation or an increase in Unit Output. The strong positive correlation between Depreciation and Unit Output at Plant A suggests this plant is at least able to realize some benefits from investment. Plant D appears to be in the best position with respect to investment, with strong negative correlations between Depreciation and both Total Cost and Hourly Compensation and a weaker correlation with Unit Output. These are high level observations based on the collected data, but another level of analysis is required to verify the initial inclusions (e.g., confirm negative correlation between depreciation and cost is not because of increased cost with decreased depreciation).

Going beyond the facility wide numbers, which necessarily require the use of simplifying assumptions, it is possible to look at how individual machines perform per the discussion in the previous section. New capital investments in the form of equipment can be evaluated by looking at how equipment performs following installation. Meaningful comparisons require establishing a baseline of performance prior to installation and measuring those same metrics following installation. One metric for focus in terms of cultural impact on a plant is the Adjusted Availability Rate Loss, which is developed in Section 3.4.1.

Another metric to evaluate between different facilities is Start-Up Time. Start-Up Time is an analysis of how long it takes to introduce new equipment and get it fully operational in an existing environment. This is a comparison between plants rather than a before and after at the same plant, but is illustrative of how different facilities respond to the introduction of new technology. The concept of plants being ready for investment, of which Start-Up Time can be a strong indicator, is more fully described in Section 5.2.5.

Retrospective evaluation of how plants respond to investment can be helpful in projecting future performance. Such evaluation is necessary on a plant, and even machine level, because as will now be discussed all manufacturing facilities do not operate the same.

3.4 Variances in Plant Performance

Variance in plant performance is to be expected in any large manufacturing portfolio. This is a function of a number of factors, including (but not limited to) the types of products facilities must manufacture, the mix-up of those products, the equipment used to manufacture those products, and the layout of the facility. However, one key factor as has been mentioned is the "culture" of a plant and the influence that has on performance.

The culture of a plant can be very difficult to measure, and traditional culture metrics such as performance on employee engagement surveys do not tell the whole story. Of particular importance is the impact that culture has on actual production performance. Given the great variances between facilities and even departments within a given facility, a goal is to compare similar situations as much as possible. This is accomplished by isolating equipment performing the same tasks and, when possible, comparing the same machines and/or the same products. The next section discusses how analysis of equipment performance can be indicative of a plant culture and be useful when making decisions on the future of the manufacturing facility portfolio.

3.4.1. Equipment Performance

Plants with a strong culture are expected to be able to keep a plant, and by extension the equipment therein, running on a regular basis. This is especially true for facilities that are capacity constrained and have a high value of capital equipment, where downtime is directly correlated to lost revenue and an increased product cost. The approach detailed here focuses on certain components of OEE as being indicative of the culture of a plant.

Briefly (see Section 2.2 for a more detailed discussion), OEE breaks equipment performance into four separate categories: Scheduled Rate, Availability Rate, Performance Rate, and Quality Rate. An overall OEE value for a manufacturing facility can be obtained by multiplying each of these components together. This value fails to capture the culture of a plant because it includes many components that are largely out of control of those working there. In order to capture culture it is necessary to build up a new metric from existing data to capture those inputs which are generally within the control of the plant, a new metric called Adjusted Availability Rate Loss.

Adjusted Availability Rate Loss provides perspective on how a plant is able to function within the limitations placed upon it from outside (e.g., the number and type of products it is asked to produce). Adjusted Availability Downtime is calculated based on downtime (in hours) over a specified period (e.g., a week) as follows:

$$\begin{aligned} &\textit{Adjusted Availability Downtime} \\ &\qquad = \textit{No Stock} + \textit{Defective Stock} + \textit{Meetings} \\ &\qquad + \textit{Unavailable Operator} + \textit{Breakdown Maintenance} \\ &\qquad + \textit{Misc. Stops} \end{aligned} \tag{1}$$

This is normalized based on expected run time and number of machines over the same period used for Adjusted Availability Downtime according to the following formula:

$$\begin{aligned} &Adjusted\ Availability\ Rate\ Loss \\ &\qquad = \frac{Adjusted\ Availability\ Downtime}{24\ Hours\ x\ \#\ Machines\ x\ \#\ Days} \end{aligned} \tag{2}$$

The resultant number represents the percent of time over the designated period during which equipment was unable to operate because of the factors contributing to Adjusted Availability Downtime. When available, Scheduled Rate should be used as the denominator to remove the influence of unscheduled time. An exemplary distribution of variation between plants is depicted in Figure 3-4.

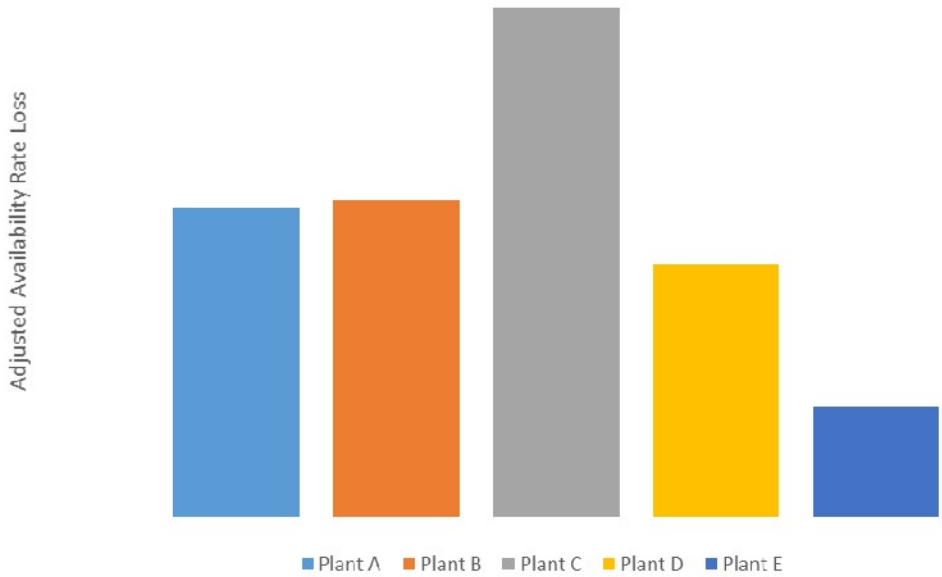

Figure 3-4: Exemplary Distribution of Average Adjusted Availability Rate Losses for One Year for Five Plants. The Low Adjusted Availability Rate Loss for Plant E is Indicative of Stronger Equipment Availability, While the High Value for Plant C is Indicative of Poorer Performance.

When looking over an extended time period, such as here when calculating weekly and averaging over one year (52 weeks), additional statistical information can provide further insight into the "culture" of productivity at a given facility. Here the standard deviation for Plant E is the lowest, while the standard deviation for Plant C is the greatest. This can be indicative of Plant E having a more consistent performance with respect to keeping its equipment running, with Plant C being more inconsistent. The larger standard deviation for Plant C and the lower standard deviation for Plant E are also in line with the scale of Adjusted Availability Rate Losses at those plants. Given the possibility of singular (or limited) periods with poor performance skewing the analysis,

adjustments to the data can be made to provide a more robust metric. This could include discarding outliers, such as those values 1.5 times the interquartile range below the first quartile of the data or above the third quartile of the data.

To better understand how Adjusted Availability Rate Loss differs from overview OEE metrics, it is instructive to look at what elements are not included in this adjusted metric. Scheduled Rate Loss is ignored as in the case of Company X it is not in the control of the manufacturing facilities but rather a centralized production planning department. Manufacturing facilities should not be penalized for downtime due to Scheduled Rate Loss when they are not supposed to be running. Adjusted Availability Rate Loss specifically excludes changeover hours as this can be an unfair measurement to facilities that are required to switch products fairly regularly while others can continue on uninterrupted long runs. Quality Rate is important, but excluded here, to help counter variances in acceptable tolerances for products made in different facilities.

Performance Rate is excluded as well, though could reasonably be included in other models. Using Performance Rate as a proxy for plant culture is a possibility but requires impeccable data as Performance Rate calculations are easier to alter than the accumulation of downtime that go into Availability Rate. This is because Performance Rate Losses are calculated as follows:

$$\begin{aligned} &Maximum\ Pieces\ Producible \\ &= \frac{24\ Hours * \#\ Machines * Days\ in\ Week - Avail.\ \&\ Sched.\ Downtime}{Cycle\ Time\ (Hours)} \end{aligned} \tag{3}$$

$$Performance\ Rate\ Loss = 1 - \frac{Total\ Pieces\ Produced}{Maximum\ Pieces\ Producible} \tag{4}$$

As can be seen, slight increases in Cycle Time can decrease the theoretical Maximum Pieces Producible. This has the effect of making a manufacturing facility look more efficient than it may be otherwise. For this reason Adjusted Availability Rate Loss is the preferred metric when looking at the costs of losses.

3.4.2. Productivity Losses

Operational losses in this context are those that arise from downtime factored in the Adjusted Availability Rate Loss metric. By focusing on those losses more controllable at the manufacturing facility level, comparing the related cost of those losses is intended to provide a more fair point of comparison.

One way of considering the cost of these productivity losses is examining the impact of lost productivity on a per product basis. For example, take the following hypothetical scenario.

A plant has a planned capacity of 3,000,000 products and fixed costs of $5,000,000 for the year. The Adjusted Availability Rate Loss has been calculated to be 30%. Looking

only at the impact on amortization of fixed cost over the products produced, this productivity loss results in an increase of nearly 43% of fixed costs on a per product basis.

This calculation is based on looking at how much each product was expected to absorb fixed costs based on the planned capacity, predicting a new fixed cost amortization with a reduced production amount because of Adjusted Availability Rate Losses, and comparing the planned and predicted costs to determine the increase. The related equations are produced below.

$$Planned\ Cost\ per\ Product = \frac{Planned\ Capacity}{Total\ Fixed\ Costs} \tag{5}$$

$$\begin{aligned} &Predicted\ Cost\ per\ Product \\ &\qquad = \frac{Capacity * (1 - Adjusted\ Availability\ Rate\ Loss)}{Total\ Fixed\ Costs} \end{aligned} \tag{6}$$

$$Fixed\ Cost\ Amortization\ Increase = \frac{Predicted\ Cost - Planned\ Cost}{Planned\ Cost} \tag{7}$$

Another approach to quantifying the impact of productivity culture losses is to first account for how much time is lost in a year due to Adjusted Availability Rate Losses:

$$Annual\ Time\ Loss = 24 * 7 * 365 * Adjusted\ Availability\ Rate\ Loss \tag{8}$$

Once the Annual Time Loss is known, a Productivity Loss Cost can be calculated with the following formula:

$$\begin{aligned} &Productivity\ Loss\ Cost \\ &\qquad = Annual\ Time\ Loss * Time\ Horizon * Multiplier \end{aligned} \tag{9}$$

The Time Horizon should be based on what is relevant to the question at hand. When comparing the losses in productivity to gains of a longer term project, e.g., building a new facility, a longer Time Horizon should be used. When focused on more immediate gains, e.g., possibility of transferring products to another more productive facility, a shorter Time Horizon could be used. The longer the Time Horizon the more important to discount costs on an annual basis given the time value of money.

The Multiplier is also important and is a key driver of the Productivity Loss Cost. This Multiplier is selectable by the company and may vary based on the circumstances. One proxy for the Multiplier is the cost that would be charged to a supplier for shutting down a plant on a per time unit basis. Other alternatives include tying productivity losses to actual increases in product cost (as done above), lost revenue, or other metrics preferred by those involved in decision making.

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4 Rationalizing Manufacturing Footprint

One of the key realizations of this project was the relationship of plant culture to performance on the individual equipment level. This relationship is important to understand because often the impact of culture is unquantifiable, though it is commonly understood that culture has a large impact on performance. Quantification of culture allows expanding the manufacturing footprint analysis beyond the capabilities of the equipment and enables greater consideration of the environment it operates within.

In many capital intensive industries, including that of Company X, excess unused capacity represents a drag on financial results. Capacity (and capability to make desired products) should match demand as closely as possible. However, as discussed above, all capacity and capability are not equal. This should be a consideration when looking to match the manufacturing network capacity and capabilities to demand. Three of the most common ways to accomplish the goal of matching capacity and capability to demand are to build a new plant (Greenfield), eliminate an existing plant (Closure), and infuse capital into an existing facility (Reinvest).

4.1 Greenfield

The Greenfield option represents one of the most dramatic courses of action a company can take. This approach requires an investment of significant time and resources to adequately address many of the issues associated with building a new facility. Chief amongst these issues are where to locate, size of facility, and equipment to install. In most industries a decision is made several years in advance of when the new facility is available to produce new product.

Pursuing a Greenfield has many advantages. Essentially starting with a clean slate, a company can often make the plant exactly how it wants. This enables the inclusion of the latest technologies and best practices from around the company and industry without concern about integrating with legacy issues. Processes can be designed to be balanced throughout the facility from the start and a planned startup period can be used to iron out issues that arise before the facility is relied on for full production. A new workforce with skills relevant to the new design can be hired and trained for the specific tasks.

Building a Greenfield also has several drawbacks in addition to the large capital expense that is required both before and during the construction process. One of the biggest issues is uncertainty regarding performance as there is no track record of performance, especially if the facility is located in a new geography for the company. Given the frequent long lead times of planning and executing on a plan for a Greenfield, conditions that led to the initial decision may change sufficiently with time so the decision of where and/or how to build the new facility may no longer be optimal at a future time.

Overall, pursuing a Greenfield strategy is a way to add additional, highly productive capacity and capability to a manufacturing network. However, doing so often comes at high cost both in terms of capital expense and long term commitment.

4.2 Closure

Directly contrasting with a Greenfield strategy, Closure is a strategy for reducing capacity. Closing a plant can be a very difficult decision as entire communities are often impacted, especially when a plant is large and one of the biggest employers in a region. However, manufacturing facilities can become unsustainable and continued investments fail to provide the required returns to be profitable. In such a situation, serious consideration needs to be given to reevaluating the role of the underperforming facility in the manufacturing portfolio.

Closing a manufacturing facility is not without costs. Though requirements of what is owed to employees varies by geography and the contractual relationship between the company and the workers, there are almost always costs associated with ending this relationship. Equipment for producing products must frequently be moved to other facilities to continue to satisfy customer demand for those products.

In the long run, reducing the costs associated with operating an underperforming plant can pay off financially through reduced expenditures and reduction of losses incurred through the use of less productive resources. However, deciding to close a plant has wide ranging impacts and is never an easy decision to make. It is an option that should be explored in certain circumstances, and this research is intended to identify those circumstances, but the ultimate decision to close is one that should be made with many interested parties involved.

4.3 Reinvest

Capacity and capability can also be modified/expanded at a pre-existing facility through reinvestment. The Reinvest approach in most cases leverages current infrastructure and other assets to reduce the total capital outlay. However, unless a facility has existing floor space (or the facility is expanded), new capacity or different capabilities are gained by replacing or upgrading existing equipment in the facility. As with Greenfields, there are advantages and disadvantages when electing to Reinvest in an existing facility.

Reduced costs are a significant driver in many decisions to Reinvest rather than Greenfield, but additional benefits should also be considered in the decision making process. Especially important is the knowledge of past performance at a particular facility. Though past performance is not always a reliable predictor of future performance, a primary goal of this research is to improve the understanding of the role plant culture plays in performance. This knowledge should improve future forecasts and thus increase the expected value of choosing a Reinvest approach in many instances.

Directly correlated to the culture is the advantage of knowing the skills and capabilities of the people already working in the plant. This also extends beyond the plant to the community and the types of workers that can be expected to run the plant if there is a turnover in employees. This familiarity can reduce some of the unknowns that are associated with a Greenfield, but care must be taken that a rational (as opposed to an emotional) approach continues to be followed.

With following an approach to Reinvest, many of the perceived advantages can also be disadvantages. Reducing cost through relying on an existing footprint may cause disruption when machines are taken off line to be upgraded or replaced. Introducing new equipment with different cycle times and/or product requirements may unbalance production lines. Even familiarity with the work force may be problematic if it prevents management from honestly assessing whether the current work force is able to adapt to the introduction of new technology. Issues related to the successful introduction of new technology into an existing facility are discussed in much greater detail in Section 5.2.5.

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5 Decision Tree

Greenfield, Closure, and Reinvest are all decisions that may be made for matching capacity and capability to demand for a manufacturing network. However, significant work must be completed before those decisions can be made. This research produced a decision tree with options of Greenfield, Closure, and Reinvest as end points. Company X should recognize the benefits of implementing the standardized, transparent decision tree proposed herein and described in detail below through an increased understanding of the common issues to be addressed by key decision makers involved with the capital investment process.

5.1 Overview

The decision tree as designed is intended to provide a framework to facilitate discussion and decision making regarding the future manufacturing footprint of Company X. The decision tree includes several branching paths based on decisions at each node. The nodes include quantitative and qualitative measurements based largely on existing metrics at Company X, though sometimes manipulated or viewed in a different context than has been done previously. Each of the nodes are described in greater detail in the next section.

The overall layout of the decision tree is depicted below in Figure 5-1.

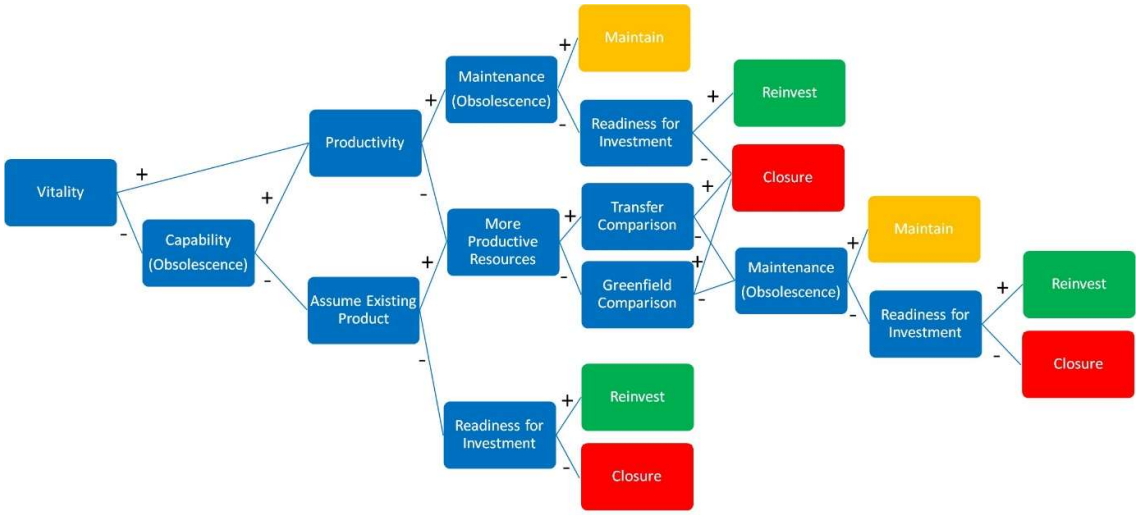

Figure 5-1: Generic Version of Decision Tree for Enhancing Manufacturing Facility Decision Process

The format of the decision tree represents an outgrowth of a logical progression in ideas. This starts with the key concept of vitality, which relates to whether a plant will need to change based on its expected product production plan in the immediate future. If a plant has high vitality (meaning it is not forced into a change), queries then focus on each plant's productivity. Highly productive plants are evaluated as to whether they can continue with their current equipment or are expected to perform well with new

equipment, while lower productive facilities are evaluated based on the costs of their lost productivity and whether there are better uses of resources elsewhere in the network (including the possibility of adding new capacity in the form of a new manufacturing facility).

If plants are being forced into a change because of low vitality, the progression varies. When a plant is destined to lose product in the future the second node focuses on the capability to handle new product. For facilities able to handle new product the queries follow a similar path as plants with high vitality with a focus on productivity, obsolescence, and alternatives. For facilities that are not equipped for new products, a separate branch focuses on whether the plant can assume other existing products and whether that is an economically viable strategy.

5.2 Nodes

The nodes are at the heart of the decision tree and dictate subsequent progression. To facilitate understanding, the criteria, measurement, and threshold for progression should be clearly identified. Each node is examined in greater detail below.

5.2.1. Vitality

Vitality is measured by the percentage of a plant's capacity that will be used by existing products over some forward looking time horizon. Vitality functions as the threshold question because it dictates whether or not a manufacturing facility can continue operating in the same manner with respect to its current product mix. The questions of whether a manufacturing facility should change are potentially different for facilities that have high vitality as compared to those with low vitality that are forced to change for survival. Accordingly, whether a plant has high or low vitality dictates the branch of the decision tree to be followed.

Two key aspects in determining whether a manufacturing facility has high or low vitality are the time horizon and threshold value. The time horizon should be related to the product planning cycle. For example, if production volumes for products are planned for Y years into the future, the time horizon for the vitality analysis can look forward no more than Y years. Reducing this horizon introduces the tradeoff of a more accurate forecast but less flexibility to respond with shifts to the manufacturing footprint as new capacity can take significant time to bring on line. While appropriate horizons will vary with industry, and potentially even by product, for Company X a horizon of Y years is useful as a baseline for decision making.

5.2.2. Productivity

Productivity is an important consideration in the management of manufacturing facilities. Naturally, there is an inclination to use facilities with higher productivity because using less productive facilities introduce losses that cannot be recaptured. Given

the great variety of manufacturing facilities at many corporations, including Company X, drawing direct comparisons between separate locations can be difficult. This is especially true at an overall facility level where different facilities are asked to create disparate products with varying equipment.

As discussed in detail in Section 3.4.2, one methodology for comparing plants on a more even basis is to look at operational losses at different facilities at a machine level. This is an improved comparison which removes certain impacts introduced by production planning (e.g., changeovers) while providing insight into aspects of how a particular plant is running. Figure 5-2 is a representation of how operational losses can vary across manufacturing facilities over time within a company.

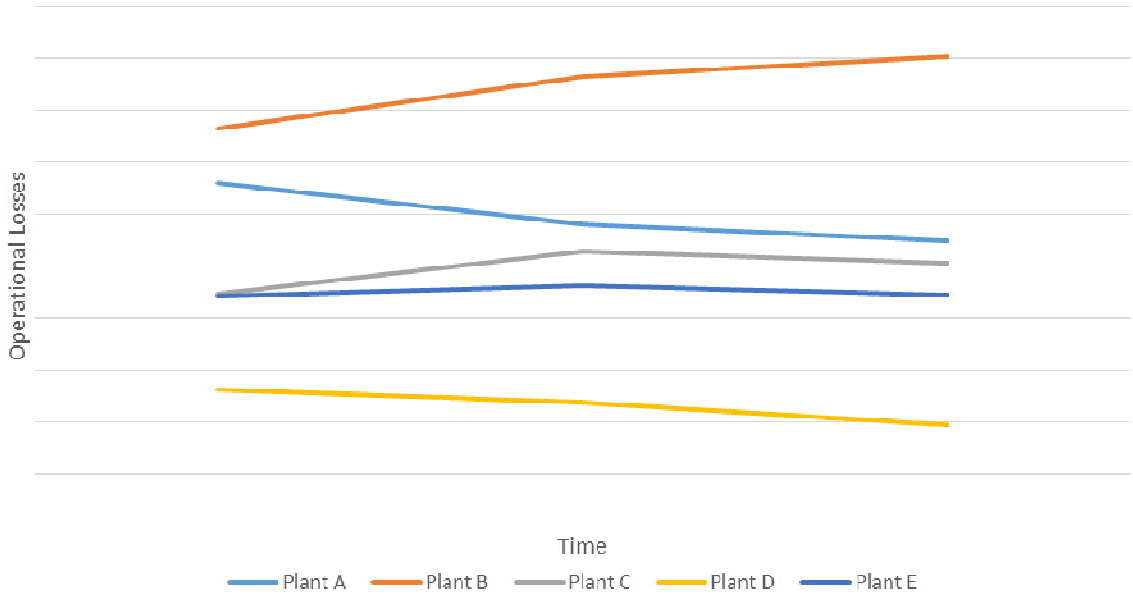

Figure 5-2: Representation of Operational Losses at Five Different Plants Over Time. The Variation is Indicative of Differences in Plant Performance Even When Controlling for External Factors.

Operational losses are calculated as Adjusted Availability Rate Losses. These losses represent time that equipment should be available but is non-operational for a variety of reasons (e.g., lacking or defective stock, missing operator, breakdown maintenance, and other causes). For example, in Figure 5-2, there are three bands in which manufacturing facilities function. Plant D is a highly productive facility with lower operational losses, while Plant B is on the other end of the spectrum with much greater operational losses. Plants A, C, and E are grouped together somewhere in the middle. This graphic presentation also allows for the monitoring of trends over time. Here Plant B is shown to be getting worse over the examined time period while the other plants are staying even or improving.

Classifying different manufacturing facilities at the productivity node as high or low can depend on the industry and the particular company, but comparisons within the

existing portfolio (and even projections for new facilities) can provide a good baseline. With the data presented here, the question is whether to consider the middle group as being "high" or "low" productivity facilities. These decisions on the margins are the difficult decisions that demonstrate the need for involvement by those with experience. One advantage of presenting the data in this manner is to enable those people to make the decisions with a common set of information and assumptions.

5.2.3. Cost Comparisons

Optimizing a manufacturing facility portfolio at a network level requires comparing costs across different facilities. This research focuses more specifically on costs associated with operating efficiencies of different facilities, but could be supplemented with a large number of additional financial analyses. The two most relevant cost comparisons for the purposes of this research are the costs of losses incurred due to decreased productivity versus the costs of: 1) closure and shifting products to other existing facilities and 2) closure and building new facilities to make product.

5.2.3.1. Shift to Other Existing Resources

One option for optimizing the manufacturing facility portfolio is to shift resources to the most productive facilities, thereby limiting productivity losses experienced by the network. To calculate whether transfers make sense from a cost perspective, it is necessary to identify the key drivers of costs and gains. Consideration should be given to closing a facility when it operates at such a level below its peers (which have available capacity to assume additional product) that the following is true:

$$\begin{aligned} &Productivity\ Loss\ Costs + Operating\ Costs \\ &\qquad > Closure\ Costs + Product\ Transfer\ Costs \end{aligned} \tag{10}$$

Productivity Loss Costs can be calculated as described in Section 3.4.2. The differential in Adjusted Availability Rate Loss between two plants being compared can be used instead of calculating total cost of losses of each individually. The two additional variables that must be accounted for to determine Productivity Loss Costs are the time horizon over which to evaluate the cost of lost productivity and operating costs and the multiplier to be used for lost time. One potential time horizon to consider could be a weighted average of the amount of time products made at the facility are expected to remain in production. This comparison could be completed at a facility level with every product needing to find a home elsewhere, at the equipment level with production on a particular piece of equipment needing to be relocated, or at a product level with a particular product needing to be relocated.

In addition to savings from more productive resources, additional savings are obtained by reducing or eliminating operating costs in the old facility. If the entire facility is closed and production relocated to another facility, the entirety of the operating costs

may be considered as savings for the sake of the analysis. However, if in the more likely scenario products must be distributed between multiple facilities the cost savings should be allocated between all the disparate facilities so that no one facility receives disparate credit in the analysis. The analysis of a strategy could again be evaluated by apportioning the operating cost savings according to a weighted average by some metric (e.g., by total current product cost within the existing facility).

Countering the savings are additional costs that are incurred through the closure of a facility. These costs can arise from many areas, including, but not limited to, costs associated with breaking contracts, fulfilling pension obligations, and rehabilitating manufacturing sites for environmental issues. Some of these costs may be offset by the sale or alternative use of the former manufacturing site, but there is expected to be a cost associated with the closure. While this closure cost is likely unknown, and never will be fully known until an actual closure event, those experienced within a company should be able to put a reasonable projection on the expected cost for the sake of analysis. As with the savings, closure costs should be allocated appropriately based on distribution of product within the network.

Another cost is that associated with moving production of products from one site to another. Depending on the product, these costs may be minimal if another site planned to assume production is already creating similar product and does not need new equipment or training. On the other end of the spectrum is when specialized equipment needs to be moved to a new facility or existing equipment must be reworked to handle the new product. In such cases the product transfer costs can be significantly higher and may alter the decision making process.

5.2.3.2. Greenfield

Much of the description in the previous section is the same for a Greenfield strategy, with some notable exceptions beyond substituting Greenfield Costs for Closure Costs in the below equation:

$$\begin{aligned} &Productivity\ Loss\ Costs + Operating\ Costs \\ &\qquad > Greenfield\ Costs + Product\ Transfer\ Costs \end{aligned} \tag{11}$$

One of the primary differences is in the time horizon when evaluating a Greenfield strategy. For Company X, as for most industrial companies, choosing to Greenfield and build a new plant is a long undertaking. Such a plant could be expected to last for 20, 30, or even more than 40 years. A significant capital expenditure is associated with choosing to Greenfield and with too short of a time horizon the equation may never result in a recommendation of pursuing a Greenfield strategy (except, perhaps, in the case of the absolute worst performing manufacturing facility and an anticipated state of the art new facility).

Another big difference is that projecting capability of a Greenfield is purely that, a projection. By its very nature there is no operating history on which to base an estimate of future productivity. Instead, an estimate of Adjusted Availability Rate Loss is required. One good source for this estimate is a compilation of the effectiveness of the best practices from around the company. Combined with expertise from those within the company (and even external consultants), a reasonable estimate for how a new facility can operate could be achieved. Particular care should be given to the impact of culture, and by association the people to be employed in the new plant, on this expected performance level.

Choosing to Greenfield is a big move for a company and one that is always treated with great care. Given the significant costs and often outsized expectations for a new facility, there is tremendous pressure to deliver on all those involved. This framework should help give leaders confidence in making the decision to Greenfield.

5.2.4. Obsolescence

Moving beyond comparing costs between facilities, attention must be paid to the capabilities of even the most productive and best performing facilities. Such facilities may be inclined to rely on previous success to carry them into the future. However, forces beyond the control of the facility may render their equipment obsolete for two reasons: 1) the equipment can no longer make the product that is in the pipeline (Capability Obsolescence) or 2) the equipment can no longer be maintained with readily available parts to make the current products (Maintenance Obsolescence).

5.2.4.1. Capability

Products in many industries, including that of Company X, are progressing rapidly with the development of new technologies throughout the industrial sector. For example, 3D printing technology is allowing geometries previously considered impractical for production to be realized. As customers learn to demand these more advanced products, existing technologies that have previously proved reliable for manufacturing may be infeasible for manufacturing new product. This can occur because current equipment is wholly incapable of making the new product or is unable to do so at reasonable yield levels.

It is important for a company to have a fundamental understanding of the capabilities of the equipment with respect to products in the pipeline. This includes a reasonable expectation for performance of existing equipment with the new products through all aspects of the manufacturing process. Manufacturing facilities should be involved with this analysis as well, and the facilities should understand obsolescence of equipment is largely out of their control and is not reflective on their viability as a going concern into the future. Rather, obsolescence of equipment because of capability limitations simply accelerates decisions that are inevitable due to the progress of time.

5.2.4.2. Maintenance

Equipment may also become obsolete because it can no longer be maintained. This is distinct from Capability Obsolescence because the products can still be made but it is untenable to maintain equipment at required levels for production. Maintenance Obsolescence is largely a result of equipment suppliers advancing their technology and no longer supporting older equipment that may have been installed for several decades. Though this has occurred with largely uninstrumented equipment in the past as parts have evolved over time, this could become increasingly common as equipment becomes more dependent upon software versions that are no longer supported by a vendor.

A difficulty in measuring Maintenance Obsolescence is that it can creep into a factory as only one part of a complex machine is in scarce demand. However this can soon become an exercise akin to plugging a series of proliferating holes in a dike. While there will likely always be a way to keep current equipment running, doing so can become burdensome to the company. This is especially true when a longer term outlook would suggest a shift to new equipment would be preferable. Involvement of the manufacturing facility is crucial in accurately understanding the maintenance costs of their equipment.

With both Capability Obsolescence and Maintenance Obsolescence, the result is largely out of the control of the facility itself. The fact that equipment becomes obsolete should not be counted against a facility for future productivity. Instead, the question becomes whether a given facility is primed to be successful if it receives a capital investment.

5.2.5. Readiness for Investment

Much of the analysis in this research has led to this key question: how will a plant respond when it receives capital investment? This most fundamental of questions is a function of the past, present, and future setup of the manufacturing network, and is crucial in establishing an optimal long term manufacturing strategy. Previous facility and equipment metrics, as discussed above, can be useful in forecasting future performance. This is especially true when a plant has earlier experience in implementing new technology. Such previous experience is not determinative, but can be instructive. Still, much of the success of an investment is dependent on factors external to the plant that exist currently and into the future.

Many of these factors are captured in the EPIC framework developed in *Global Supply Chains: Evaluating Regions on an Epic Framework* [8]. The four main pillars of EPIC are the following: Economy, Politics, Infrastructure, and Competence.

Economy in the context of the decision tree focuses on how well a particular locality around a plant is performing and its long term outlook, such as growth rate and the population. Other factors, including exchange rate stability, consumer price inflation, and tax environment are also important when evaluating the economic conditions of an area. Plants in better performing economies could be expected to better handle

investment as outside economic concerns would likely provide less of a drag on plant performance.

Politics can play a large role in how well a plant can respond to a new investment. Some examples of political considerations are stability of a local area, ease of doing business, legal and regulatory hurdles, and other barriers to business (e.g., tariffs and intellectual property protections). Increased stability and lower barriers could be indicative of an environment that facilitates future success.

Infrastructure comes in many forms, and in the EPIC framework is broken into three categories: physical, energy, and telecommunication. Physical focuses on roadways, railway network, and air and water transportation. Energy looks at supply of electricity, fuel, and water. Telecommunications considers telephonic and internet-based activity. Poor scores in these areas indicate infrastructure could be a hindrance on future investment returns.

Competence is perhaps the most important consideration for the purposes of the decision tree as it focuses on the critical component of facility culture: the people. Some of the elements of competence to look at are labor productivity, labor relations, availability of skilled labor, and education level of staff and management. Other features of a region beyond these common ones, such as how people in a region regard work, can also be considered. Regions with poor education and an attitude of working to just get paid and not being proud of the work could be indicative of a lower return on investment.

All of these factors, in combination with demonstrated previous performance, are important in projecting the success of a capital investment. Nothing can truly guarantee success, but facilitating conversation around these standardized pillars furthers the probability of success of the immediate decision that is made and creates learning opportunities to revise the process based on the outcome of the decision. With standardization, these learnings should be more readily available and understandable by those who were not involved in the prior process.

5.3 Case Studies

The value of the proposed decision tree to Company X is in its applicability to situations it may face as it evaluates how to modify and maintain its manufacturing facility footprint. Two hypothetical scenarios below are used as examples of how an analysis progress through the decision tree to a recommended potential course of action. Plant Y is a high performing facility but one that engenders great debate about whether to invest or allow to run its course. Plant Z is a lower performing plant that continues to maintain a place in the manufacturing portfolio despite widespread agreement about its prior performance.

5.3.1. Plant Y

Plant Y makes products that continue to be a part of the company's manufacturing strategy into the immediate future (e.g., greater than 80% of the volume of current products currently in the facility are projected to be there in four years). The facility is highly productive, with an Adjusted Availability Rate Loss of less than 15%. Plant Y is achieving this success despite having older equipment with replacement parts that frequently must be found on the secondary market. The plant is in a stable region and has a highly educated workforce in a fairly flat organizational structure.

The decision tree developed herein suggests the company should consider Reinvesting in Plant Y. Plant Y has a high vitality, so change is not absolutely necessary to keep a sufficient level of product in the plant to keep it viable. Plant Y is also very highly productive, and by the Adjusted Availability Rate Loss metric is determined to be the most productive manufacturing facility. The next question is then about the level of Maintenance Obsolescence, which here is quite high and getting worse as equipment maintenance parts become more and more difficult and costly to obtain. The key question then becomes how the plant can be expected to respond to a capital investment. Many of the EPIC factors suggest investment could be successful at Plant Y, and when supplemented with anecdotal evidence (e.g., previous success in quickly starting up new equipment) the logic for further considering to reinvest in the facility is clearly laid out.

5.3.2. Plant Z

Hypothetical Plant Z provides a stark contrast to Plant Y. Plant Z makes many products that are planned to be phased out in the immediate future, leaving less than 50% of its capacity accounted for in current planning scenarios. Even if production planning wanted to put new products into Plant Z, it would be unable to do so because the current equipment is unable to handle the newer products. Plant Z is an older facility that has gone through multiple equipment transitions, yet these have often failed to deliver the expected performance. Some of the most recent equipment updates would allow for transferring product in from other facilities. This possibility is influenced by the fairly high Adjusted Availability Rate Loss (> 40%) for Plant Z.

Evaluating this scenario with the decision tree results in a recommendation of Closure. Plant Z's low vitality shifts focus first to the possibility of introducing new product into the facility, and when this is determined not to be viable because of capability limitations (Capability Obsolescence) and the inability to assume other existing products, the analysis turns to the readiness of Plant Z to receive investment. Though the EPIC framework suggests some positives in the region and at the facility, previous poor performance with new equipment suggests the plant is not as primed as others to respond well to new investment (or at least further investigation of this aspect is warranted). Plant Z's low productivity and lacking culture, as suggested by the high Adjusted Availability Rate Loss metric, result in the recommendation for Closure.

5.4 Implementation

The decision tree approach to managing the manufacturing footprint of a company, which is a function of managing the lifecycle of the manufacturing facilities that make up the network, is a new idea for Company X. Despite the novelty of this approach, implementation can be successful at Company X (and other manufacturing companies) by following some key principles. These principles include: 1) using existing metrics and frameworks when available; 2) identifying the key roles to be played by decision makers; 3) making the decision tree as transparent as possible to those affected by the decisions; and 4) establishing a recurrent process for repeating the analysis.

The decision tree provides a more formalized process for proceeding with the decision making process related to the future of manufacturing facilities within a company by building on many existing metrics and approaches that are currently in place at Company X. The use of existing metrics is an acknowledgment that the current process is not fundamentally flawed and that people are not required to learn a whole new way of performing their duties. Instead, the decision tree structures the work of those involved with the process and lays bare the assumptions and data at each node to be discussed amongst the decision makers. Engagement and support of decision makers is critical to long term success and development of the model, and this engagement should be helped in part by basing the model on many familiar elements.

Additionally, the decision tree is not intended to be, nor can it function, completely independent of human input. Starting with the underlying assumptions that lead to how data is collected and continuing all the way through to the ultimate decision of how to structure the future manufacturing portfolio strategy of a company, the decision tree does not work without wide ranging involvement from interested parties. It is important for decision makers to understand that the decision tree is not intended to take their power away. The decision tree actually gives the decision makers more information for guiding the future of the company and for influencing how others respond to their positions. Transparency of the roles to be played by various team members involved in the decision making process (particularly when these roles are closely tied to functions they have already been performing) can further help achieve and maintain critical levels of engagement.

Transparency of information is also vital to the current and long term success of the decision tree approach. The decision tree addresses some of the potential downfalls of long term capital planning related to loss of knowledge with time and lack of understanding by stakeholders. Through standardization of processes in the form of the decision tree, future decision makers will be able to revisit previous decisions and understand the rationale behind them. Strong, consistent documentation will enable even further retrospective evaluation of the decision-making process once results are known, thereby facilitating a virtuous cycle of continuous improvement and knowledge sharing.

Transparency in decision making is also valuable when it is visible at the plant level. When manufacturing facilities are unclear of their future, and particularly how their current performance affects that future, they may become discouraged and lessen the overall morale of the facility. As previously discussed, the expectation is that culture plays a significant role in how a manufacturing facility performs. Therefore, when plant management becomes discouraged, this very reasonably can trickle down to performance. This could be the triggering event of a vicious cycle where performance continues to decline, leading to the plant to look worse to decision makers, to plant management becoming more frustrated, and so on. Keeping plants involved, or at least aware of how decision makers evaluate the future of a facility, can help avoid this downward spiral.

Finally, and key to the success of implementing the decision tree, is that it must be implemented as part of a planned, recurrent review process. These decisions about how to manage the lifecycle of a manufacturing facility can have wide ranging, long term repercussions on entire regions. Making such decisions based on the situation at a particular moment in time could be rash and set a company back several years, if it ever recovers. A one-time, project-based analysis could encourage this type of instant decision making. In contrast, a recurrent process facilitates a longer term outlook and suggests adaptability to changing conditions over time. The ability to adapt with changing circumstances over a period of time is essential to sustained success, and making the decision tree analysis a fixed aspect of any company's planning strategy is a good step.

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6 Recommendations

Managing the lifecycle of manufacturing facilities is an important and difficult task. Timing is key to making these decisions. Holding onto underperforming facilities can function as a large drain on company resources, as can failing to extract full value out of better performing facilities. In a global, mass producing corporation like Company X, lost time for manufacturing operations truly is money.

The decision tree proposed herein is intended as a tool to improve this decision making process. The value of this tool goes beyond the specific analyses at nodes on the decision tree to the greater understanding and cultural shifts that can be achieved at a company through implementation of this process. Acceptance by key decision makers is important to implementation and is affected by the faith of others in the accuracy and efficacy of the model and the way it handles the problems it is intended to solve. Accordingly, the decision tree must be continuously improved and developed.

The focus on manufacturing cost and the way manufacturing costs are calculated is one area in particular that could be the focus of additional work. Manufacturing costs are clearly important and need to be monitored and controlled, but there are other metrics relating to the total cost of ownership. These metrics can include measures such as cost of flexibility, cost of lead time, and cost of added risk. [8] In addition, looking at profitability metrics could provide additional insight into how well a facility is contributing to the goals of the company as opposed to how cheaply it is making product. This can include looking at the contribution of a manufacturing facility to the profit of the company and performing some of the analyses discussed above using profit as a comparison instead of cost. When looking at profit, the analysis would focus on maximization of gains rather than minimization of losses. This is a step toward treating manufacturing as a key driver to success rather than just a necessary cost.

Data must be available and reliable to help ensure success of any analysis. While this early version of the decision tree is based on the data available, there is room for growth using the metrics identified above by collecting and enabling access to data required for the analysis. For example, with profitability measurements it would be necessary to track the sales and prices of products coming out of a particular facility and matched with the related costs. These are complex issues that require collection of a wide variety of information that may not be already tracked, and implementing new data collection processes will require the efforts of a broad-based team. However, putting in the time to properly measure and track the relevant information could provide dividends in the long run in the form of improved decision making.

Collection of current data could also be an area for improvement if collection and recordation is inconsistent between (or even within) facilities. Inconsistencies lead to additional data processing and may raise doubts about the trustworthiness of the source if significant data alteration is required. Taking a proactive approach and identifying the information and analyses that are desired, whether in the context of the decision

tree or otherwise, can reduce these inconsistencies and improve the overall reliability of data in the network. This additional focus on the value of data collection is yet another area in which behaviors in the manufacturing facility can be expected to improve, or at a minimum provide another data point in the analysis of how plants respond to investment.

Focusing on how ready plants are for investment is a potentially enormous area for expansion of the work introduced in this research. Future work could go well beyond the high level measurements identified above and delve deep into different areas that could have an impact on whether a plant is ready to receive investment. Particular focus could be paid to how a plant can be conditioned for investment over time. Though this type of work is beyond the scope of this research, it is closely related as unlocking the secrets of investing in a plant could be key to extracting a long, productive life from investments.

In conclusion, the decision tree resulting from this research is a starting point, not an end point. It represents the first step in pursuit of continuous improvement across an entire manufacturing network by helping determine what that manufacturing network should look like. The decision tree establishes the questions that should be asked, and can provide recommendations of future actions based on the current status. However, the decision tree should not be the ultimate arbiter and should instead be used as an additional tool in the decision making process about how to proceed with respect to the handling of the manufacturing footprint.

Implementation of the decision tree is expected to have benefits well beyond the output recommendations as the mere process of transitioning thinking to this framework can have benefits throughout an organization. Shifting to the mentality of the decision tree requires clearly establishing the questions to be asked and the data that can be used to answer those questions, including laying bare any underlying assumptions. This mentality can also allow for additional transparency vertically throughout an organization, both now and in the future. Manufacturing facilities that understand why decisions are being made in a certain direction will be more likely to accept those decisions or change their behaviors in a way to alter the analysis. This is especially true if the manufacturing facilities are judged on behaviors that take into account differences between facilities and focus is placed on those behaviors that are within the control of the plant.

In the end, the decision tree really comes down to a focus on people and the culture of not just a plant, but an entire company. People want to succeed and a company can help facilitate mutual success for both individual and corporation. The decision tree represents the beginning of a tool and a process that can help lead to this brighter future. The decision tree does not eliminate the hard questions, but does make them more understandable to both decision makers and other stakeholders. And when it comes to determining the life of a manufacturing facility and all those affected, both personally and professionally, a company would be doing a great disservice by not doing the best it can with these hard lifecycle questions.

7 References

[1] R. W. Shmenner, »Every factory has a life cycle,« pp. 123-129.

[2] O. Myklebust, »Zero Defect Manufacturing: A Product and Plant Oriented Lifecycle Approach,« *Procedia CIRP,* årg. 12, pp. 246-251, 2013.

[3] Leaders for Manufacturing, and Technologies Enabling Agile Manufacturing, »Next-Generation Manufacturing: A Framework for Action,« 1997.

[4] Manufacturing Enterprise Solutions Association, »2013-2014 Manufacturing Metrics That Really Matter Summary Report,« April 2014.

[5] The Productivity Development Team, OEE for Operators - Overall Equipment Effectiveness, New York: Productivity Press, 1999.

[6] R. H. H. a. G. P. Pisano, »Beyond World-Class: The New Manufacturing Strategy,« *Harvard Business Review,* pp. 77-86, 1994.

[7] R. H. H. a. R. W. Schmenner, »How should you organize manufacturing?,« *Harvard Business Review,* pp. 105-118, 1978.

[8] B. D. Stank, »Global Supply Chains,« November 2014.