DEVELOPMENT OF A DYNAMIC COSTING MODEL FOR ASSESSING DOWNTIME AND UNUSED CAPACITY COSTS IN MANUFACTURING

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DEVELOPMENT OF A DYNAMIC COSTING MODEL FOR ASSESSING DOWNTIME AND UNUSED CAPACITY COSTS IN MANUFACTURING

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[To everyone who helped]

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SUMMARY

While costing methods have developed over the years, they are often static in nature and ill-suited to the dynamic nature of production lines. Static costing systems are often developed for long-term analysis and rely on averaged data. Due to this, they lack the ability to aid short-term decision-making. In addition, the use of averaged data prohibits a static costing system from accurately capturing and tracing the cost effects of changing system behavior like random downtime events. A dynamic costing system, on the other hand, can capture the effects of events and their true costs in a manner that can aid short-term operational management. For example, a dynamic costing system that accurately calculates and traces the costs of downtime can help managers to more effectively allocate resources and identify areas for improvement.

The proposed methodology is a dynamic activity-based costing method that relies on real-time production line data to track costs, specifically the costs of unused capacity and the added costs due to downtime events such as machine breakdowns. The methodology aims to trace these costs to responsible cost centers, activities, and stations on the production line to give a better representation of the total cost of production, specifically in regards to normal manufacturing costs, added downtime costs, and added costs from excess capacity. In addition to monetary costs, the methodology provides a framework for tracking environmental “costs”, such as energy use and waste, in order to aid plant managers with determining the environmental impact of their operations.

The methodology addresses a gap between activity-based costing and downtime costing by combining the two under a single methodology. It traces both monetary and

environmental costs to cost centers on the manufacturing line to aid continuous improvement efforts and the allocation of resources. By using real-time data, the methodology alerts management to changing system performance in a shorter timeframe than static costing systems. The methodology quantifies system performance in monetary values, which elicit more emotion and attention than traditional non-financial production metrics.

The methodology is shown in a case study of an automotive assembly plant. Specifically, the case study models the cost and resource use of an automotive paint shop and trace this resource use to specific areas of the paint shop to highlight possible areas for improvement. The case study provides results that show how the proposed methodology can allocate costs to normal production and the added costs of downtime and unused capacity. The case study splits these costs over the modeled case study stations and highlights possible areas of improvement.

This work primarily focuses on the development of the methodology and a framework for implementation. This thesis does not address the logistics of implementing a costing system based on the proposed methodology using actual automated data from actual production line data acquisition systems. Additional work is needed to address these logistics and to further refine the methodology to compensate for these logistics.

CHAPTER 1

INTRODUCTION

1.1 Motivation for Work

Globalization and advanced manufacturing have led to increased competition in the global marketplace. This increased competition pressures manufacturers to continually reduce costs in order to remain competitive. Companies have developed costing methods in order to better calculate and trace their costs, as discussed in Chapter 2, Section 2.2. While these costing methods have developed over the years, they are often static in nature and are ill-suited to the dynamic nature of production lines. Due to this, they lack the ability to aid short-term decision-making. In addition, the use of averaged data prohibits a static costing system from accurately capturing and tracing the cost effects of changing system behavior and random downtime events. This delays decision-making which could help to reduce costs.

A dynamic costing system, however, can capture changing system behavior and the effects and true costs of events in a manner than can aid short-term operational management. For example, a dynamic costing system that accurately calculates and traces the costs of downtime can help managers to more effectively allocate resources and identify areas for improvement. With the widespread adoption of real-time data systems on production lines, a dynamic costing system is possible. A dynamic costing system that relies on already gathered production line data is more easily developed and accepted than a costing system that requires additional sensors and hardware.

Presently, many companies are not able to accurately assess the costs of their downtime. Some efforts have been made in order to calculate these costs and are discussed in Chapter 2, Section 2.3. In addition to these downtime costs, companies often have trouble quantifying the costs of unused, or excess, capacity. Chapter 2, Section 2.3 discusses some efforts to calculate excess capacity costs.

This thesis presents a dynamic activity-based costing methodology that relies on near real-time production line data to track costs, specifically the added costs of unused capacity and added costs due to downtime events like machine breakdowns. The proposed methodology aims to trace these costs to responsible cost centers, activities, and stations on production lines by building off of previous activity-based costing and downtime costing methods. The goal is to provide a better representation of the total cost of production, specifically in regards to normal manufacturing costs, added downtime costs, and added costs from excess capacity.

In addition to monetary costs, manufacturers are increasingly concerned with their environmental "costs", such as energy use or waste, due to governmental regulations and consumer pressure. The proposed methodology also provides a framework to track these environmental costs in order to aid plant managers with determining the environmental impact of their operations. These environmental costs are calculated in parallel with monetary costs in a method that will be further discussed in Chapter 3.

Chapter 1 provides a general discussion of the thesis topic including some background motivation for the work and an overview of the thesis layout. Chapter 2 provides a literature review of related topics relevant to this thesis. Chapter 3 discusses the development of the proposed methodology from a traditional activity-based costing system to a dynamic costing system that tracks normal production costs, added downtime costs, and added costs due to unused capacity. Chapter 4 discusses a case study that was performed to test the validity and usefulness of the proposed methodology and to illustrate an example of the methodology's use. The thesis concludes with a final summary and recommendations in Chapter 5.

1.2 Industry Needs

Traditionally, companies have always been pushed by competition and demands by the marketplace. With increased competition in the global marketplace, there is a need to provide goods and services that are demanded by consumers at a price point that satisfies both the consumer and the producer. For the consumer, the price needs to provide a good value in terms of quality and cost. For the producer, the price needs to cover the costs of producing the product and hopefully provide a decent profit margin as well (disregarding cases where a producer may offer a product at a price below cost to achieve a goal outside of profitability such as building market share). Because of this, the producer needs to accurately track costs in order to determine the necessary price point for the good or service. Perhaps more importantly, a good costing system can also highlight possible cost-saving measures that will improve profitability.

In addition to these economic considerations, producers may make decisions based on environmental considerations. Companies may investigate their environmental impact because of pressure by consumers, governmental regulations and obligations, and social obligations. In order to accurately assess their environmental impact, companies need systems to track resource consumption and waste production. Ideally, such systems will allow companies to also decrease their environmental impact.

Previous authors have discussed these economic and environmental considerations, in addition to social considerations, as a “triple bottom line”. The triple bottom line concept is an accounting framework that measures the company’s environmental and social impacts, in addition to profits and other traditional financial measures (Slaper and Hall 2011). Andrew Savitz and Karl Weber say that the triple bottom line concept “captures the essence of sustainability by measuring the impact of an organization’s activities on the world… including both its profitability and shareholder values and its social, human, and environmental capital” (Savitz and Weber 2006).

While this work does not deal with the social aspect of the triple bottom line concept, it does look at the economic and environmental aspects. These economic and environmental considerations are further discussed in the subsections below.

1.2.1 Economic Considerations

Economic considerations range from appeasing shareholders and attracting new shareholders to meeting revenue projections. Overall, the most important goal of any company is to make a profit. The revenue aspect of a company’s recorded profit is largely determined by the marketplace. On the other hand, the cost aspect is largely determined by the company itself. Other than regulations that implicitly lead to some guaranteed costs, companies can choose their method of spending however they see fit to produce their product.

Because companies are largely in control of their costs, it is important that they track these costs accurately and determine from where these costs come. By accurately assessing and allocating costs to their responsible cost centers, companies can hope to decrease costs and, in turn, increase profits.

1.2.2 Environmental Considerations

In addition to economic goals, companies have become increasingly interested in achieving various environmental goals, such as limiting environmental impact in order to garner consumer support or limiting waste production in order to meet government-regulated quotas.

Consumers have begun to put additional pressure on companies to practice in an environmentally-conscious manner. Elkington refers to this as the "emergence of the green consumer." Elkington suggested that this has led to a "greening" of the marketplace, beginning in the early 1990s, as consumers began to consider environmental issues. Previously, consumers were largely seen as indifferent to such issues when choosing products in the marketplace (Elkington 1994). Mintel Group, a market research firm, stated in its prediction of 2010 global consumer trends that environmental issues are viewed as important by "nearly half of UK adults" and that "90% of Americans buy green products at least sometimes" (Mintel Group 2009).

In addition to this consumer pressure, producers face government regulations concerning their environmental impact. These pressures have pushed producers to track their environmental impact more closely for both reporting purposes and minimizing their impact. If producers can accurately assess their environmental impact and allocate this impact to the responsible sources of this impact, they can hope to make improvements to decrease their environmental impact and better satisfy the demands of both consumers and regulatory agencies.

1.3 System of Interest

While costing systems may be developed to survey costs and aid decisions at the company level, the system of interest in this work is a manufacturing system. More specifically, the manufacturing system of interest is a production line with real-time or near real-time data acquisition systems. Ideally, these data acquisition systems are previously installed and track system behavior such as the current system state, the current production count, and current buffer levels.

The research in this thesis is meant to leverage previously installed data information systems to provide costing system input data. Using this data, the costing system will determine both monetary and environmental costs using pre-assigned allocation drivers. This cost data is meant to aid plant management with decision-making in a shorter time span than traditional, static costing systems.

Because the costing system uses dynamic data from the production line, it can accurately depict changing system behavior in a short time frame. This can alert plant management to changing behavior quickly. The costing system provides tangible figures (e.g. monetary costs and environmental costs like energy usage and waste production) for plant management to consider and compare to benchmarks and goals.

1.4 General Approach

This thesis builds on previous research in the domain of activity-based costing (ABC), particularly focusing on the use of activity-based costing framework to differentiate normal production costs from added costs due to downtime or excess capacity. The goal of this new methodology is to more accurately and more quickly quantify the costs of changing manufacturing system behavior in hopes of aiding short-term decision-making that will reduce costs.

Static costing models may not update data quickly enough to capture these changes in system behavior in a short time frame. Because dynamic models update more often, they are better suited for aiding short-term decisions while still aggregating data over a longer time period in order to aid long-term decisions.

In this thesis the methodology is first presented in a general way, detailing the development of the methodology from previous ABC methodologies. Afterwards, a costing model that was based on the presented methodology is presented in order to show the practical use of the methodology with a quantifiable example.

The model presented in the case study leverages simple spreadsheet software, Microsoft Excel, that could be used in a costing system to show a specific application of the methodology. The spreadsheet relies on simulated production line data. This is done to replicate how an actual costing system based on the presented methodology would behave. Actual production line data is not used due to proprietary and logistical concerns; however, actual production line information was considered when developing the model in order to produce a model that is reasonably close to a real world production line.

Simulation code was developed to replicate available production line data. The simulation code is programmed within Microsoft Excel using the Visual Basic for Applications programming language. The simulation code is relatively simple in order to satisfy the data requirements of the costing model. It is important to remember that this thesis does not intend to present a new method of production line simulation. The simple simulation code was created only to test the costing model without the need to link the costing model with outside commercially available simulation software.

The simulation code is discrete in nature with production line units moving through the system as full units; therefore, stations in the production line will not release work-in-progress (WIP) until all work on the individual unit is completed at that station and the unit is requested by the following station or buffer. In addition to this, buffers and stations will not accept a unit from a previous station or buffer until there is a request and space at the present station or buffer. The discrete nature of the simulation is discussed in more detail in Chapter 4, Section 4.3.

The costing model uses data from the simulation to determine resource use and allocate costs to responsible cost centers. The costing model assesses both monetary and environmental costs. The costing model updates for every simulated minute in order to replicate a costing system based on real-time minute-by-minute data from a production line. The costing model sums these minutely results to determine total costs for a simulated eight-hour shift.

1.5 Research Questions

This research was conducted with a higher level scope and meant to introduce a concept. Therefore, this work focuses on the concepts behind the proposed methodology and theoretical framework of the methodology. The case study is presented merely as an example to elaborate on the proposed methodology and describe a possible theoretical implementation. This work does not focus on the specific logistics of implementing such a system's implementation.

This thesis focuses on the following research questions which guided this work:

1. **Can an activity-based costing methodology be developed to accurately capture the effects of dynamic events that occur during manufacturing?**
2. **Can the proposed methodology separate manufacturing costs into normal production costs and added costs due to downtime events and unused capacity?**
3. **Can this methodology be implemented within a realistic case study of an industrial facility to model an actual activity-based costing model using spreadsheet software?**
4. **Does this model produce results and insights that can be used to aid short-term and long-term decision-making to ultimately help the company's bottom line?**

1.6 Thesis Overview

This document presents the research and application of this methodology within five chapters. In Chapter 2 a review of pertinent literature is given to provide background of previous work, to discuss the relevance of previous work to the research, and to provide a justification for the current research. Chapter 2 aims to answer *why* this research was done.

After the literature review is presented in Chapter 2, the development of the methodology is discussed in Chapter 3. Chapter 3 discusses *how* this research was done. Chapter 3 first discusses the system of interest for the methodology and then discusses the development of the methodology. Chapter 3 ends with a discussion of the implementation of the methodology and presents a small example implementation.

Following this presentation of the methodology, Chapter 4 presents a case study that was performed using the methodology to show the development of a specific costing model based on the developed methodology. This shows *what* was done to implement the costing model for a complex manufacturing system. The case study is performed using various scenarios to see the effectiveness of the model in different circumstances. The results of these scenarios are discussed to see how well the model works.

Lastly in Chapter 5, the research is summarized and final conclusions are drawn from the research and case study. Chapter 5 examines how well the research answers the research questions presented in Chapter 1, Section 1.5 and discusses lessons learned during the research and possible future improvements on the work.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter Overview

This chapter provides a brief review of pertinent literature for this thesis. There are three major topics covered in this chapter: activity-based costing, downtime and unused capacity costing, and environmental monitoring in manufacturing. Each major topic is discussed in a separate section. Each section is broken into four subsections: description and behavior, current uses and applications, issues with current uses and applications, and thesis relevance. This chapter provides background for this thesis as well as a basis for validating the need for the work contained in this thesis. The goal of this chapter is to give the reader a basic understanding of previous work in this field and to illustrate the motivation for this work.

2.2 Activity-Based Costing

2.2.1 Description and Background

Companies track their costs and revenues for a variety of reasons. In addition to reporting to regulators and shareholders, the most important reason for a company to properly quantify their expenditures and revenues is to aid management in decision making that will lead to higher company profits.

As discussed in Chapter 1, Section 1.2, costs are largely determined by the company while revenues are largely determined by the marketplace. By accurately quantifying costs and tracing these costs to responsible cost centers and products, a company's management gains a better perspective of the cost aspect of their profit calculations. This also provides insight for where costs can possibly be cut in order to increase company profits.

Traditionally, costs are split into two categories: direct costs and indirect costs. Direct costs are costs that go directly into the production of a good or service such as raw material costs. Direct costs are easy to allocate to the responsible products because they are inherently dependent on the production of that product. Indirect costs (often called overhead costs) are costs that help to support production. The allocation of these costs to responsible cost centers and products is a little more difficult because this overhead may support numerous products. In traditional or conventional costing, these indirect costs are allocated to cost objects by prescribed percentages that are typically based on production related quantities like number of labor hours, number of machine hours, or number of units produced.

The allocation of indirect costs can be simple such as using the number of units produced to allocate overhead costs; however, this may lead to inaccurate allocation and cause a distorted view of cost generation. In such an allocation scheme, high-volume products are allocated a higher burden of indirect costs than low-volume products. This allocation method may distort costs. This distortion comes from the fact that a high-volume product often requires less overhead per unit (such as shipping costs or marketing costs) than a low-volume product (Cooper and Kaplan 1988). Accuracy in the allocation of indirect costs is less important when overhead costs are a small percentage of total costs; however, with increased costs from advanced capital-intensive machinery and other overhead costs, there is a need for better accuracy and precision for costing systems (Latshaw and Cortese-Danile 2002).

Activity-based costing was developed by Cooper and Kaplan to address the shortfalls of traditional costing (Cooper and Kaplan 1988). Activity-based costing, commonly called ABC, uses a different structure than traditional costing. Whereas in traditional costing cost objects consume resources directly, activity-based costing adds a layer between the two called activities. In activity-based costing, cost objects consume activities which, in turn, consume resources. The figure below illustrates the difference between traditional costing and activity-based costing.

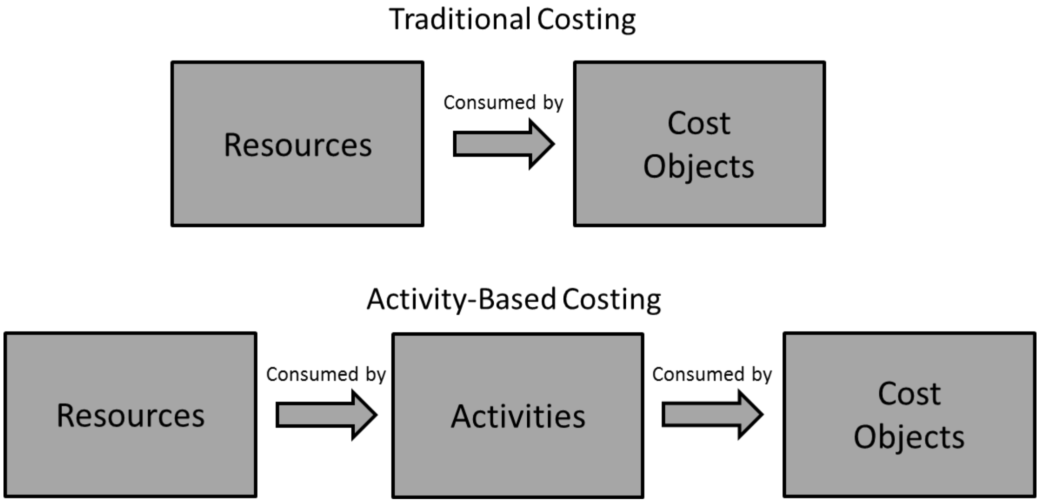


Figure 2.1: Traditional Costing and Activity-Based Costing Structures

Activity-based costing divides the production of cost objects into various activities such as direct manufacturing, marketing, or shipping. These activities can be further broken down into smaller sub-activities. For example, the activity of manufacturing could be broken into machining or forging subactivities. Cost objects consume their needed activities at specific rates called activity drivers. These activities require various resources (e.g. raw materials or labor) in order to perform. Activities consume resources at specific rates called resource drivers. Using this hierarchy from the cost object level to the activity level to the resource level (or reversely from the resource level to the activity level to the cost object level), one can follow the consumption of activities and then resources (or vice versa). This two-part consumption leads to a more accurate allocation of resource use across cost objects.

2.2.2 Current Uses and Applications

Since its inception ABC has become widespread. ABC has been used in a variety of industries and businesses. Jones discussed the implementation of activity-based costing and activity-based management (ABM) by armed forces in order to reduce costs, promote a culture of continuous improvement, and easily share and spread best practices (Jones 1998). Nachtmann and Al-Rifai showed the application of ABC in the air conditioning manufacturing industry (Nachtmann and Al-Rifai 2004). Becker et al showed the use of ABC for process-based governance in public administrations (Becker, Bergener et al. 2009). Chea illustrated how an ABC system can be used in the service sector to improve competiveness (Chea 2011).

In addition to the "traditional" use in various industries, activity-based costing has been modified in various ways to expedite the development of ABC systems. Kaplan and Anderson proposed a variant of activity-based costing named "time-driven activity-based costing". This variation aims to ease the implementation and maintenance of an activity-based costing system by estimating the unit times of activities and the cost per time unit of capacity instead of relying on employee surveys. The authors claim that this variant quickens the process of updating the ABC system by allowing managers to use their best knowledge to directly estimate resource use and update this estimate as needed (Kaplan and Anderson 2004).

Afonso and Paisana developed a method for performing ABC calculations in matrix form in order to simplify and expedite calculation (Afonso and Paisana 2009). Their method promotes developing matrices corresponding to each component of activity-based costing. The authors suggest first creating a "resource-activity" matrix corresponding to resource consumption drivers and an "activity-product" matrix corresponding to activity consumption drivers. Next, the authors propose creating a "resources" matrix which contains the cost of each resource per unit consumption by the various activities. By performing matrix multiplication between the "resource-activity" and "resources" matrices, one can find an "activities" matrix which shows the costs attributed to each activity. Matrix multiplication can then be performed between the "activities" and "activity-product" matrices to find the "products" matrix which details the costs associated with each product. The figures below illustrate this procedure (Afonso and Paisana 2009).

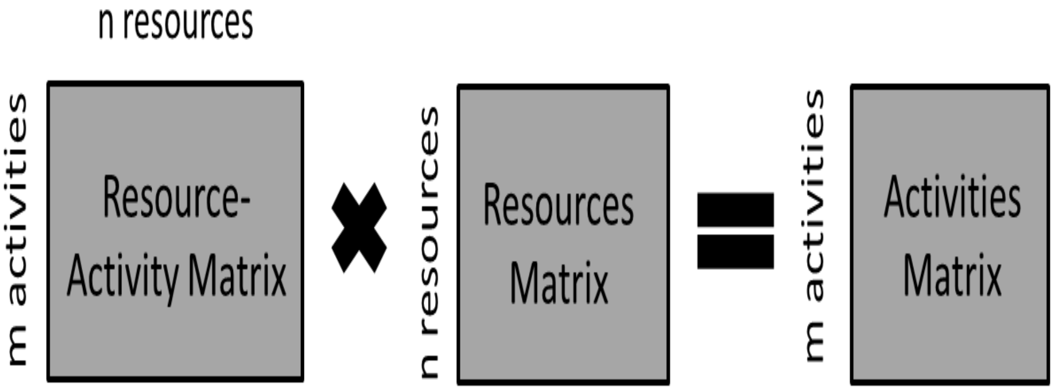


Figure 2.2: Activities Matrix Calculation (Adapted from Afonso and Paisana, 2009)

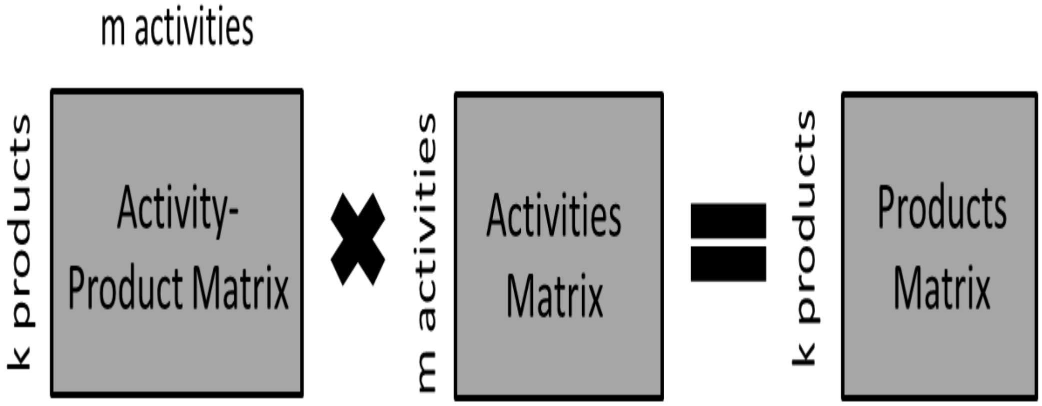


Figure 2.3: Products Matrix Calculation (Adapted from Afonso and Paisana, 2009)

In addition to these methods to expedite ABC system development and maintenance, several authors have identified the benefits of developing a dynamic or real-time costing system instead of a static costing system that is updated over longer time intervals. Karlsson discussed the use of real-time costing in the paper industry for determining the costs of specific units. Karlsson also noted that using real-time monetary production metrics is more in line with a company's financial goals than using traditional nonfinancial metrics. He suggested that metrics in terms of dollars naturally elicit more attention and emotion for continuous improvement activities than nonfinancial metrics (Karlsson 2007).

Ittner and Larckner discussed how the use of nonfinancial metrics alone may lead to worse financial performance. While the authors note the benefits of nonfinancial performance metrics, they also suggest that a lack of causal links between nonfinancial performance and financial performance may lead to companies focusing attention on the wrong areas for improvement. The authors note that, "Many companies adopt non-financial metrics without articulating the relations between the measures or verifying that they have a bearing on accounting…" (Ittner and Larckner 2000) While the authors primarily inspect company-wide performance measures like customer satisfaction, these issues are also relevant for nonfinancial performance metrics in manufacturing like overall equipment effectiveness or throughput. In some cases, improving these metrics may actually lead to worse financial outcomes.

Simmons notes that traditional ABC projects have a poor success rate due to their static and historical nature that has limited use in operational management of dynamic systems. He suggests that companies update their ABC systems readily to best inform decision-makers through the use of dynamic costing. Simmons defines dynamic costing as "the process of modeling the operations of the business to reflect how costs and profitability will vary with changes in any of the cost drivers and how changes in activities can affect the behavior of those drivers." The authors suggests that readily updating cost drivers with automated data can aid management with the distribution of resources and activities depending on current system behavior (Simmons 2005).

Macedo et al developed a real-time cost monitoring system in conjunction with system dynamics in an attempt to identify improvements to a microbiology laboratory's culture media production process with the goal of lowering the cost of the process. The authors used the system as a cost calculator and as a method of warning the user if current production is yielding a poor unit cost (Macedo, Ruiz Usano et al. 1997). Khataie et al looked at this basic idea and began to further develop it into a system dynamics model as opposed to a cost calculator (Khataie, Bulgak et al. 2010).

Cooper and Kaplan were quick to point out that the use of integrated cost systems is not without some possible troubles. The authors stress the importance of keeping short-term and long-term costing systems separate. Specifically, the authors warn against making long-term decisions based on short-term information and using real-time data to generate per-unit cost figures when determining customer or product costs. Cooper and Kaplan suggest that using real-time information to calculate per-unit costs may also lead to unnecessary pressures or complacency, depending on the current level of demand. For instance, when demand is low, per-unit cost will appear to increase despite possibly being no difference in productivity or efficiency. The authors do note, however, that operational control systems that incorporate ABC concepts into them can be useful for production facility managers, but the ABC system at this operational control level will be vastly different than the one used at the corporate level. The authors suggest that, despite the difference in scope between the two levels, some links could be made between operational control systems and higher level costing systems (Cooper and Kaplan 1998).

Some authors have used dynamic ABC cost models to simulate potential costs as opposed to tracking actual costs. Zeng et al developed a dynamic cost estimation model based on activity-based costing. The goal of their spreadsheet algorithm was to estimate the cost of running a production line before the line is built. In their simulation, the authors simulated random failure events in order to better replicate an actual manufacturing line. The authors noted that by using a dynamic simulation that simulated failure events, they determined that there would be a higher average cost per part than their static cost estimation model had shown (Zeng, Wang et al. 2012). This work shows the advantages and feasibility of dynamic cost models, specifically when looking at dynamic behavior such as random downtime events.

Some work has used the activity-based structure and applied it to other measurements besides monetary costing. Emblemsvåg and Bras built an environmental "costing" approach that runs parallel with a traditional activity-based costing methodology. They called the method "activity-based costing and environmental management" (ABCEM) and listed environmental "costs" of resources in parallel with monetary costs of resources. This use of environmental resource costs continues through the ABC hierarchy to determine the environmental impact of different cost objects (Emblemsvåg and Bras 2001).

Based on Emblemsvåg and Bras' work, Romaniw used an activity-based structure to model environmental impacts of different manufacturing processes (Romaniw 2010). Bargmann used the ABCEM methodology to develop a spreadsheet-based tool for small- and medium-sized enterprises to track their environmental performance (Bargmann 2002).

Jurek et al used an ABCEM approach to trace resource consumption to specific areas of a paint shop in an automotive assembly plant to highlight the biggest users of different resources (Jurek, Bras et al. 2012). Similarly, Oh and Hildreth used an activity-based structure and stochastic programming to aid decision-making in regards to energy demand response option contracts by tracing energy usage to specific manufacturing activities (Oh and Hildreth 2013). These environmentally-conscious methods will be discussed in more detail in Section 2.4 of this chapter.

2.2.3 Issues with Current Uses and Applications

While current costing methods are useful for long-term planning and budgeting, they are found to be lacking when it comes to shorter term goals like day-to-day or shift-to-shirt operations. Current costing methods are very static in nature and are incapable of capturing dynamic events on a production line. The current literature seems to largely discuss the use of activity-based costing only for long-term decisions and planning.

Concerns have been raised around the maintenance of ABC systems due to the large amounts of information required to develop and maintain such a system. Time-driven activity-based costing is meant to address this concern, but it still requires data entry that may be tedious or may only be performed over long time intervals.

To combat the tediousness of ABC system maintenance, some authors suggest the use of automated production line data to dynamically update ABC systems, but this discussion has largely been focused on aggregating automated updates to have a better picture of actual costs. This approach is certainly useful and considered in the presented work; however, it does not address the idea of using dynamic activity-based costing to guide short-term operational control. Alternatively, some work has discussed using dynamic activity-based costing to determine the unit costs of specific units, something that is promoted by Karlsson but dismissed by Cooper and Kaplan (Cooper and Kaplan 1998; Karlsson 2007).

2.2.4 Thesis Relevance

The previous subsections give background on the development and use of activity-based costing in the current literature. This review of ABC literature shows that traditional ABC and activity-based concepts have become widespread; however, traditional ABC is not without its faults. Specifically, ABC systems have been found to be difficult to develop and maintain. Some work has been done to automate ABC input data. This shows that an automated ABC system is possible and useful. Additionally, work by Zeng et al shows the usefulness of capturing dynamic events in the cost modeling of manufacturing lines in order to more accurately capture costs (Zeng, Wang et al. 2012).

This thesis draws on much of the previous work in activity-based costing, namely its basic structure. In addition to this structure, this thesis heeds some of the warnings made by Cooper and Kaplan and others in regards to some possible pitfalls when implementing an ABC system (Cooper and Kaplan 1998). The case study in Chapter 4 and example in Chapter 3 also use aspects of Afonso and Paisana's ABC algorithm that leverages matrix multiplication (Afonso and Paisana 2009).

While the proposed methodology does not strictly follow activity-based costing as presented by Cooper and Kaplan and further developed by other authors, it uses the basic framework of tracing resource use to specific activities and tracing activity use to specific cost objects. Whereas ABC is largely used to trace costs to specific products, the proposed methodology looks to trace costs to specific cost centers by determining their responsibility in the consumption of resources and activities. This difference will be further explored and discussed in Chapter 3.

2.3 Downtime and Unused Capacity Costing

2.3.1 Description and Background

While activity-based costing aims to determine the total costs of production, downtime costing aims to quantify the effect that random downtime events, such as machine breakdowns, have on the total cost of production. It is important to quantify downtime costs in order to aid company decision-making. Crumrine and Post referenced downtime consultants that estimated that only 20% of industrial facilities are able to accurately estimate downtime costs. These downtime consultants also suggested that many facilities underestimate their total downtime costs, sometimes by as much as 200-300% (Crumrine and Post 2006).

Crumrine and Post suggested that knowing the added costs of downtime would help management to pick the best capital projects as well as help management with justifying additional projects that will reduce downtime costs. The authors suggest that it is common for total downtime costs to approach or exceed the costs of capital projects to address downtime costs. The authors listed ten sources of added downtime costs (shown in the following table) and suggest that these downtime costs be calculated separately from other costs (Crumrine and Post 2006).

Table 2.1: Sources of Added Downtime Costs (Source: Crumrine and Post, 2006)

Source of Costs	**Explanation**
Equipment Related	Amortized costs accrued during downtime
Labor	Labor costs accrued during downtime
Product	Value of product lost due to downtime, "opportunity cost"
Startup	Energy surge costs, set up materials and manpower, scrap produced during startup, inspection and rework costs
Bottleneck	Effect on downstream equipment
Scrap	Costs associated from scrapped parts because of downtime failure
"Band-Aid"	Cost to temporarily fix failure events until permanent fixes are installed
Tooling	Rework and replacement tooling costs from downtime events
Parts/Shipping	Special handling and shipping of repair parts and late parts
Consulting, Contractor, Etc.	Costs of supporting downtime and solving downtime

While companies are concerned with the limited capacity that downtime causes, they are also concerned with having excess, or unused, capacity. Unused capacity can be defined as the difference between available resources and consumed resources (Tse and Gong 2009). There are costs that accompany this unused capacity because resources are still provided even though they go unused. Unused capacity costing aims to cut down on unneeded resources by quantifying the cost of resources that are unused during production and prioritizing possible cost-cutting projects.

It is often difficult to calculate unused capacity due to various reasons, such as the uncertainty of demand, extraordinary situations, and unexpected employee or machine behavior (Tanış and Özyapıcı 2012). It has been suggested that this complexity leads to the costs of unused capacity rarely being used (Paranko 1996). The use of unused capacity cost information can be helpful for a company's profitability in times of negative growth in demand; however, unused capacity cost information can lead to harmful business decisions in times of positive growth in demand due to the reducing of current capacity at the expense of future production (Buchheit 2003).

Even in times of negative growth in demand, the use of unused capacity cost information can lead to poor decision making. Brüggen et al profiled the role of excess capacity in the U.S. auto industry. In their work, the authors determined that the inclusion of excess capacity costs in the determination of production cost per vehicle led to a push for overproduction. This overproduction, while lowering the production cost per unit, caused an excess supply of vehicles for the limited demand. This led to massive rebates that hurt profit margins per vehicle and brand image overall (Brüggen, Krishnan et al. 2011). This suggests that it is important to calculate unused capacity costs separately from normal production costs, but unused capacity costs should also be considered with other available information before important decisions are made.

2.3.2 Current Uses and Applications

There has been some work that has attempted to quantify downtime costs. Much of this work has been focused on specific industries and situations. Edwards et al, for instance, attempted to predict downtime costs pertaining to the use of tracked hydraulic escalators in opencast mining in the United Kingdom. This work was a high level look at various pieces of hydraulic escalator equipment in an attempt to recognize trends for added costs due to downtime of the machines. The authors used regression analysis to estimate machine cycle times and hire costs per hour. Using these factors as well as machine operational conditions and job efficiency, the authors were able to estimate downtime costs across different pieces of equipment (Edwards, Holt et al. 2002).

Pascual et al provided an approach to minimize the life-cycle maintenance cost of production line machines by looking at the costs of different preventative maintenance and replacement policies. The authors specifically looked at the costs of routine preventative maintenance and equipment overhaul. The authors then attempted to compare these costs to the costs of repairing breakdowns to find optimal maintenance and replacement strategies (Pascual, Meruane et al. 2007).

Faria et al looked at the effect of downtime events on the production cost of producers in supply chain contracts. This work focused on balancing the added production costs of producing a large safety supply and the added costs due to loss of sales and due to penalties for not supplying the contracted amount of product to the buyer. The authors simulated the assembly line of an employer and incorporated random downtime events in an effort to optimize the internal design for minimal cost (Faria, Nunes et al. 2010).

Liu et al developed an algorithm for determining downtime costs based on the idea of opportunity windows. Their work quantified the cost of downtime events by determining the permanent loss of production caused by downtime events and then multiplying this permanent production loss by a prescribed cost per unit of lost production. In order to determine the permanent production loss of a random downtime event, the authors compared the length of the downtime event to the amount of time that it would take to either fill or empty all of the buffer space between the down station and the slowest station, causing the slowest station to stop. The authors proved that there is not a permanent loss of production unless the slowest station is stopped and suggested that a permanent production loss is the basis of added downtime costs (Liu, Chang et al. 2012).

There has also been some work that has attempted to quantify the costs of unused capacity. Cooper and Kaplan stressed that activity-based costing is useful for determining excess capacity (Cooper and Kaplan 1998). Several authors have mentioned ABC's usefulness for determining excess capacity. Cooper and Kaplan showed that the activity provided is equal to the activity that is used plus the activity that is unused (Cooper and Kaplan 1992). Several authors have used time-driven activity-based costing in an attempt to capture unused capacity costs (Kaplan and Anderson 2004; Tse and Gong 2009; Tanış and Özyapıcı 2012)

Tanış and Özyapıcı discussed the measurement and management of unused capacity using a time-driven activity-based costing system. Their efforts focused on determining the real unused capacity and the compulsory unused capacity of a company's labor force. Their work provided a method for calculating the real unused capacity (the number of employees that should be released or reassigned) and the compulsory unused capacity (unused capacity that is needed in order to fulfill company orders) by focusing on the practical capacity of an employee and the time required for a task (Tanış and Özyapıcı 2012).

Öker and Adigüzel implemented time-driven activity-based costing (TDABC) in a manufacturing company in an attempt to quantify unused capacity costs. This case study was performed for the entire manufacturing company (and not just the manufacturing departments). The authors noted that the TDABC implementation process was significantly easier for non-manufacturing departments due to their labor capacity being based on time. The authors suggest that the TDABC method may be better suited to service departments and companies than manufacturing departments. The authors do note, however, that different capacity measures, such as machine hours or production floor space, could be used to determine unused capacity costs (Öker and Adigüzel 2010).

2.3.3 Issues with Current Uses and Applications

Current uses of downtime costing have largely been focused on planning, production line design, maintenance schedules, and long-term capital improvements. While these concerns are certainly worthwhile and should be pursued, there is also a need to quantify the added costs of downtime within a shorter time frame in order to aid operation management. Work by Liu et al has begun groundwork for quantifying the costs of downtime in a shorter time frame; however, their work depends on a prescribed cost per unit of production in order to quantify downtime costs. The authors do not give a basis for determining this cost. In addition to this, the authors do not consider added downtime costs that occur even if there is not a permanent loss of production (Liu, Chang et al. 2012). Previous authors also seemed to only look at downtime costs associated with production loss and disregarded other possible added costs due to downtime (Edwards, Holt et al. 2002; Faria, Nunes et al. 2010).

Much of the work in determining excess capacity has been focused on long-term reduction of resources. Much of the literature also focuses on the reduction of labor resources through the use of unused capacity information (Buchheit 2003; Tanış and Özyapıcı 2012). One work notes the difficulty of determining unused capacity in a manufacturing setting using the method of time-driven activity-based costing (Öker and

Adigüzel 2010). The literature, to the best of this author's knowledge, does not discuss finding excess capacity in the short-term for redistributing resources from an operations management point-of-view.

2.3.4 Thesis Relevance

This thesis incorporates and alters some aspects of the discussed previous work in downtime costing and excess capacity costing. This thesis applies previous work in this area to a dynamic total costing methodology. The goal of the proposed methodology is to separate the total cost of production into normal production costs and the added costs of downtime and excess capacity within a short time frame to aid operations management. Such a system could possibly alert plant management of areas where there is a lack of resources and areas where there is an abundance of resources in order to shift resources to allow production to run more smoothly and cheaply.

Specifically, this thesis uses Liu et al's definition of opportunity windows and permanent production loss for the quantification of some downtime costs (Liu, Chang et al. 2012). This thesis also incorporates other added costs of downtime as suggested by Crumrine and Post (2006), mainly the costs of idling equipment. This thesis also incorporates Cooper and Kaplan's idea that the cost of unused capacity is the difference between the cost of activity supplied and the cost of activity used (Cooper and Kaplan 1992).

This thesis aims to help managers with operations control in the short-term by showing areas where there are limited resources (in the case of downtime costs) and areas where there is an excess of resources (in the case of excess capacity costs). The goal is to minimize costs with available resources. This thesis also aims to be useful when used over a long time period in order to reduce costs in the long-term by highlighting areas for capital improvements to reduce downtime and by highlighting areas with unused resources.

2.4 Environmental Monitoring in Manufacturing

2.4.1 Description and Background

While tracking and controlling monetary costs has always been a major concern for manufacturers, companies have also begun to consider the environmental costs of their products and business processes. Pressures from government bodies as well as consumers have pushed companies to take a closer look at their environmental impact.

Companies are often forced to comply with environmental regulations. Noncompliance can lead to fines or more stringent penalties. Compliance measures come at a price such as disposal costs or permitting fees; therefore, Brooks et al suggested that these costs should be included in a company's activity-based costing system to highlight the explicit (such as disposal) and implicit (such as training in environmental compliance) costs of business processes. The authors suggest that this method helps companies comply with environmental regulations in a cost-effective manner (Brooks, Davidson et al. 1993).

Elkington has referred to the increasing consumer pressure on companies to operate in environmentally-responsible ways as the "emergence of the green consumer". Elkington suggested that this "greening" of the marketplace began in the early 1990s and has grown since then (Elkington 1994). Market research from Mintel Group confirms this, stating that "nearly half of UK adults" view environmental issues as very important when choosing products (Mintel Group 2009).

Both regulatory pressures and consumer pressures have pushed companies to trace their environmental impact and attempt to reduce it. This thesis focuses on the manufacturing aspect of the product life cycle and discusses some activity-based methods that can be helpful for monitoring the environmental impact of manufacturing.

2.4.2 Current Uses and Applications

Companies currently strive to meet rigorous standards, regulations, and goals for energy usage, emissions, and other environmental aspects. Companies have long monitored utility usage at the plant or high-level process levels; however, it is often cost-prohibitive to meter utility usage at a granular level that would allow better understanding of utility usage within a manufacturing system. This metering also may not be able to track environmental concerns besides energy usage, e.g. waste production. Many authors have proposed other possible methods for companies to track their environmental impact.

As previously mentioned in Section 2.2.2, Emblemsvåg and Bras used the activity-based structure of activity-based costing to develop a methodology called “activity-based costing and environmental management” (ABCEM). This methodology is different than that of Brooks et al which tracked the monetary costs of environmental regulation compliance (Brooks, Davidson et al. 1993). Emblemsvåg and Bras’ methodology provides a framework for companies to track their (non-monetary) environmental “costs”, such as waste generation, energy use, or carbon dioxide emissions, in a manner similar to how ABC tracks monetary costs. The authors suggest describing resources by their environmental impacts, or “costs”, and propagating these costs through the ABC allocation process in parallel with the monetary costs of resources (Emblemsvåg and Bras 2001). This method can also be useful for monitoring energy use within processes. This method is useful because it allows management to investigate energy consumption at a sub-system level without investing in costly metering devices (Jurek, Bras et al. 2012).

The ABCEM approach has been used by several authors since Emblemsvåg and Bras' work. Bargmann used the ABCEM approach, specifically the ABCEM "Dashboard" discussed by Wilgenbusch (2001) and Bras et al (2001), to develop a support tool to aid environmental management within small- and medium-sized enterprises (Bargmann 2002). Duncan also looked at the logistics of implementing such a "Dashboard" system in order to monitor energy and mass data in real-time for a carpet manufacturer (Duncan 2003).

Romaniw developed a model-based environmental assessment of different manufacturing processes using an activity-based approach. Romaniw's model computes the carbon dioxide emissions, energy consumption, and waste mass generation of manufacturing scenarios and allows the user to model different scenarios to compare the environmental impact of each (Romaniw 2010).

The ABCEM methodology has also been shown to be useful with the adoption of "smart grid" technology in the electric utility sector. This smart grid refers to an electric grid that contains sophisticated information technology systems in order to more efficiently provide electricity. Jurek et al looked at a possible outcome of the smart grid: demand-response energy contracts. The authors used an ABCEM approach to estimate utility resource usage within the paint shop of an automotive assembly plant and used this model to aid decisions with demand-response energy contracts (Jurek, Bras et al. 2012). Oh and Hildreth also looked at the use of activity-based costing and stochastic programming to aid decision-making when considering demand response contracts (Oh and Hildreth 2013).

2.4.3 Issues with Current Uses and Applications

While there have been advances in monitoring environmental aspects, issues remain with the current uses and applications. Monitoring at the process or plant level lacks the resolution to aid plant management in addressing specific areas for improvement. Monitoring at the station or line level is often cost-prohibitive due to the need for many expensive sensors.

Romaniw’s environmental assessment of manufacturing processes is very well-suited for planning and static assessments; however it lacks the ability to track environmental impacts dynamically (Romaniw 2010). Duncan highlighted limitations in data-gathering due to sensor system shortcomings in his work with a real-time ABCEM “Dashboard” (Duncan 2003). The development of a dynamic ABCEM system that uses data from previously-installed data acquisition systems may alleviate these data-gathering issues; however, this thesis only looks at the theoretical framework of this type of system and does not delve into the logistics of full implementation of such a system.

2.4.4 Thesis Relevance

This work addresses the idea of environmental monitoring in manufacturing and aims to help plant managers to better understand the dynamic environmental impact of their production lines in addition to the monetary costs. Specifically, the thesis uses Emblemsvåg and Bras’ approach of activity-based costing and environmental management (ABCEM) in order to track environmental costs parallel to monetary costs

(Emblemsvåg and Bras 2001). By providing plant managers with real-time environmental impact information, the proposed methodology would give plant management a better idea of their current environmental impact. This could possibly allow management to adjust operations in order to stay below different energy quotas or adjust to demand-response contracts, for example.

Oh and Hildreth's work shows an example of how an ABCEM model that tracks energy use could be used to aid plant management in executing demand response contracts by identifying possible activities to suspend during energy load curtailments (Oh and Hildreth 2013). This provides an additional possible use of the proposed methodology and additional justification for implementing a methodology similar to the one presented in this thesis.

CHAPTER 3

DYNAMIC ABC METHOD

3.1 Chapter Overview

This chapter discusses the development of the presented dynamic ABC methodology. This chapter begins by defining the scope and system boundary of this methodology. After defining the system and scope, the development of the methodology is discussed, beginning from an initial concept to a full-fledged methodology. This full methodology is then presented and discussed. An example implementation is also presented to illustrate the use of the methodology.

3.2 System Definition and Scope

The system of interest for this methodology is a manufacturing line. Specifically, the production line of interest for this methodology is assumed to have automated data acquisition systems that already provide plant management with information about line behavior. The methodology aims to use this previously captured information in a different way in order to more accurately assess costs, particularly the added costs of downtime and excess capacity in the short term. By presenting this previously captured information in monetary units, the proposed methodology presents system behavior in a way that is more in line with the financial goals of the organization than nonfinancial performance metrics as suggested by Karlsson and discussed in Section 2.3 of this thesis (Karlsson 2007).

A short example implementation of the methodology is provided in Section 3.4. This example examines a fictitious internal combustion engine assembly line. This engine assembly line is presumed to be highly automated and, therefore, has a sophisticated data acquisition and information technology systems. The example will be discussed in more detail in Section 3.4 after discussing the general methodology in more detail.

The case study presented in Chapter 4 is applied to an automated paint shop at an automotive assembly plant. This paint shop is heavily automated with robots and conveyor systems doing the bulk of the work. The example production line of this case study will be discussed in more detail with the presentation of the case study.

3.3 Methodology Development and Overview

The methodology draws mainly from traditional activity-based costing as proposed by Cooper and Kaplan (Cooper and Kaplan 1988). Activity-based costing follows the idea that cost objects consume activities which, in turn, consume resources. Activity-based costing is logical in its approach because when a cost object such as a good or service is created, there are a combination of performed activities to deliver the end result. For instance, these activities could be machining activities or shipping operations. Every activity requires at least one resource and could require several resources. Example resources include electricity, water, labor, raw materials, and supplied components. Figure 3-1 shows the flow of consumption from resources to activities to cost objects.

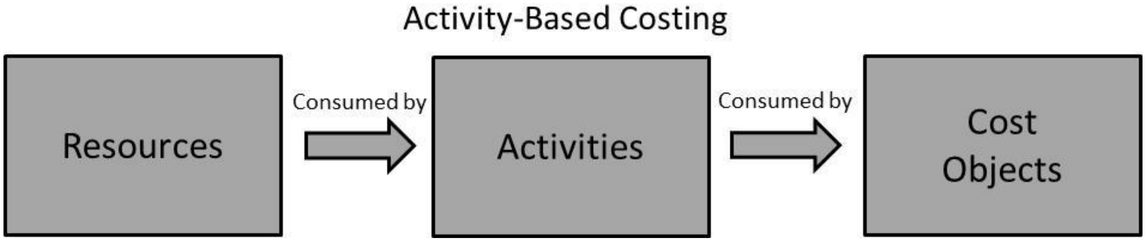


Figure 3.1: ABC Consumption Flow

The concept of ABC is easily understood in a manufacturing environment. For example, one can look at the production of a wooden baseball bat. In this example, the lone cost object may be the wooden baseball bat. There are many activities that are performed to produce this cost object. An activity is any process or task that is performed within the system being studied, in this case a baseball bat production line. Some activities directly alter the bat from a split of wood into a finished product such as shaping or staining the bat. In addition to these direct activities, there are several indirect activities, such as material handling, maintaining production equipment, or even lighting the production floor. All of these activities, both direct and indirect, help to create the cost object, in this case, a wooden baseball bat.

Just as a cost object cannot be created without activities, activities cannot be performed without resources. The concept of resources is fairly intuitive. A resource can be anything that is used during the completion of an activity. In the baseball bat production example, resources could include the wood used to make the bat, the machines used to shape the bat, and workers that operate the machines.

Resources and activities are consumed in specific amounts. The rates of consumption are characterized by resource drivers and activity drivers. Resource drivers describe the rate of consumption of each resource when an activity is performed.

Activity drivers describe the rate of consumption of each activity as cost objects are created. These consumption drivers can be defined in many ways. For example, an activity driver can be defined on a "per job" basis. In this case, for every cost object produced, there would be a specific unit of the activity consumed. Likewise, consumption drivers can be defined on a per unit time basis such as an hourly labor rate.

Development of an activity-based costing system is largely up to the designer. An ABC system can be defined on any reasonable scale, from the facility or company level to the most basic activity level. The scope of the ABC system should be defined at the level for which the system will most directly impact. ABC systems developed for creating external reports, for instance, will be quite different than ABC systems developed to aid management on a specific production line.

Returning to the previous baseball bat example, one has a wide array of choices for the level of detail with the choice of activities alone. When defining the direct activities in this example (and disregarding indirect activities such as maintenance and material handling), one could simply define two activities, creating the bat and testing the bat. Alternatively, one could break these two activities down into sub-activities. The creation activity contains many sub-activities: selecting appropriate wooden splits, lathing the wooden splits into billets, seasoning the billets to remove sap and gum, lathing and sanding the billets into bat shape, and varnishing or painting the bat. One could continue to break these sub-activities down further and further.

With the development of any system, it is important to properly define the scope and level of detail that will produce the wanted results, ideally in the simplest way. Information comes at a price. As the level of detail increases, the costs of achieving that level of detail increase. It is similarly true that when the scope of the system increases, the costs of the system increase. It is important to strike the right balance between costs and benefits. An ABC system is useless if it does not capture enough information to increase the user's knowledge of the system of interest and help the user make better decisions. Conversely, an ABC system that captures too much information may be too costly or too unwieldy to implement or, more importantly, maintain.

Static activity-based costing systems may rely on intermittent updates to keep the information contained within up-to-date. If the system is large or the data is not automated, maintenance of this system quickly becomes unwieldy, and the benefits of the system could quickly be outweighed by the negatives of maintaining such a system. If the system is smaller in scale and/or uses automated data, maintenance is significantly easier, and the benefits of the system become readily apparent.

Much data is already captured by modern manufacturing lines. This data corresponds to statistics such as production counts, throughput, cycle time, or availability. In order to ease the level of effort required to develop a dynamic ABC system, it is important to structure the system around the data types that are already captured by line equipment as much as possible. By structuring the dynamic costing system around the data that is presently available, one minimizes the amount of additional data that needs to be captured manually.

For instance, a dynamic ABC system may use automated production count data to determine the consumption of direct resources. This real-time production count data allows managers to see the amount of direct resources used until that point in time. Information about the current state of a station or line could be used to determine utility resource use. These data types are already captured by many data acquisition systems. The proposed methodology merely uses this data and relevant cost information to present system information in a different way.

The proposed methodology differs from “traditional activity-based costing” significantly. Whereas ABC systems are often used to determine the costs generated by different product lines, the proposed methodology looks to determine the costs caused by different areas of the production line. “Traditional” ABC systems will look at what resources are used and what activities use these resources. Then, the system will determine what activities each product uses in order to determine the costs caused by each product.

The proposed methodology is slightly different in terms of its structure, scope, and overall goal. While a traditional ABC system is interested in the costs allocated to different product lines, the proposed methodology is more interested in the costs allocated to different areas of the production line in order to improve operational control and identify areas for improvement during the manufacturing phase. Because of this connection between physical locations of a production line and resource and activity usage in this proposed ABC methodology, there is a need to address the interface between the physical line and the setup of the ABC system. This interface is discussed in Section 3.3.1.

The goal of this methodology is to split production costs into three categories: normal production costs, added costs caused by downtime, and added costs due to excess capacity. As discussed in Section 2.3, Cooper and Kaplan suggested that the cost of activity supplied is equal to the cost of activity used plus the cost of unused activity. This idea seems logical. Often, there is a difference in the amount of activity supplied and the amount of activity used. For instance, a company may employ a worker for eight hours a day; however, the worker may only perform seven hours of actual work during the shift.

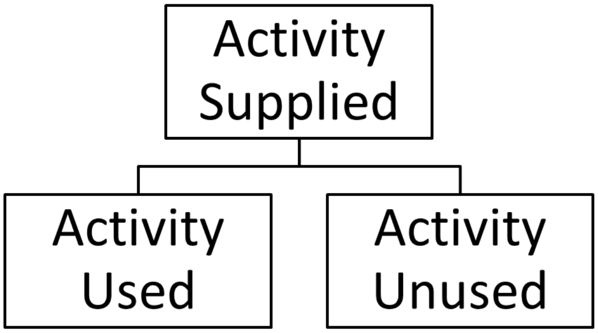


Figure 3.2: Usage of Supplied Activity

In addition to this split between used and unused activity, one can split the cost of activity used into the cost of normal activity usage and the cost of abnormal activity usage. Normal activity usage in a manufacturing system would correspond to normal production. This pertains to times when the manufacturing line is producing product without incident. For instance if a line segment is rated to produce 40 jobs per hour (JPH), the line segment will produce 40 jobs during an hour of normal production.

Conversely, abnormal activity usage corresponds to times when the manufacturing system (or a subsection of it) is not producing normally. This could correspond to times when a section of the line is broken down or if a section of the line is idling while waiting to return to production.

The abnormal activity usage corresponding to times when a section of the manufacturing system fails adds costs in the form of downtime costs. This provides the basis of the downtime costing portion of the proposed methodology. The calculation of these added downtime costs is more fully discussed in Section 3.3.2.

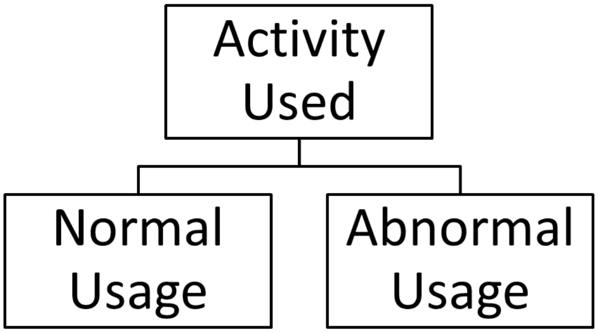


Figure 3.3: Ways Activity Can Be Used

The cost of activity unused is described in this thesis as the added costs of unused capacity. These costs are come from providing excess capacity compared to what is needed. This unused capacity may be in labor, machinery, etc. The calculation of these added unused capacity costs is further discussed in Section 3.3.3.

Because the proposed methodology looks to separate costs into normal production costs, added downtime costs, and added unused capacity costs, its structure is slightly different from the "traditional" structure of ABC. The activities of the proposed methodology closely match with individual workstations on the production line. For each station, there are three types of costs associated with it: normal production costs, added downtime costs, and added unused capacity costs. Effectively, each of these separate cost types for each station is a cost object.

Each station may have subactivities associated with it, but these are merely used to determine resource drivers for the main activity (the activity associated with the station). For instance, a workstation may exist to paint the exterior of a vehicle. This main activity (painting the vehicle exterior) may have many subactivities such as mixing the paint or evacuating airborne paint particles. These subactivities merely give more information about the resources being used by the station.

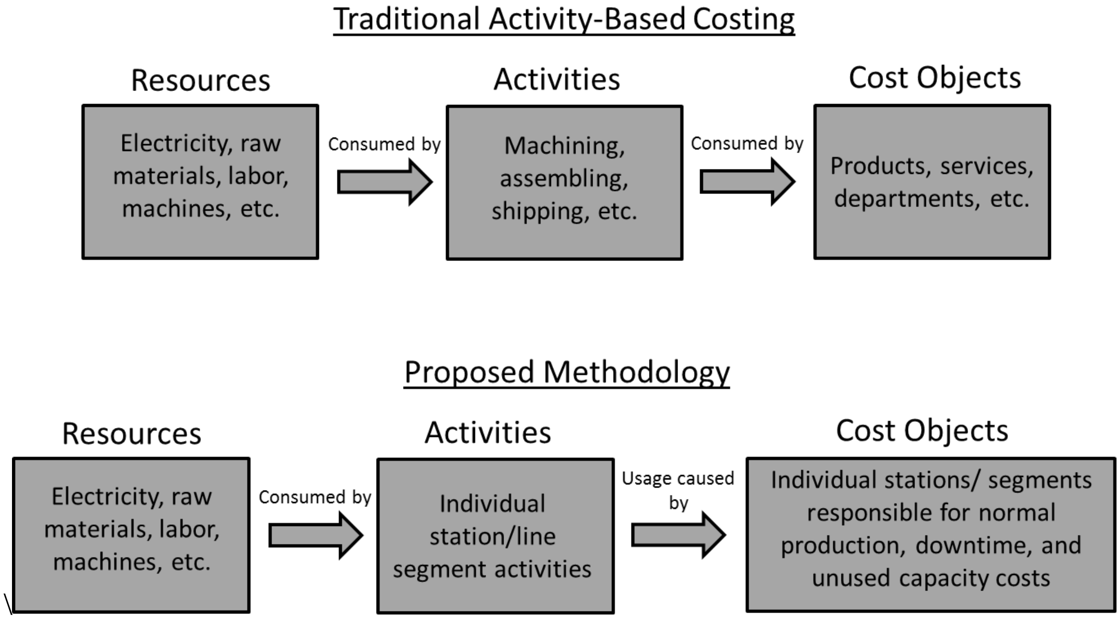


Figure 3.4: Comparison of Traditional ABC and Proposed Methodology Structures

3.3.1 <u>Interface between ABC and Physical Production Line</u>

There is a need to define the interface between the dynamic activity-based costing system and the physical manufacturing line and facility. Throughout the discussion thus far, the emphasis has been on the concept of activities. Manufacturing lines consist of a series or several series of stations and buffers. It is important to note that, depending on the level of detail when defining activities, there may not be a direct match between the defined activities of the ABC system and the physical stations and buffers. Because this dynamic ABC concept relies on already captured production line data, it is important to define the activities for the dynamic activity-based costing system in a way that aids the easy integration of captured data into the system. For example, it does not make sense to define the activities at a higher level of detail than the available data or at a higher level of detail than input data can be estimated. For the purposes of this thesis, each activity corresponds to a specific station.

Perhaps the largest difference between previous static and dynamic ABC methodologies and the presented methodology is the need to link current manufacturing line system dynamics to costing. Previous static methods have relied on averaged data over longer time frames and do not include the dynamic effects of changing system behavior. It appears that previous dynamic ABC models have used data that is updated regularly and over shorter time intervals than static models; however, these dynamic models have not relied or depended on the actual line dynamics and interconnections between stations on a dynamic line. Because of this, previous dynamic ABC methods do not seem capable of adequately assessing added downtime costs and added excess capacity costs to the responsible cost centers.

The presented methodology aims to allocate costs to the cost centers responsible for resource and activity usage, not just the cost center where the actual usage took place. This is slightly different than traditional thought in activity-based costing where costs may only be allocated to the areas where the costs *occurred*. The proposed methodology also traces costs to areas that are *responsible* for the cost occurrence.

For example, one can look at a simple serial production line with two stations. If the first station breaks down, the second station idles until the first station is repaired and resumes production. During this repair time, the second station is still using resources (e.g. electricity, labor, machinery, etc.); however, the second station is not *responsible* for this resource use while idling. The first station is responsible for this resource usage (and the costs associated with it) because its failed state is forcing the second station into an idle state. The costing system in this example needs to capture and understand the behavioral dynamics between the two stations in order to accurately allocate the costs to the responsible station.

This need to capture system dynamics also leads to a more complex model that is more difficult to implement. The model must properly assign costs using information about these dynamics. In order to properly assign costs based on these dynamics, it is important that the dynamic ABC system have access to data about the current state of each station (or each area that is of interest for the dynamic ABC system). For the purposes of this methodology, the manufacturing line and subsections (e.g. stations and line segments) of the line can be in one of five system states as defined by Jurek et al (Jurek, Bras et al. 2012). These five system states are shown in the figure below.

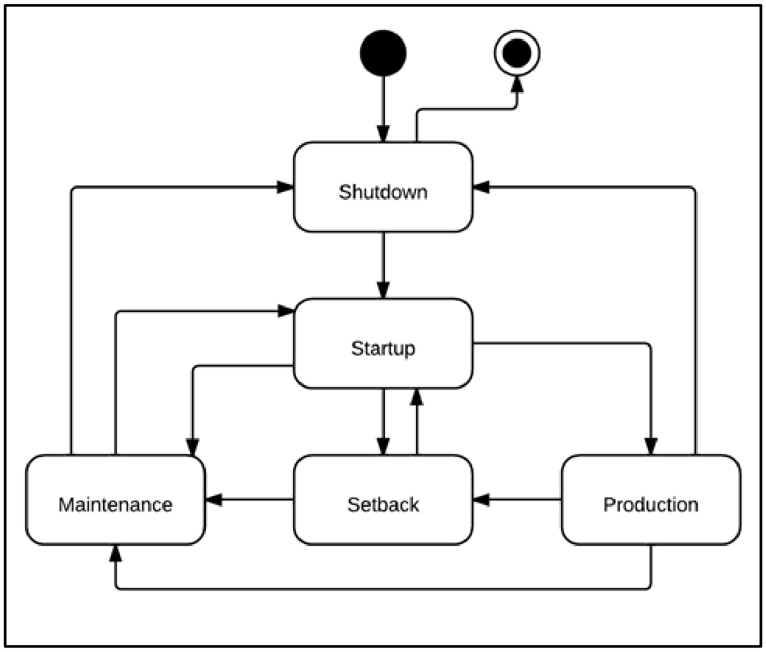


Figure 3.5: UML State Diagram of Paint System Operating States (Source: Jurek et al., 2012)

Jurek et al defined five distinct states in which a manufacturing line system can be: 1) startup, 2) production, 3) setback, 4) maintenance, and 5) shutdown (Jurek, Bras et al. 2012). These states are comprehensively exhaustive and mutually exclusive, meaning that a station can only be in one of these states at a specific time. The production state is when the station is actually generating product normally. The setback state refers to times when the system is, in effect, "idling", such as during short breaks or between breaks. This state also corresponds to times when a station is blocked or starved due to a random downtime event at another station or a slower station on the line.

If a station will be down for a long period of time, it can be shifted into a shutdown state. This state uses the least amount of resources and is also the state of the manufacturing line system on days when the manufacturing facility is not in operation. The system must go through a startup state after coming out of a shutdown state, whether it is at the beginning of a shift or during a line shutdown in the middle of a shift. During this startup phase, the manufacturing system quickly reaches normal operating conditions before entering the production state. The maintenance state corresponds to when the system (or system subset) undergoes either routine preventative or emergency maintenance due to random downtime events.

Using this system state information for each station as well as other information such as buffer capacity and buffer inventory, one can appropriately assess the dynamics of the production line within the dynamic ABC system. This system state information also proves useful when determining resource and activity use. The following sections discuss in more detail the process of allocating costs to responsible cost centers.

3.3.2 Downtime Costing

Manufacturing lines are dynamic in nature. Conditions constantly change depending on resources, behaviors, etc. Specifically, there are random downtime events. For the purposes of this thesis, downtime events can be defined as situations which cause a station to spontaneously enter a maintenance state. This downtime event may cause other stations within the line to enter a setback state. A downtime event causes additional costs for a manufacturer.

It is possible to combine the costs caused by a downtime event in the same way that products are assigned costs in a traditional ABC system. As shown in Section 2.2, cost objects consume activities, and activities consume resources which have associated costs. Events consume activities directly and indirectly. Directly, events consume activities that replenish the lack of resource. For a breakdown event, repair activities replenish the lack of the "functioning machine" resource. Indirectly, events consume activities that are needed to make up for any losses of production caused by the event or that are needed to keep the line in operation (such as idling costs). For the purposes of this thesis, downtime costs will be considered as a subsection of the total cost due to a station's operation. These downtime costs with the normal costs of production and the added costs of unused capacity will form the total cost associated with the station's operation.

In order to accurately determine the costs of a random downtime event, one must take into account the dynamics of the production line. Material flows through a production line from one station to the next until a finish product is created; however, the next production activity does not typically occur immediately after the previous production activity. Production lines often have buffers between stations to compensate for differences in station cycle time (the amount of time to complete one cycle of the activity or job) and for discrepancies caused by random downtime events.

The presence of buffers alters the dynamics of a production line greatly. Buffers help to regulate production line behavior and mitigate the effects of asynchronous stations. In the absence of buffers, an entire manufacturing line would quickly come to a halt if one of the stations in the line broke down. Buffers help to smooth the effects of the breakdown event. This leads into the concept of "opportunity windows". When a random downtime event occurs, there exists a window of opportunity for resolution of the downtime event before there is a permanent loss in production. A permanent production loss is defined by Chang et al as production that is lost and cannot be replenished with a normal production schedule. This production loss can only be replenished with overtime. The time value of this permanent production loss is the amount of time that the slowest station in the production line is stopped (Chang, Biller et al. 2010).

The opportunity window for a station was shown by Chang et al to be the maximum duration of a downtime event at that station before the slowest station in the line stops. For a station before the slowest rated station, the opportunity window corresponds to the amount of time until all buffers between the two stations would become empty. For a station after the slowest rated station in the line, the opportunity window corresponds to the amount of time until all buffers between the two stations would become full. The authors summarized these calculations in the figure below where T_{M^*} is the cycle time of the slowest station, b_k is the current buffer level of buffer k, B_k is the buffer capacity of buffer *k*, *M** is the index of the slowest station, and *m* is the index of the station of interest (Chang, Biller et al. 2010).

$$W_m(T_d) = \begin{cases} T_{M*} \displaystyle\sum_{k=m+1}^{M*} b_k(T_d), & m < M^* \\ 0, & m = M^* \\ T_{M*} \displaystyle\sum_{k=M*+1}^{m} (B_k - b_k(T_d)), & m > M^* \end{cases}$$

Figure 3.6: Opportunity Window Calculation (Adapted from Chang et al, 2010)

While it is important to determine the costs of these events, it is also important to assign these costs correctly in hopes of aiding plant management with the identification of areas for improvement. Plant managers would be able to rank areas by their downtime costs and determine where the most improvement can be made. This would allow plant managers to prioritize some improvement projects over others and provide justification for this prioritization.

As shown in Section 2.3, Liu et al provided a method for allocating the costs of permanent production loss caused by downtime events. In their work, the authors provided this method for a serial production line (Liu, Chang et al. 2012). The given serial production line consisted of M stations with M-1 buffers. A buffer was located between each pair of stations in the line. The figure below from Chang et al illustrates this serial production line (Chang, Biller et al. 2010).

Figure 3.7: Serial Production Line with M Stations and M-1 Buffers (Adapted from Chang et al, 2010)

Liu et al then used the opportunity window calculation method described above to determine the amount of permanent production loss caused by downtime events and allocated this permanent production loss to the responsible station. This permanent production loss can be multiplied by a standard added cost per unit lost or per unit production time lost to determine some of the added costs caused by the downtime event. The permanent production loss of a single downtime event is shown in the figure below.

$$L(\vec{e}_i; E) = \begin{cases} d_i - d_i^*, & d_i > d_i^* \\ 0, & d_i \leq d_i^* \end{cases}$$

Figure 3.8: Calculation of Permanent Production Loss Caused by the ith Downtime Event for Continuous Flow Model (Based on Liu et al, 2012)

In Figure 3.8, $L(\overrightarrow{e_i}; E)$ is the permanent production loss caused by downtime event $\overrightarrow{e_i}$ in the sequence of downtime events E, and d_i and d_i^* are the duration of the *i-th* downtime event and the minimum duration of the *i-th* downtime event to cause a stoppage of the slowest station in the line (the opportunity window), respectively.

Liu et al stressed that the equation in Figure 3.8 was developed for a continuous flow model. The authors noted that in a discrete flow model there is an “asynchrony between the occurrence of downtime events and their manifestation at the slowest station” (Liu, Chang et al. 2012). In order to address this asynchrony, an additional term should be added to the top line of the equation in Figure 3.8. Instead of only finding the difference between the duration of the *i-th* downtime event and the opportunity window at the beginning of the downtime event, one should also include the amount of time that it takes the slowest station to resume production. This asynchrony can be difficult to estimate, and the effects on permanent production loss will be different depending on the production scenario and downtime event.

In the case where a station before the slowest station breaks down, one needs to include in permanent production loss calculations the amount of time it will take a unit to reach the slowest station after the down station is repaired. This can be approximated as the summation of the rated cycle times of the stations located between the slowest station and the location of the downtime event.

In the case where a station after the slowest station in the line breaks down, the slowest station will return to production after the broken down station completes or discards any work-in-progress.

The figure below shows this updated equation for calculating the permanent production loss caused by a random downtime event in a serial production line with the discrete flow model that more accurately represents many production lines. The top equation pertains to random downtime events before the slowest station, and the bottom equation refers to random downtime events after the slowest station. In the case of the slowest station breaking down, the related permanent production loss is equal to the length of the downtime event.

$$\text{m < M*:}\quad L(\overrightarrow{e_i}; E) = \begin{cases} (d_i - d_i^*) + \sum_m^{M^*-1} T_m\,, d_i > d_i^* \\ 0, \qquad\qquad\qquad\qquad d_i \leq d_i^* \end{cases}$$

$$\text{m > M*:}\quad L(\overrightarrow{e_i}; E) = \begin{cases} (d_i - d_i^*) + T_m \, * (1 - WIP), & d_i > d_i^* \\ 0, & d_i \leq d_i^* \end{cases}$$

Figure 3.9: Calculation of Permanent Production Loss from the i-th Downtime Event for Discrete Flow Model

In Figure 3.9, $L(\overrightarrow{e_i}; E)$ is the permanent production loss caused by downtime event $\overrightarrow{e_i}$ in the sequence of downtime events E, and d_i and d_i^* are the duration of the *i-th* downtime event and the minimum duration of the *i-th* downtime event to cause a stoppage of the slowest station in the line (the opportunity window), respectively. T_m is the rated cycle time of station m. *WIP* is the completion percentage of the work-in-progress in the broken down station.

Figure 3.10 shows the relationship between downtime costs and permanent production loss, as discussed by Liu et al (2012). In this figure, $\overline{DTC}(\overrightarrow{e_i}; E)$ is the downtime cost associated with downtime event $\overrightarrow{e_i}$. $\bar{L}(\overrightarrow{e_i}; E)$ is the permanent production loss associated with downtime event $\overrightarrow{e_i}$. T is the duration of the downtime event. The total number of stations is M. Lastly, $C_m^f(T)$ is the fixed cost of station m for duration T of the downtime event. These fixed costs are costs of activity supplied before usage, such as wages for workers.

Using the calculation and allocation methods of permanent production loss caused by downtime events discussed by Chang et al (2010) and Liu et al (2012), one can allocate some additional costs caused by downtime. These additional costs range from loss of sales opportunity to customer penalties from production counts below the contracted amount. Liu et al suggested multiplying the permanent production loss of a downtime event by the total cost overhead over the total observation time, as shown in the figure below. Instead of using this approach, the proposed methodology uses permanent production loss as a basis for allocating costs such as the costs of lost sales.

$$\overline{\mathrm{DTC}}(\vec{e}_i;E) = \frac{\bar{L}(\vec{e}_i;E)}{T}\sum_{m=1}^{M} C_m^{\mathrm{f}}(T)$$

Figure 3.10: Downtime Cost Relationship from Liu et al (2012)

In addition to these added costs of downtime that are connected to a permanent loss of production, there are also additional downtime costs due to neighboring stations entering a state of rest, called a setback state. When this happens, the neighboring stations are still consuming resources (such as labor or electricity) despite not being in production. These "idling" resource costs should be included in the calculation of the added costs of downtime.

A station may enter a setback state one of four reasons: (1) the station is blocked by a slower station downstream, (2) the station is blocked by a broken down station downstream, (3) the station is starved by a slower station upstream, or (4) the station is starved by a broken down station upstream. The reason for the setback state determines how the costs of that setback state are allocated. The allocation method for each of these situations will be discussed in more detail below.

In order to determine cost allocation based on the previous four situations, it is important to look at two pieces of information: buffer levels and station states. By moving down the line and looking at this data for buffers and stations both upstream and downstream from the affected station, one can determine the station responsible for the station setback. In situations (2) and (4), the added costs due to station resource use while in a setback state should be included in the downtime portion of total cost. The other situations (1) and (3) describe situations that can be characterized by unused capacity. These costs will be discussed in Section 3.3.3.

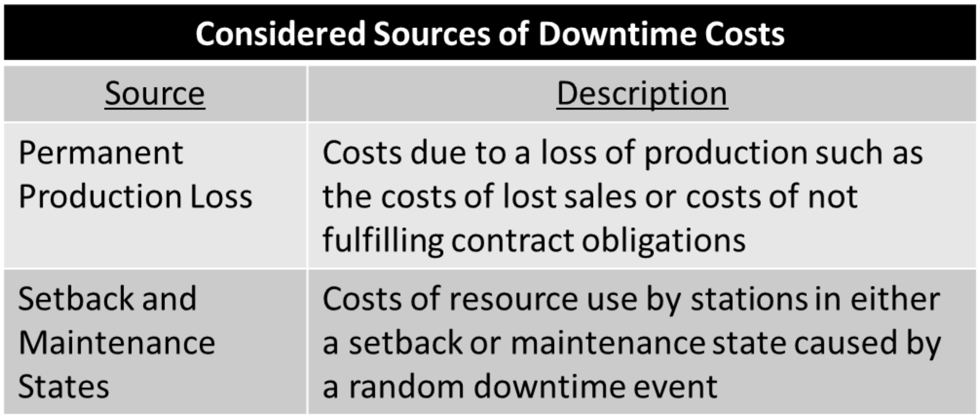
The costs accrued by idling stations due to a downtime event are allocated to the down station. For example, assume there are two stations in the production line. The first station suffers a random downtime event. The costs accrued by the second station (which enters a setback state) during the downtime event are allocated to the first station as downtime costs. In addition to this, costs accrued by the first station while it is being repaired are also included in the downtime costs of the first station. This allows the methodology to track downtime costs to the *responsible* station, even if the resources generating these costs were consumed by another station.

In the case of multiple downtime events, downtime costs corresponding to station state (as opposed to permanent production loss) should be allocated to the state that caused a station's setback. For example, assume a production line with three stations with two buffer areas between each pair of stations. For this example, assume that both the first station and the third station break down at the same time and remain broken down for the same amount of time. Station 1's costs during this downtime event are allocated to Station 1 as downtime costs; likewise, Station 3's costs during this downtime event are allocated to Station 3 as downtime costs. If either of these downtime events is long enough in duration, Station 2 will be forced into a setback state due to starvation or blockage. If Station 2 is starved before it is blocked, its costs during this downtime event will be allocated to Station 1 as downtime costs. Conversely, if Station 2 is blocked before it is starved, its costs during this downtime event will be allocated to Station 3 as downtime costs. In the highly unlikely event that Station 2 becomes both starved and blocked at the exact same time; costs may be allocated to either station, depending on user preference. The example implementations performed in the example in Section 3.4.2 and the case study in Chapter 4 are structured to allocate station costs during these unlikely synced events to the station upstream, the station causing the starvation. Starvation and blockage events caused by unused capacity are allocated in a similar manner.

In the case of multiple downtime events, downtime costs due to permanent production loss are allocated to station that caused the slowest station in the line to stop first. Revisiting the example in the previous paragraph, assume a line with three stations and two buffers. Assume both Station 1 and Station 3 suffer downtime events at the same time for the same duration. Assume Station 2 is the slowest station. If Station 2 is forced to stop due to starvation, the costs of permanent production loss will be allocated to Station 1's downtime costs. Conversely, if Station 2 is forced to stop due to blockage, the costs of permanent production loss will be allocated to Station 3's downtime costs. In the highly unlikely case that Station 2 is starved and blocked at the exact same time, the costs of permanent production loss will be shared by Station 1's downtime costs and Station 3's downtime costs. In this unlikely scenario, Station 2 will likely remain starved longer than it is blocked (or blocked longer than it is starved). In this case, the costs of permanent production loss for the end of this stoppage will be allocated to the station that is still affecting Station 2; therefore if Station 2 is starved longer than it is blocked, Station 1 will be allocated the costs of permanent production loss of that time period between the end of blockage and the end of starvation as downtime costs. If Station 2 is blocked longer than it is starved, Station 3 will be allocated the costs of permanent production loss of that time period between the end of starvation and the end of blockage.

There may be additional costs associated with downtime such as those suggested by Crumrine and Post (2006) and discussed in Section 2.3. These costs could include amortization costs on idle equipment, the costs of temporary fixes to bring the affected station back to production state, or the costs of a permanent fix. For the purposes of this thesis, these other downtime costs will not be discussed because they cannot be easily captured by an automated data acquisition system on the production line. This work will only deal with downtime costs associated with station setback and maintenance states and downtime costs associated with a permanent loss of production.

Table 3.1: Considered Sources of Downtime Costs



Considered Sources of Downtime Costs

Source	Description
Permanent Production Loss	Costs due to a loss of production such as the costs of lost sales or costs of not fulfilling contract obligations
Setback and Maintenance States	Costs of resource use by stations in either a setback or maintenance state caused by a random downtime event

3.3.3 Unused Capacity Costing

Excess capacity also adds costs to the normal costs of production. As discussed by Tanis et al (2012), not all unused capacity is unneeded capacity. Some unused capacity is needed in order to provide the ability to provide an activity or cost object. Other unused capacity truly is in excess, either in the short-term or long-term. An example of short-term excess capacity would be a machine that is not currently used because the goods currently in production do not need the machine, but there will be a need for the machine when production shifts to a different product type. An example of long-term excess capacity would be excess labor force after the installation of new automated machinery. This thesis aims to quantify the costs of unused capacity; however, it does not explicitly deal with designations between needed unused capacity and unneeded excess capacity. It is expected that this designation would be made by plant management after reviewing all available information.

For this thesis, the added costs of unused capacity will be determined using automated data from a production line regarding the state of each station. In Section 3.3.2, four situations were described that could pertain to a station in the setback state. For two of these situations, the setback state was caused by a slower station upstream or downstream starving or blocking the affected stations production. In these scenarios, the faster station has some unused capacity because it could produce product if it were allowed the opportunity. The slower station prevents this. Because the idling station still consumes resources while idling, there are costs associated with this idling that do not contribute value to product production. These added costs are considered unused capacity costs.

For this thesis, these unused capacity costs are tracked to the station where they occur, not to the slower station. Depending on the interests of plant management, these costs could be tracked to the slower station instead. In the former allocation method, stations which have too high of a capacity would be highlighted, but in the latter allocation method, stations which have too low of a capacity would be highlighted. For the latter allocation method, one could simply follow the guidelines discussed for downtime costing in Section 3.3.2.

3.3.4 Additional Considerations

One can easily combine environmental aspects into this dynamic activity-based costing method. Emblemsvåg and Bras included environmental aspects in an activity-based costing framework, creating a new framework called activity-based cost and environmental management, ABCEM (Emblemsvåg and Bras 2001). This approach has been replicated by Romaniw (2010), Jurek et al (2012), and Oh et al (2013) for various uses. Because activity-based costing is based on the premise of cost objects consuming activities which in turn consume resources, one can assign environmental costs to resources in a similar fashion as one assigns financial costs. For instance, one could track energy usage in kilowatt-hours (kWh) or track the release of greenhouse gases (GHGs) in kilograms of carbon dioxide equivalents (kgCO_2e). Figure 3.11 below shows the working principle behind ABCEM.

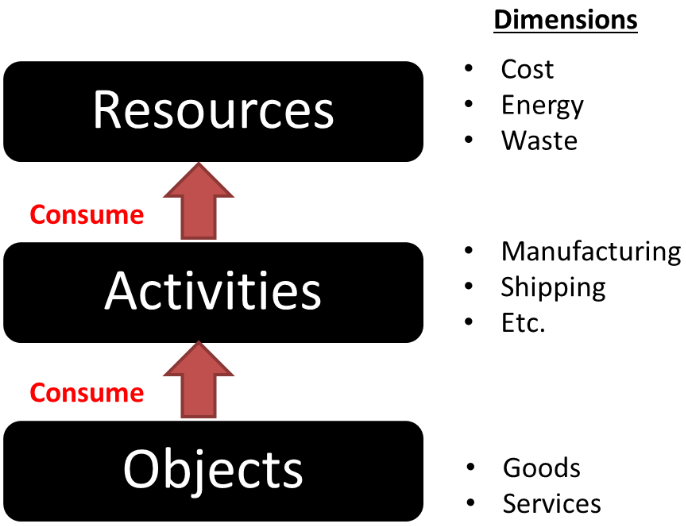


Figure 3.11: Working Principle of Activity-Based Cost and Environmental Management (Adapted from Bras et al, 2001)

Some energy usage statistics are likely already determined when implementing an activity-based costing system in order to accurately determine utility resource cost. Including these energy and environmental aspects in the dynamic activity-based costing framework can help plant managers track their actual short-term use. This could be useful for issues like demand-response contracts (as shown by Oh and Hildreth and Jurek et al). Plant management could more easily track their electricity usage and identify activities available for load shaving. This could also be used to determine which areas and activities need improvement to best reduce the environmental impact of the production line.

For example, plant management could enter into a demand-response contract with the electric utility company. Under this demand-response contract, plant management agrees to a few things. First of all, the plant management agrees to pay a higher rate for electricity consumed during defined "peak" hours, usually early to late-afternoon. During these peak hours, the price of electricity will be considerably higher; however during non-peak hours, the price of electricity will be considerably lower. In addition to this time-of-use pricing plan, plant management agree to dramatically cut electricity consumption when they receive an interruption call from the electric utility during periods of heavy strain on the electric grid. If the plant reduces its electricity consumption to a level which is below that specified in the demand-response contract during this demand call, the plant will be paid according to the contract; however if the plant fails to reach this low level of electricity consumption, the plant will be penalized and forced to pay an additional fee to the electric utility.

In a demand-response situation, the proposed methodology can help to track electricity use in real-time to aid plant management in determining if they have met their electricity quota before exceeding it. It can also help plant management determine which activities it should stop or setback to minimize electricity consumption depending on the current system state.

This differs from the ideas proposed by Jurek et al and Oh et al. Those authors largely focused on the static decision-making of plant management when deciding to enter into a demand-response contract. In addition to this static decision-making, the proposed methodology can also aid plant management with dynamic choices and operational control in order to meet the terms of the demand-response contract.

3.3.5 Cost Allocation Method

The proposed methodology contains two main steps for each update interval when production line data is input into the costing model. The first step involves determining resource use and the cost of resources used by each station over the previous update interval. This is called the station activity cost. Calculation of station activity cost over the previous update interval is done by determining the consumption intensity for each unit of resource, such as dollars per kilowatt-hour or kilograms of carbon dioxide per million BTU, and then multiplying this amount by the station's resource drivers for the previous update interval. This station resource driver is determined by combining the resource drivers (resource usage rate) for the previous update interval of each piece of equipment associated with the station. These resource drivers can be defined dynamically in order to reflect different station states. The figure below illustrates the calculation process for station activity cost.

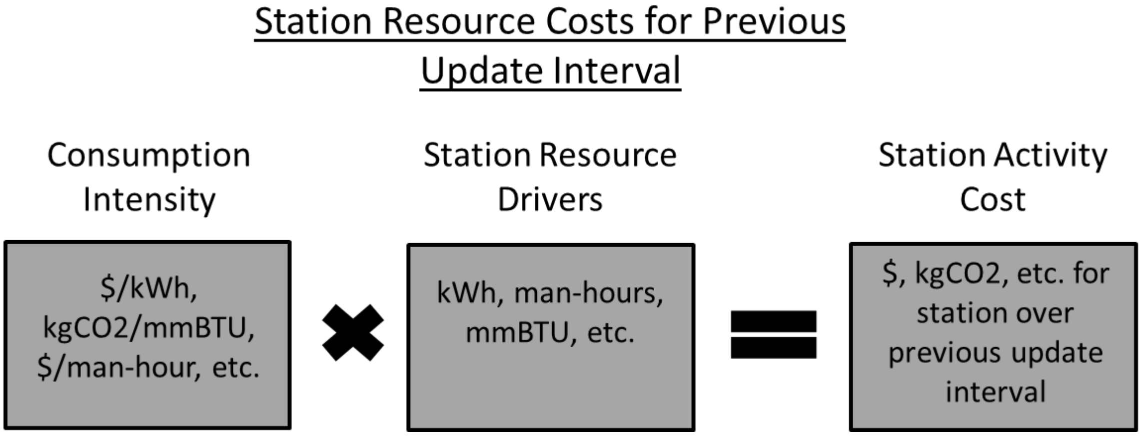


Figure 3.12: Calculation of Station Activity Costs for Previous Update Interval

After determining the activity cost for each station over the previous update interval, this activity cost needs to be allocated to the responsible cost center (in this case, the responsible station) depending on production line and station behaviors. The following figure illustrates the allocation process for normal production costs, downtime costs, and unused capacity costs corresponding to station activity costs dependent on station state. Downtime costs due to permanent production loss are allocated to the station that caused the permanent loss of production.

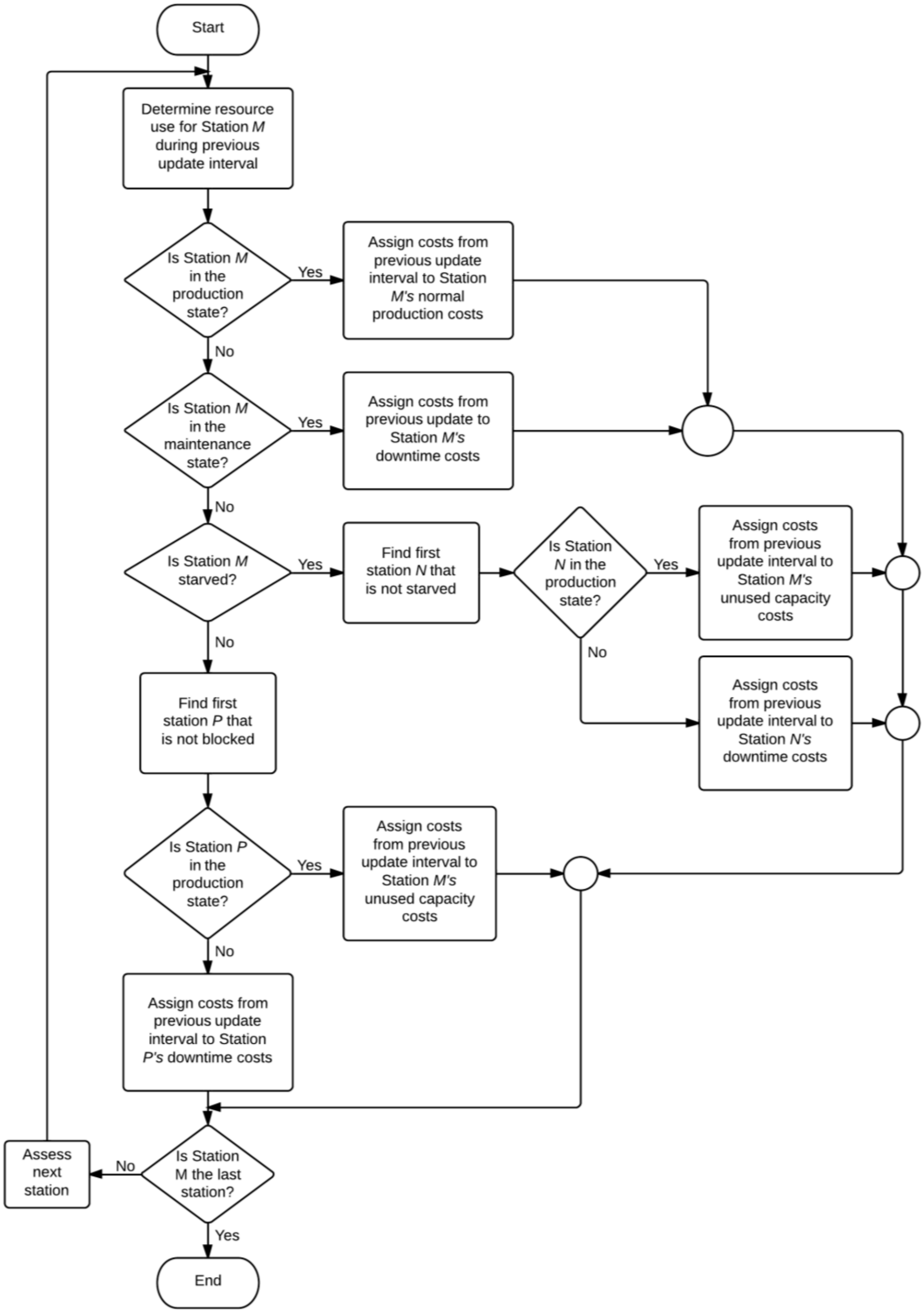


Figure 3.13: Flowchart for Cost Allocation Logic

3.4 Implementation

3.4.1 Implementation Overview

The first stage of implementation of the proposed costing methodology is to determine the important areas of the production line to be monitored. These areas will be studied for possible areas of improvement and will be considered the cost objects of this costing system. After the production line areas have been selected, relevant production and support activities need to be selected to reflect all of the pertinent activity consumption of the various production areas. These activities are selected to closely match physical workstations on the production line. This is done to match areas for improvement to specific stations and to better use information captured by automated data acquisition systems on the production line. The resources that are used by the different activities then need to be listed. These resources could be labor, machinery, facility space, utilities, raw materials, and many other things. These resources will also correspond to any resources used by subactivities that are used by the station.

After listing and separating the different cost objects, activities, and resources, it is important to determine the activity drivers and resource drivers which will need to be calculated and tracked. One can look at the available production line data to determine how consumption drivers can be derived and defined. It is important to define consumption drivers based on previously and/or easily available automated data. By doing this, costing system maintenance is much easier, and the costing system is much more accurate.

A case study is presented in Chapter 4. This case study shows one method of implementation for this presented methodology through the use of spreadsheet software, namely Microsoft Excel. The methodology could be implemented into an actual costing system in this way or using dedicated software. Microsoft Excel was chosen due to its ease of use and simple interface, allowing work to focus on the implementation of the methodology and not on learning new software.

3.4.2 Implementation Example

In order to illustrate a possible implementation of the proposed methodology, an example implementation is presented in this section. This small example is meant to briefly show how the methodology could be implemented for a simple system and to compare results of the proposed methodology to results from a more traditional allocation methodology. The case study presented in Chapter 4 covers a much larger and more complex system.

The system of interest for this example is a heavily automated internal combustion engine assembly line. This assembly line produces small four-cylinder engines from supplied engine components. The assembly line performs some light machining of the engine block before assembling the full engine assembly. This assembly line is modeled as a supplier that produces a set contracted amount every day for a customer. It is assumed that the assembly line can only produce for one eight-hour shift a day; therefore, overtime is not possible to replenish a permanent loss of production during a shift.

This example assembly line consists of six stations with five buffers. Each buffer is located between two stations like the serial production line shown in Figure 3.7 in Section 3.3.2. The assembly line layout is shown in the figure below.

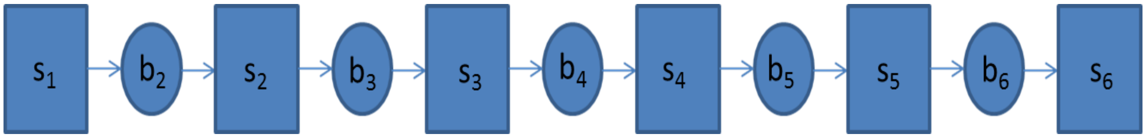


Figure 3.14: Engine Assembly Line Example Layout

Each station corresponds to a main activity of the assembly line. The list of stations in the assembly line and their station mean time between failure (MTBF), mean time to repair (MTTR), and rated speeds are listed in Table 3.2 below. Buffer information is included in Table 3.3. The information within these tables is used as input data for a simulation of one eight-hour shift of the assembly line. This example uses the same simulation code as the case study and is discussed briefly in Section 4.3. The goal of this example is to illustrate the differences between "traditional" cost allocation and the cost allocation proposed in the presented methodology.

Table 3.2: Engine Assembly Line Station Information

Section	Station Description	Station	MTBF (min)	MTTR (min)	Rated Speed (part/min)
Engine Assembly Line	Machine engine block	1	80	12	0.4
	Install crankshaft	2	45	4	0.4
	Install piston assembly	3	180	8	0.3
	Install rear engine cover assembly	4	55	12	0.4
	Install cylinder head assembly	5	100	6	0.4
	Install front engine cover assembly	6	200	30	0.4

Table 3.3: Engine Assembly Line Buffer Information

Buffer	Buffer capacity	Initial buffer level
2	3	2
3	3	2
4	3	2
5	3	2
6	3	2

Two resources are modeled in this example: electricity and labor. Each station consumes electricity at a predefined rate depending on station state. In addition to this, each station has one worker. In addition to these six station workers, there are two maintenance workers that standby until there is a station breakdown and then repair any breakdowns. The resource drivers for this example are shown in Table 3.4. The seven activities of this example model are the six stations on the assembly line and the standby maintenance crew. The cost objects for this example are the normal production costs, downtime costs, and unused capacity costs for each station as well as the unused capacity costs of maintenance workers on standby.

Table 3.4: Resource Drivers for Engine Assembly Line Example

Station	State	Electricity (kWh/min)	Labor (man-hours/min)
1	Production	0.2000	0.0167
	Setback	0.1000	0.0167
	Maintenance	0	0.0167
2	Production	0.0500	0.0167
	Setback	0.0250	0.0167
	Maintenance	0	0.0167
3	Production	0.0250	0.0167
	Setback	0.0125	0.0167
	Maintenance	0	0.0167
4	Production	0.1000	0.0167
	Setback	0.0500	0.0167
	Maintenance	0	0.0167
5	Production	0.0500	0.0167
	Setback	0.0250	0.0167
	Maintenance	0	0.0167
6	Production	0.1000	0.0167
	Setback	0.0500	0.0167
	Maintenance	0	0.0167
Repair	Standby	0	0.0333

Station activity cost for each update interval is calculated using the resource drivers in Table 3.4, consumption intensities (the monetary cost per unit of resource) shown in Table 3.5, and a dynamically-updated array of station state for the previous time interval (an example is shown in Table 3.6). The calculation process is shown in the figure below which is slightly more detailed version of Figure 3.14. It should be noted that for this model consumption intensity is multiplied to total resource use at the end of the allocation process. The station state resource drivers matrix (in Table 3.4) and the station state update matrix are multiplied to create an activities matrix that follows the method shown in Figure 2.2 (Afonso and Paisana 2009).

Table 3.5: Consumption Intensities for Engine Assembly Line Example

Consumption Intensities	
Specific Cost of Electricity ($/kWh)	0.05
Specific Cost of Labor ($/man-hour)	25

Table 3.6: Example Station State Update Matrix

Station	State	1			2			3			4			5			6			R
1	Production	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Setback	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Production	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Setback	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Production	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Setback	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Production	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Setback	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Production	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Setback	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Production	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Setback	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
	Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Repair	Standby	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

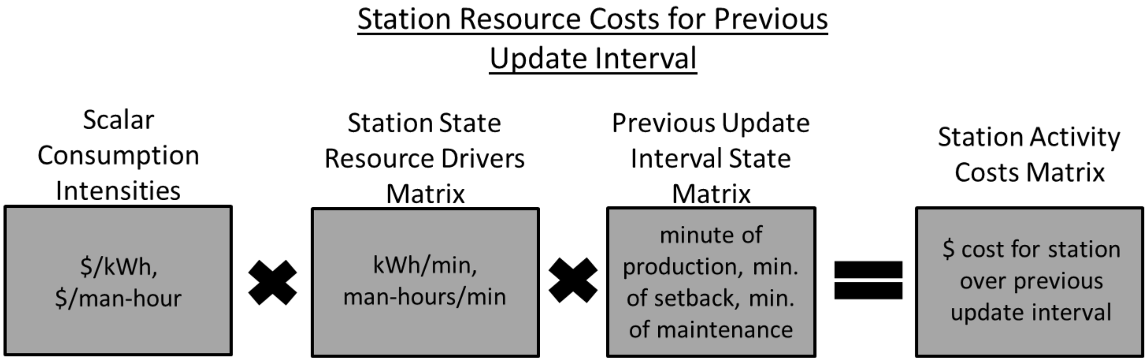


Figure 3.15: Station Activity Cost Calculation Process for Engine Assembly Line Example

For this example, two types of downtime costs are considered: costs pertaining to idling station resource use caused by random downtime events and costs associated with not reaching the contracted production quota. Downtime costs associated with low production volume are calculated by multiplying the number of units short of the set quota by a combined lost sales and penalty cost. These costs are shown in the table below. Unused capacity costs stem from stations entering a setback state because of a slower station. These costs are merely the cost of resource use by the idling station and are assigned to the idling station.

Table 3.7: Per Unit Costs of Low Production for Engine Assembly Line Example

Cost of Lost Sale ($/unit):	100
Penalty Cost per Unit under Quota ($/unit):	10
Total Cost of Lost Unit ($/unit):	110
Quota (units):	95

The simulation code for this example runs until enough engines are assembled to reach the contracted daily production quota plus five additional surplus units. If the assembly line produces enough engines to satisfy the daily production quota but not enough to reach the wanted surplus level, no additional downtime costs are caused by a permanent loss of production. If the assembly line does not satisfy the production quota, it is assessed additional downtime costs due to the cost of lost sales and penalty fees for not supplying enough units to the customer. These costs are allocated based on the percentage of total permanent production loss caused by each station.

Allocation of station activity costs to station normal production costs, added downtime costs, and added unused capacity costs is done through the use of matrix multiplication similar to the determination of station activity costs method shown in Figure 3.15. The calculation for this process is shown in Figure 3.16 below. Table 3.8 shows an example station activity drivers matrix.

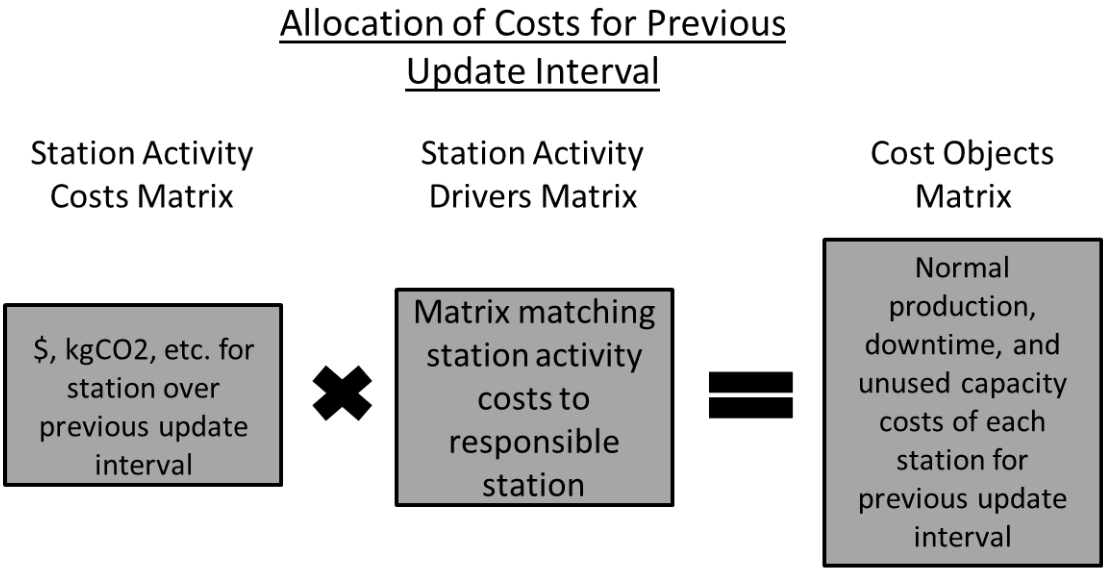


Figure 3.16: Cost Objects Calculation Process for Engine Assembly Line Example

Table 3.8: Example Activity Drivers Matrix

Cost Type	Station	1	2	3	4	5	6	R
Normal	1	0	0	0	0	0	0	0
Downtime		0	0	0	0	0	0	0
Unused		1	0	0	0	0	0	0
Normal	2	0	0	0	0	0	0	0
Downtime		0	0	0	0	0	0	0
Unused		0	1	0	0	0	0	0
Normal	3	0	0	0	0	0	0	0
Downtime		0	0	0	0	0	0	0
Unused		0	0	1	0	0	0	0
Normal	4	0	0	0	0	0	0	0
Downtime		0	0	0	0	0	0	0
Unused		0	0	0	1	0	0	0
Normal	5	0	0	0	0	0	0	0
Downtime		0	0	0	0	0	0	0
Unused		0	0	0	0	1	0	0
Normal	6	0	0	0	0	0	0	0
Downtime		0	0	0	0	0	0	0
Unused		0	0	0	0	0	1	0
Unused	Repair	0	0	0	0	0	0	1

The engine assembly line model was simulated for an eight-hour shift to produce results for this example. This simulation was done twice in order to compare the proposed methodology of separating normal production costs, added downtime costs, and added unused capacity costs to a more traditional costing methodology. This "traditional" methodology traces costs only to the stations where the costs occur and does not split these costs into normal production, downtime, and unused capacity costs. The results of the two simulations are compared in the figures below. These figures show the total costs associated with each station under the two allocation methodologies. The blue columns correspond to station costs when excluding added downtime costs from producing a number of units below the shift production quota. The red columns correspond to total station costs when downtime costs from falling short of the production quota are included. Under the traditional methodology, these downtime costs are allocated evenly across the six stations. Under the proposed methodology, these downtime costs are allocated using the percentage of total permanent production loss caused by each station. The simulation runs produced 85 assembled engines which was ten engines below the assigned production quota.

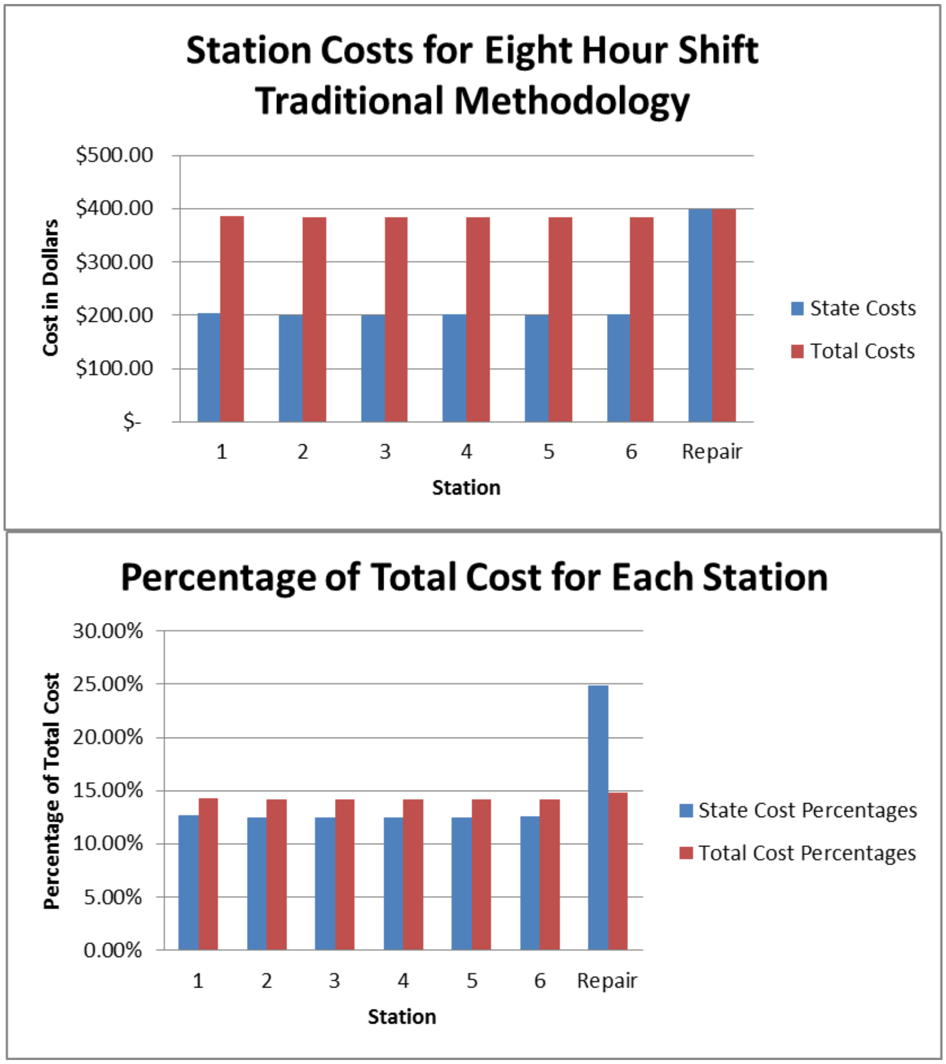


Figure 3.17: Engine Assembly Station Costs Using Traditional Methodology

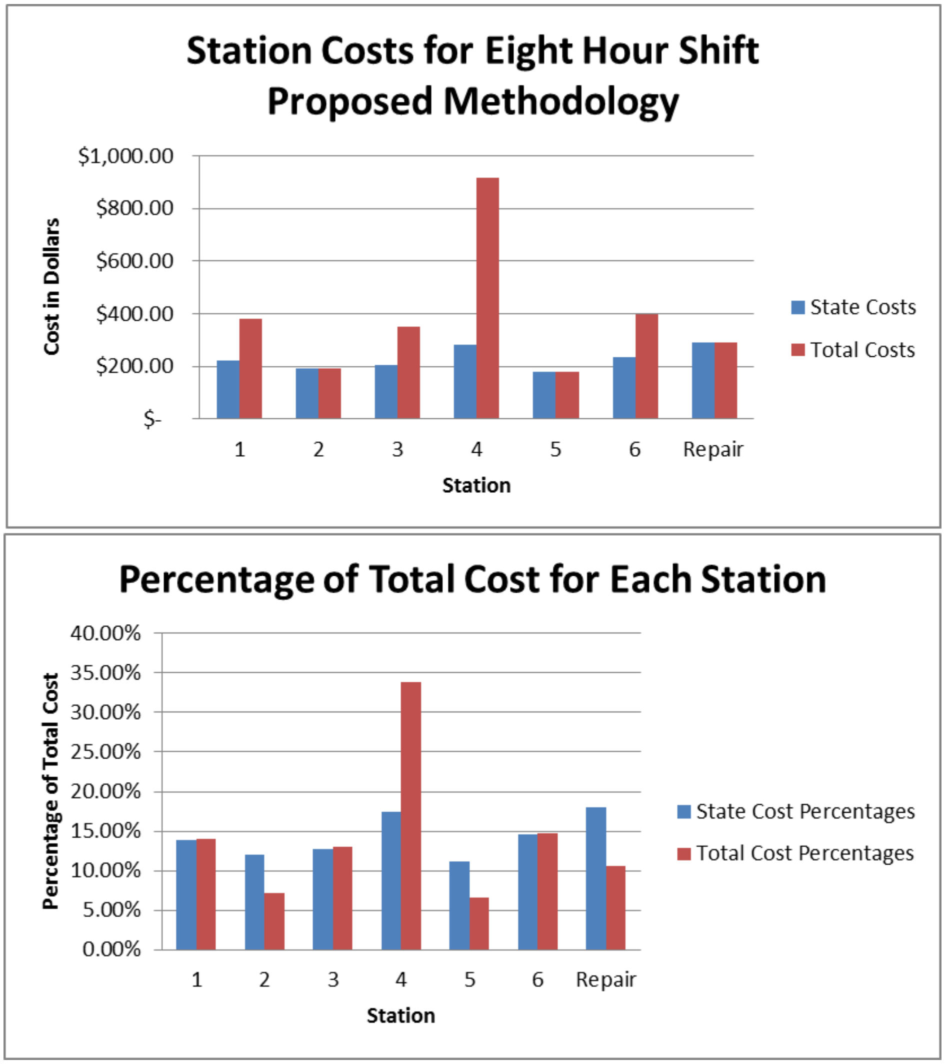


Figure 3.18: Engine Assembly Station Costs Using Proposed Methodology

One can see that there is a large difference between the allocated station costs between the two methodologies. The traditional methodology portrayed costs very evenly across all stations for both system state related costs and total costs. The proposed methodology, on the other hand, allocated additional costs to “trouble” stations that suffered from a lot of downtime. In the traditional methodology, the standby maintenance activity was the largest source of costs; however, station four was the largest source of costs under the proposed methodology.

This example shows the usefulness of the proposed methodology. Under the traditional methodology, the management of this assembly line would have little direction for determining areas for improvement and little idea of the cost benefits of improving different areas. By using the proposed methodology, the management of this assembly line knows that it can focus improvement efforts towards station four in order to make the largest impact on total cost. Management could use this proposed methodology over a long timeline to get a better idea of system behavioral trends and possible areas for process or capital improvement.

Chapter 4 provides another example implementation of the proposed methodology. The case study performed in Chapter 4 will be of a much larger and more complex system and will track more resource types. The case study illustrates the scalability of the methodology. The example presented above and the case study in Chapter 4 aim to illustrate the feasibility and usefulness of the proposed methodology.

CHAPTER 4

CASE STUDY: AUTOMOTIVE PAINT SHOP

4.1 Chapter Overview

This chapter details a case study which was performed to illustrate and validate the use of the developed methodology. The selected case study was of a paint shop in an automotive assembly plant. This case study was chosen due to the highly automated nature of the automotive painting process. The case study draws heavily from previous work performed by Paul Jurek on a previous project sponsored by General Motors and discussed in a paper (Jurek, Bras et al. 2012). In Jurek's previous work, he modeled the energy and resource use of the plant shop at an actual General Motors assembly plant using an activity-based approach. This work characterized resource use over the course of the year and was static. Jurek's model used standard, measured rates to give plant management an approximate idea of resource use and the responsible activities and cost objects.

This case study builds off of the previous work by using the predetermined resource and activity drivers from Jurek's model and recalibrating them for use in the dynamic ABC system presented here. In addition to changing static drivers to dynamically-defined drivers, this case study adds an additional layer to the previous work by adding cost aspects and by assessing cost objects that were not previously considered. This case study also incorporates a simulation that includes random downtime events and dynamic line behavior.

The purpose of this thesis is to present work pertaining to a dynamic, short-term production line costing model. In order to fully show an example of this methodology and its use of rapid production line data, it is necessary to simulate a production line to replicate the data. Because the costing model and methodology are the focus of this work, the simulation that was developed and used for this work is relatively simple and will not be discussed in intense detail; however, a brief discussion is presented in this chapter to give the reader some important background. Some simulation aspects that heavily affect the costing model are discussed in Appendix B.

This chapter first provides some background on the system of interest for this case study, an automated paint line in an automotive assembly plant. Next, the simulation portion of the project is discussed to give the reader background. After the simulation code is briefly discussed, the costing system is described and developed. This section highlights some important modeling aspects for the costing model. Next, the system layout, including station order, is discussed to present the reader with a look at how the actual line was modeled. After the system layout is presented, the spreadsheet portion of the costing model is discussed. This costing spreadsheet updates based on minute-by-minute data from the production simulation. It then calculates and allocates costs to the responsible stations. After the spreadsheet model is discussed, a few sample scenarios are presented, and the results of these scenarios are then shown and discussed.

4.2 Case Study System Background

An automotive production facility typically has three main areas: the body shop, the paint shop, and the general assembly shop. The body shop is where the frame of the vehicle is welded and built. The general assembly area is where the various mechanical components of the vehicle, such as the engine and the transmission, are installed as well as the interior components of the vehicle. Between these two shops is the paint shop, the system of interest for this case study. The general paint shop process is illustrated in Figure 4-1; though, this illustration does not exactly match the paint shop process presented in this case study.

The completed chassis of the vehicle enters the paint shop from the body shop and proceeds to the first main process, pretreatment. In pretreatment, the chassis first enters a series of cleaning steps in order to remove any grease and other contaminants that may be present on the vehicle from the body shop. After cleaning, a process called "phosphating" is performed, coating the vehicle with a layer of phosphate. This phosphate layer helps to both protect the metal and help the later paint applications adhere to the vehicle. A final cleaning, rinsing, and draining process is performed before the vehicle moves to the next main process area.

The next main process is Electro Coat Primer Operation (often called ELPO). The ELPO process applies a layer of charged primer solution that further increases the effectiveness of paint application. During the ELPO process, the vehicle is first submerged in a pool of charged primer solution. In order to get the correct thickness layer, the vehicle remains submerged for a predetermined amount of time. The vehicle is then drained to remove excess solution before the charged solution is baked onto the vehicle.

The vehicle enters the sealing line after the ELPO process. This sealing process further protects the frame from the elements. Sealants are applied and baked onto the frame before the vehicle enters the paint booth. Much of the sealing process is performed by robots, though there is some manual sealing performed.

Within the paint booth, primer, basecoat, and topcoat layers of paint are applied. Typically, this process is automated and performed by robots in order to ensure precise painting of even thickness. Because automobiles are offered in a variety of colors, the paint booth has several indirect activities to accommodate these color choices with high quality. This includes cleaning paint guns to remove the previous paint color whenever a different color is to be painted. Buffer areas are also included to accommodate color changes by batching cars until a certain number of cars with the same color are needed. These buffer areas help to reduce the number of color changes and to minimize the impact on other stations during color changes. The environment of the paint booth must also be rigidly maintained to precise conditions. Appropriate temperature and humidity levels must be maintained due to the sensitive nature of the painting process. In order to ensure proper paint layer thickness and to prevent airborne paint particles from previous paint jobs from landing on the current job, a very large volume of air is continuously cycled through the paint booth.

After the paint booth, the vehicle enters the post-paint stage for inspection. If a vehicle does not pass inspection, it is repaired. For small defects such as spot repairs, the vehicle may enter a side repair zone where the defect is sanded and repainted. For more serious quality issues, the vehicle is reinserted into the line, and the process is performed again. Understandably, quality issues can cause a large amount of repair and rework activity which, in turn, greatly increases the cost to paint a vehicle and affect the company’s bottom line.

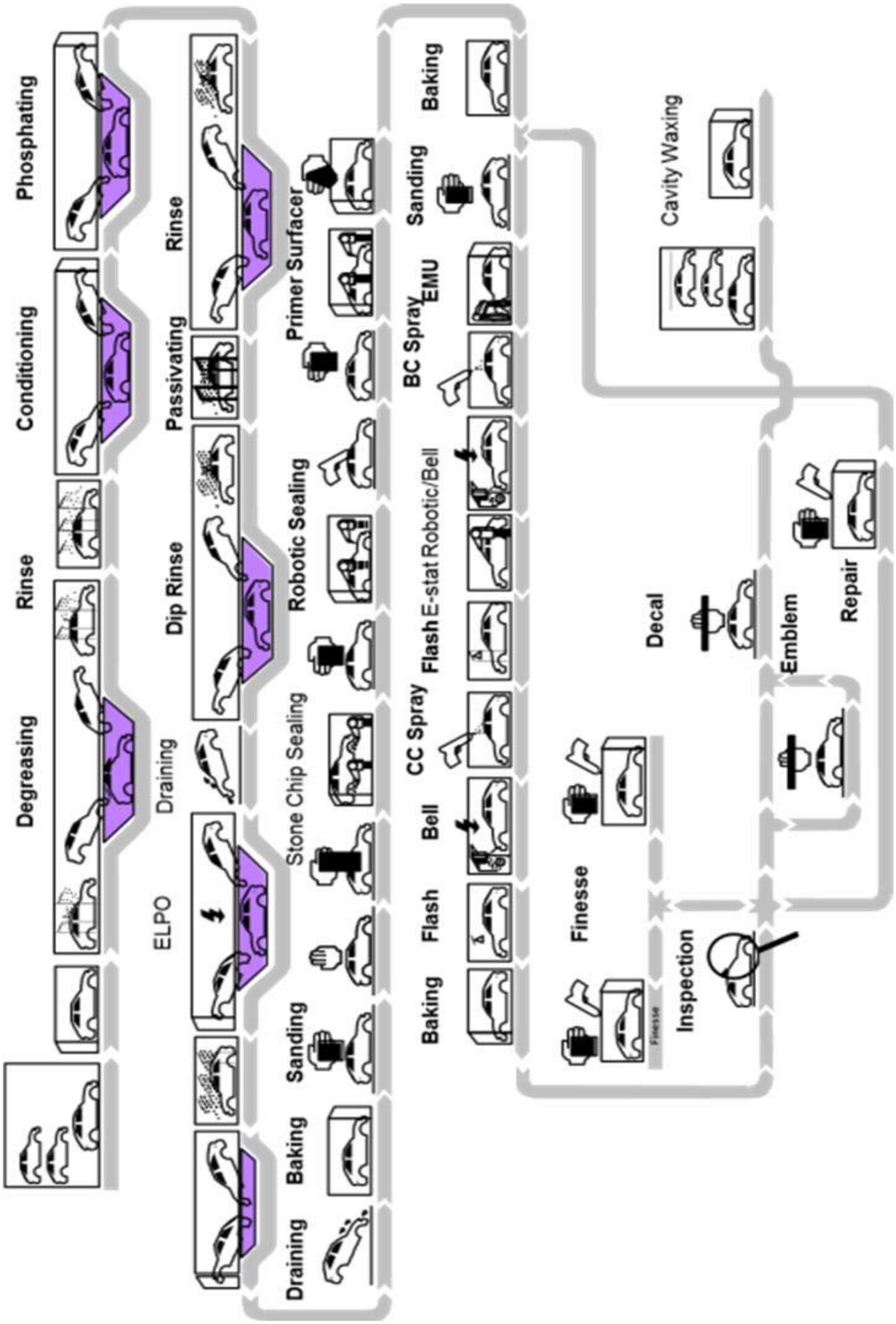


Figure 4.1: Automotive Paint Shop Process (Jurek et al, 2011)

Jurek et al defined five distinct states in which a manufacturing line system can be: 1) startup, 2) production, 3) setback, 4) maintenance, and 5) shutdown (Jurek, Bras et al. 2012). These states are comprehensively exhaustive and mutually exclusive, meaning that a station can only be in one state at a specific time. The production state is when the production line is producing normally. In this case study, this refers to when the line is actively pretreating, sealing, or painting vehicles. The setback state refers to times when the system is, in effect, "idling", such as during short breaks or between breaks. This state also corresponds to times when a station is blocked or starved due to a random downtime event at another station.

If a station will be down for a long period of time, it can be shifted into a shutdown state. This state uses the least amount of resources. The manufacturing system enters this state on days when the manufacturing facility is not in operation. After being in a shutdown state, the system must go through a startup state. During this startup phase, the manufacturing system quickly reaches normal operating conditions before entering the production state. The maintenance state corresponds to when the system (or system subset) undergoes either routine preventative or emergency maintenance due to random downtime events. The five distinct states are illustrated in Figure 3.5 in Section 3.3.1.

These defined system states can be useful for determining resource use in an activity-based costing system. In Jurek et al, they used these five defined system states to estimate utility resource use over a year and to test the feasibility of entering a demand-response contract with an energy supplier (Jurek, Bras et al. 2012). This method is useful because it allows plant management to estimate utility usage at a much lower level without installing expensive monitoring equipment. While this estimation may not be exact due to occurrences such as spikes in electricity amperage or voltage, it provides a reasonable approximation.

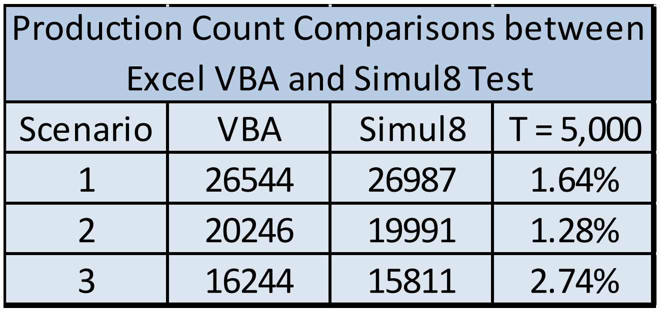
4.3 Case Study Simulation Description

In order to fully test the costing model and replicate how it would be used by an actual production line, a simulation of the production line was needed. Simulation code was created within Microsoft Excel using the Visual Basic for Applications programming language (Excel VBA). This method of simulation was used due to its ease-of-use and ability to be quickly changed depending on the scenario. The simulation code is programmed within the costing model spreadsheet workbook in order to ease data transfer between the various costing spreadsheets and the simulation code. In addition to this, the simulation code had already been developed previously; therefore, its use reduced case study development time.

A commercially-available software package was not chosen for the simulation aspect of this case study in order to focus efforts on the actual costing model instead of the integration of outside software with the costing model. For this initial work, efforts were focused merely on developing the costing methodology. In the future, additional work should be done in order to better adapt this methodology for use with commercially-available discrete event software, particularly for simulation uses for system design or the development of preventative maintenance policies. Because simulation code was used instead of commercial software, it is likely that the created simulation code is not as robust as commercially-available software packages; however, care was taken to ensure that the created simulation code was reasonably accurate and realistic.

In order to test the accuracy of the created simulation code, a sample line was quickly modeled within a commercial simulation package named Simul8. Runs of the Simul8 model were then compared to runs of the created simulation code. The table below shows the results of this comparison for an arbitrary example. Each scenario included different mean time between failure (MTBF) information and different initial buffer levels. The simulation code was within 3% of the Simul8 commercial software results for each scenario. This suggests that the simulation code is reasonably accurate and useful for the purposes of this case study.

Table 4.1: Comparison Tests between Simulation Code and Commercial Software



Production Count Comparisons between Excel VBA and Simul8 Test			
Scenario	VBA	Simul8	T = 5,000
1	26544	26987	1.64%
2	20246	19991	1.28%
3	16244	15811	2.74%

Originally, the simulation code was developed using a continuous flow model. In a continuous flow model, work-in-progress can flow freely through the system as fractions of a part, similar to how water may flow through a system of pipes. The simulation code was quickly changed to a discrete flow model in order to more accurately represent the nature of the chosen production line. A discrete flow model separates work-in-progress into separates units that must be released and accepted by the individual stations and buffers of the production line. Whereas a continuous flow model allows fractions of a unit to move onto the next station or buffer, a discrete model requires the work on a unit within an individual station to be completely finished before the unit can move to the next station or buffer. This is similar to an automotive paint line in real-life. Each car must move through the paint line as a single unit, i.e. half of a vehicle cannot be a work-in-progress at one workstation with the other half of the vehicle as a work-in-progress at the next workstation.

The simulation code replicates this discrete nature by completing a percentage of the needed work on a unit at a workstation during each time step. When all work is completed on the unit, the current station allows the unit to be released; however, the unit will not be released unless the next station or buffer in the line calls for the unit to be released. This release system is based on a simple "flagging" system between adjacent stations and buffers. If the next entity in the line is a buffer, the unit will be released if the buffer is not at maximum capacity. If the next entity is a workstation, the unit will be released when the next station is in operation, is empty, and is ready for the next unit. This "flag" system allows the simulation code to replicate blockage and starvation events that occur on actual production lines.

Buffers may or may not be physical job banks. A physical buffer may hold numerous units that are waiting to enter the next workstation and may have the capacity to hold many more units. In addition to these physical buffers, one can also think of jobs that are in waiting or exiting a station as being located in "buffers". By including jobs that are entering and exiting a workstation in the buffer area for that station, the simulation code is significantly simplified. The inclusion of these “buffers” is discussed further in Section 4.5.

The simulation code is capable of simulating random downtime events. The time and duration of these events can be preprogrammed into the simulation, or mean time between failure (MTBF) and mean time to repair (MTTR) data can be given for each station. In the latter case, timers “count down” from the last random downtime event at a workstation until the next failure event based on the station’s MTBF. The simulation uses the mean time to repair (MTTR) of each station to determine the amount of time that a station is broken down for each failure event. This breakdown time is computed using MTTR, similar to the occurrence of failure events described above. These events are deterministic for the purposes of this case study in order to more easily replicate results. In this case study, the only modeled downtime events are preprogrammed in the simulation code and do not require MTBF or MTTR values.

The simulation code runs for a predefined time period with a prescribed time step. This time step is small enough to replicate line behavior, but its shortness is limited for both practical and technical reasons. Practically, it made little sense to have a very small time step because the very minor increase in accuracy would lead to a much longer simulation runtime. Technically, Excel VBA limits array sizes. Too small of a time step would lead to data arrays that are out of the bounds of what Excel VBA can handle.

In order to both better replicate how the costing system would use real-time production line data and to shorten simulation runtime, some calculations are only performed every simulated minute. These calculations are those that are most pertinent to the costing portion of this model. While this may lead to a slight discrepancy in the calculated costs due to changing states over a single minute, it is assumed that these discrepancies are not large and are “evened out” over time. For instance, a station may break down after 45.5 minutes. While this would only generate downtime costs for the last 30 seconds that minute, the costing spreadsheet will update as if the station broke down after 45.0 minutes. This slight discrepancy is assumed to be minor from the costing point-of-view.

The simulation takes input from the first spreadsheet of the Excel workbook. This spreadsheet contains the list of stations and each station’s rated speed. The spreadsheet also includes buffer information such as buffer capacity and initial buffer inventory level.

It should also be noted that the simulation code follows a “push” control methodology where units are started at the beginning of the system and “pushed” through the line. This is different from a “pull” control methodology that sends calls for unit production from the end to the beginning of the line and “pulls” product through the system. As such, stations will continually produce even if a station downstream is broken down and will not stop until all buffers between the two stations are full.

4.4 System Description and Development

To begin this case study, the paint shop was first split into its cost objects, activities, and resources. For this case study, the goal is to highlight to plant management areas for attention and improvement. Therefore, the cost objects are defined as the 57 stations of the first four areas of the paint line: the pretreatment, ELPO, sealing line, and paint booth areas. These cost objects can each be broken down into three sub-cost objects: normal production costs, downtime costs, and excess capacity costs. The activities for this case study are the 57 stations considered for this case study.

For this case study, the post-paint section of the paint shop is not considered. This was done to simplify the model. Inclusion of this last section would both greatly increase the complexity of the model due to the nature of the post-paint section as a section of quality control with process usage differing widely based on individual quality inspections. Conceivably, a full implementation of this methodology on a real-life production line could pull data from quality tracking systems to determine the costs of quality issues and resource usage in the post-paint stage. For the sake of this model however, this is not considered.

Five resources are considered in this case study – electricity, natural gas, compressed air, hot water, and chilled water. This matches the resources that were considered in Jurek's model. These five resources were chosen because they are inherently dependent on system state and are used at set ratios depending on the current state of each station. Additionally, information on the resource drivers for these five resources was readily available with Jurek's model and limited the need to seek much additional information.

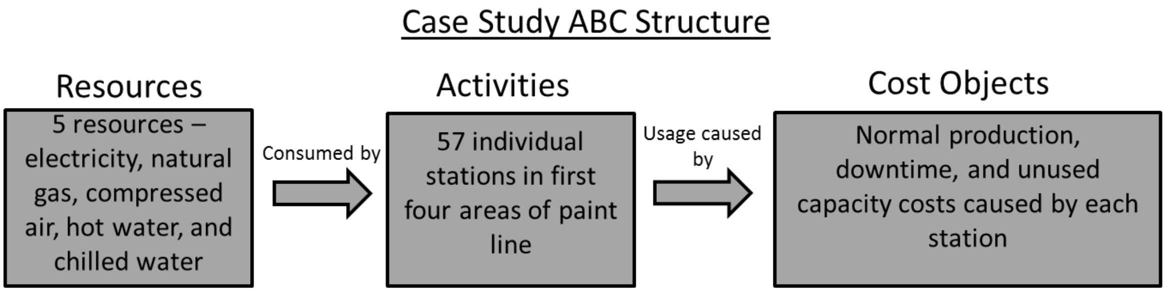


Figure 4.2: Case Study ABC Structure

Other resources were not considered for a myriad of reasons. Labor was not considered due to the highly automated nature of the paint shop. For instance, the application of topcoat paint is performed entirely by robots. Because the bulk of the costs pertain to equipment usage; it was assumed that the costs of labor would be relatively small compared to the cost of utilities. Most importantly, there was also a lack of data corresponding to labor costs that heavily influenced the decision to not consider the labor resource. Direct resources (e.g. paint, sealant, cleaner solution, etc.) were not considered because they were inherently dependent on production volume and must be consumed in order to paint the vehicle. Therefore, the inclusion of these resources would not lead to useful information in regards to the added downtime and unused capacity costs of the paint line. Additionally, some of this information was unavailable during the development of this case study.

4.4.1 Discussion of Considered Costs

For this case study, only the utility costs of the paint shop are considered. There are several reasons for this decision. Some of these reasons were briefly touched upon in the previous subsection and will be further examined below.

As mentioned previously, direct material (raw materials and supplied components) costs are not included in the model because it is outside of the main goal of this case study – to track the costs of changing system behavior. Including the costs of resources that are directly correlated with production volume would lead to a skewed view of the costs of different stations and cost centers. The inclusion of these costs would possibly help to “hide” added costs in other stations from downtime because the down station would use fewer direct materials since it spends less time in production. Meanwhile, stations that are functioning normally would seem more expensive because they are using extra resources. This method of excluding the costs of direct materials is also consistent with the approach taken by Liu et al (2012).

The amortization of purchasing machinery, buildings, and other capital costs is also excluded from this case study due to a lack of information. Feasibly, these costs could be included in an implementation for this methodology to give a better idea of how well a piece of equipment is used compared to its forecasted usage. This would also better highlight the additional costs of downtime because of the amortized costs of idle equipment.

The costs of lost sales are not considered in this case study due to a lack of information about these costs. In order to accurately determine the value of lost sales, one would need to have an accurate view of the product's demand as well as the profit margin on each sale. This information was not readily available for this product; therefore, the costs of lost sales were not included in the costing model.

Lastly, only utility costs were modeled because their usage rates were already determined for Jurek's model. This allowed input data to be determined fairly quickly and relatively easily by merely converting Jurek's resource usage rates to a short time unit in order to be used for a dynamic simulation. Labor resource usage rates were not available; therefore, labor was not included as a resource.

4.4.2 Modeling of System States

In Jurek's model, he defined and modeled five distinct system states – startup, production, setback, maintenance, and shutdown. For this thesis, however, only three states are modeled for the case study – production, setback, and maintenance. These three states were chosen because this research only aims to model system behavior and costs during a normal production shift. There were several reasons, both practical and theoretical, for limiting the number of system states for this model. The most compelling reason to exclude some states was to limit computation time and setup. In any costing system, there is a need to balance costs and benefits. For this model, two states were excluded in order to decrease the "cost" (time, effort, computational resources, etc.) without markedly decreasing the quality of the model. The theoretical reasons for eliminating the two excluded system states – shutdown and startup – are discussed further below after a discussion of the included states.

The production, setback, and maintenance states were considered in the model for this case study. A station currently in the production state produces units normally at its rated speed. If a station breaks down on the line, this station enters the maintenance state. A broken down station can cause other stations to be blocked or starved. In this case, the blocked and starved stations enter the setback state. Stations may also enter the setback state when they are blocked or starved by a slower station on the line.

Due to the nature of the system being modeled, it is assumed that no sections of the paint shop enter the shutdown state during a normal production shift. This model only models the line during production hours, and it is assumed that the line is never down long enough to necessitate shutting down the line or portions of it. In addition to this, the resource usage for the bulk of the equipment considered in this case study had a similar usage rate for both the maintenance and shutdown states.

Partially because of this model's exclusion of the shutdown system state, the startup system state is also excluded. It is assumed that, because a station in the paint shop will never shut down during a normal production shift, a station will never need to enter the startup system state in order to exit a shutdown period. The startup state is also excluded due to the closeness of many of the resource use rates between the startup system state and the production state. Lastly, the initial startup state of the system at the very beginning of a shift is not included due to the "necessity" of the step. The purpose of this model is to provide plant management with a detailed look at how normal production costs and the added costs of downtime and excess capacity are distributed across different cost centers. This is done in a dynamic and near real-time way in order to assess changing system behavior. It is assumed that the startup phase of the system will not change unless the equipment within the system changes. It is assumed that disregarding this system state will have a negligible effect on the results of the model.

After dividing the system behavior into three distinct states, the resource use rates of each station in each of these states were programmed and organized. As mentioned previously, only utilities are considered for this costing model. Also, it is assumed that these three states reasonably approximate utility usage for an entire production shift.

4.4.3 Resource Use and Costs Modeling

Five resources are considered in this model: electricity, natural gas, compressed air, hot water, and chilled water. These resources are the same resources that were considered in Jurek et al (2012). The resource use rate is assumed to be constant for a particular station in each state. Realistically, there are likely spikes and dips in resource usage as a station performs its tasks, but the defined resource use rate is meant to be an average over a simulated minute. This provides more granularity than Jurek's model because this model considers resource use on a minute-by-minute basis whereas Jurek's model looked over annual resource use.

Raw material resources (e.g. paint, coating solutions, etc.) and supplied component resources (e.g. the car frame entering the paint shop from the body shop) are not considered. These resources are excluded because this model is intended to capture the costs of changing system behavior. These resources are only consumed during normal production, and their costs are directly correlated with production volume. This model aims to capture the costs of downtime and excess capacity in addition to production costs. Including these "direct" resources would not aid the goal of this model.

In other implementations, the model developer may be interested in determining the costs of lost profit due to lower production volumes. These costs are not included due to a lack of information. Also, these costs were considered less important because the production line considered in this case study is in a position where demand changes; therefore, the sale of a produced unit is not guaranteed. This is different than the production line of the supplier discussed in Faria et al (2010) where the supplier was issued penalty costs in addition to the costs of lost sales.

Resource use is updated every simulated minute. This is based on the assumption that production line data updates on a per-minute basis. The state of the system for the previous time step is used to determine the system state for the previous minute. This could lead to some slight differences between the actual system state for the previous minute and the updated state. For instance, a station may be in a normal production state for the majority of a simulated minute and then break down just before the cost model is updated. The update to the costing spreadsheet would suggest that the station was broken down for the entire previous minute. This will lead to slightly different resource usage totals. However, it is assumed that these differences are minor and that these differences "even out" over time. Therefore, the accuracy is not dramatically affected.

Resource use rates were determined by using the hard data in Jurek's model that provided hourly usage rates for various pieces of equipment in the paint shop system. This also illustrates a key difference between this model and Jurek's model. In Jurek's model, all equipment resource usage rates are summed to determine the total resource usage over a year. After these totals are calculated, they are traced to the different paint shop areas by the use of several activity drivers.

This model, however, relies on information for specific stations, not just entire areas. This requires a more detailed approach to determining resource usage rates. In order to determine the resource usage rates of a specific station, equipment was traced to specific stations. Once this equipment was traced, it was possible to sum the resource usage rates of the different pieces of equipment associated with a station to come to a single usage rate for each resource in each state. This proved to be a tedious process.

Equipment was traced to specific stations by referencing comments within Jurek's model, some limited process flow information about the paint line, and some plant drawings relevant to the paint line. This proved to be an imperfect process due to some lack of information. In some cases, the placement of some pieces of equipment was not possible due to a lack of available information. The resource use of this equipment was not included in the costing model.

This method of determining resource usage rates introduces some error because it is possible that not all of the equipment associated with a station was included in the model. In other cases, a piece of equipment might serve several stations at the same time. In this case, the resource usage was split among the stations evenly unless information was available to better allocate the percentage of use. For instance, resource use corresponding to conveyor systems was allocated to each station on the basis of the station's length.

This introduced error is acceptable because this case study is meant to merely show the usefulness of the methodology and not to be a full implementation of the system on an actual line. During a full implementation of this methodology in a real-life plant, plant management will more easily be able to trace equipment to specific stations and better assign allocation percentages for equipment that is used in several stations.

4.4.4 Allocation of Costs to Responsible Cost Centers

Comparisons can be made between how a "traditional" ABC system would allocate costs and how the presented system allocates costs. "Traditional" ABC systems only focus on where resources and activities are actually consumed. On the other hand, the presented methodology focuses on why resources are consumed and what cost center is responsible for this consumption.

The model quantifies the resource consumption by a station over the previous time unit by using the station's state (production, setback, or maintenance) for the previous time unit. This is relatively straightforward. The station's state also helps to trace the resource use to the responsible cost center. If the station was in the normal production state, then it is responsible for its resource use for the previous time unit because it is behaving normally. The costs of this resource use will be allocated to the station as normal production costs. Similarly, the station is responsible for its resource use if it is in the maintenance state because it is solely responsible for its state. In this case, the costs of this resource use in the maintenance state would be allocated as downtime costs for the station. These two system states allow relatively simple allocation to responsible cost centers. However, allocating resource use by a station in the setback state is much less straightforward.

There are different reasons for a station to be in a setback state. A station enters the setback state when it is either blocked or starved by an adjacent station. There are four reasons why a station may be in setback mode – 1) the station is blocked because of a slower station after it, 2) the station is blocked because of a breakdown of a station after it, 3) the station is starved because of a slower station before it, or 4) the station is starved because of a breakdown of a station before it. Depending on the reason for the setback state, the allocation of this resource use will be different. If a station is in setback because of a breakdown upstream or downstream from the station, the resource use by that station will be allocated to the broken down station as a downtime cost; however if the setback is caused by a slower station, the costs of resource use will be allocated to the setback station as unused capacity costs. The cost allocation flowchart from Figure 3.13 is repeated below to illustrate the cost allocation method logic.

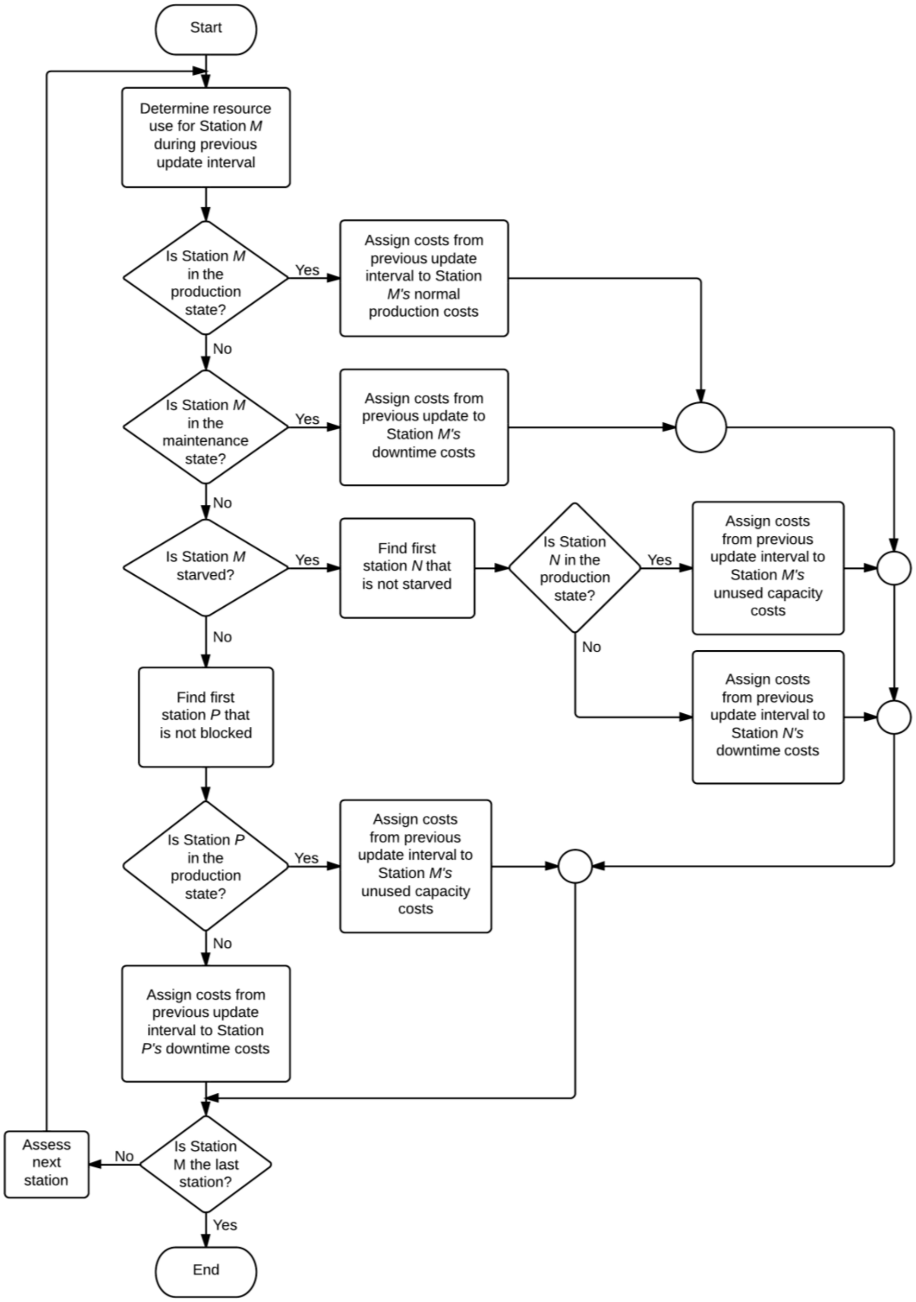


Figure 4.3: Flowchart for Cost Allocation Logic

Depending on the goals of plant management, unused capacity costs could be allocated differently. In the allocation method shown in Figure 4.3, unused capacity costs are allocated to the faster station that is forced into a setback state because of a slower station on the line. This concentrates costs on faster stations. Such an allocation method may be useful when determining the cost benefits of adding buffer space around faster stations or the cost benefits of changing the production schedule by running faster stations in shorter shifts.

Conversely, plant management may be interested in determining the cost benefits of updating slower machinery or the cost benefits of improving process times for slower stations. In this scenario, plant management may find it more useful to allocate unused capacity costs to slower stations. In a manufacturing line that is fairly inflexible, such as the automotive paint shop examined in this case study, it may be more beneficial to use this latter allocation method for the costs of unused capacity.

4.4.5 Summary of Assumptions

In order to generate this case study, several assumptions were made. These assumptions helped to simplify the case study. Main assumptions are listed below:

1. The first station is never starved, and the last station is never blocked.
2. Stations that hold numerous jobs in real-life, such as the ovens in the ELPO, sealing line, and paint booth areas, can be reasonably modeled as containing only one job with a shorter time cycle and a larger buffer area around the station.
3. The area between stations may be modeled as a buffer, even if there is not an actual job bank on the actual paint line. This is done to compensate for jobs waiting to enter a station and jobs leaving a station.
4. Resource usage can be reasonably modeled using dynamic station state information and static resource drivers corresponding to different station

states. These static resource drivers are estimated combining the resource usage rates of all pieces of equipment that are used by the station.

5. Stations operate only at their rated speed while in the production state.
6. There is zero lag time between the time of failure and the beginning of repair during random downtime events. The duration of an individual station downtime event is equal to the mean time to repair (MTTR) of that station.
7. Work-in-progress within a station can still be used after a station failure occurs. The percentage complete on a station's current work-in-progress is the same before and after a situation where the station fails. Work-in-progress is not scrapped during a downtime event.

In addition to the above assumptions, it is important to note that this case study was performed using deterministic events. This was done to make repeatable results for use in comparing cost allocation methods. In the future, stochastic events should be used to better test the methodology with more realistic simulations.

4.5 Production Line Layout

As mentioned previously, the first four major segments of the paint shop are modeled: the pretreatment area, the ELPO area, the sealing line, and the paint booth. The post-paint area is not included. The post-paint area was not included due to its irregular nature as a quality control area. In the post-paint area, quality inspections are performed on the painted vehicles. Depending on the severity of a quality issue, vehicles may go through spot repair or a full rerun of the paint process. In order to ease simulation and modeling difficulty, the post-paint area was not included because of this irregular process flow.

This case study is based off of an actual paint shop at an automotive assembly plant. However, it has been slightly altered for two reasons: 1) to protect proprietary information and 2) to simplify the model's complexity. In order to protect proprietary information, the input parameters (e.g. station speed, buffer size, etc.) have been slightly altered. Resource consumption rates may also be slightly different than actual consumption due to lack of information about all of the equipment associated with a station.

Several alterations were made in order to simplify the model, particularly the simulation aspect of the model. In an actual paint line, stations may hold several jobs at the same time, even though it may only be actively working on a single job. For instance, the dip rinse station at the end of the pretreatment phase may have one car exiting the rinse pool while the next car is entering the dip pool at the same time. In order to simplify the modeling of this, a station in the model can only hold one job (in this case, a single car). The area around each station is modeled as a "buffer" area, even though there may not be an actual buffer. This allows the station information to be input into the simulation model without having to make various operation rules for each individual station. Modeling each station with a buffer area around it allows the simulation portion of the model to be easily scaled while still reasonably mimicking the actual behavior of the real-life station. This also allows actual large buffer areas to also be easily included.

It is assumed that the first station of the model is never starved. This means that there is always a car standing by at the beginning of the paint shop after exiting the body shop. This is done to limit the scope of the model. If the first station were allowed to be starved, the model would need to account for added costs caused by an area outside of the system. The focus of this model is the system behavior of the paint shop; therefore, it is assumed that the first station is never starved.

Similarly, the last station of the model is assumed to never be blocked. This means that there is always room to accommodate jobs as they are finished by the final stage. This prevents the paint line system from stopping due to an outside area and focuses the model on the behavior of the paint shop system.

Throughout the four process areas of this case study, there are several inspection and observation decks. These stations are not modeled for this case study in order to limit the scope and complexity of this model. This model does not include quality issues; therefore, stations that deal predominantly with quality control are not included.

The entire line is modeled as a series of stations and buffers in a serial production line. In real-life, there may be several pull-off areas or re-entry points. These areas are not modeled for this case study in order to ease the complexity of the simulation and costing model. The robotic painting area of the paint booth is modeled as a single line, despite the fact that there are two robotic painting lines in the actual paint shop. In order to compensate, robotic painting stations are modeled as being twice as fast in order to match the production of two robotic painting lines.

4.5.1 Pretreatment Station Layout

The pretreatment area cleans and pretreats incoming vehicles from the body shop before they can enter the ELPO process and the rest of the paint shop. The pretreatment area consists of ten automated stations with nine buffers in a serial production line. Cycle times (and therefore, rated speeds) are approximated based on system design information. The pretreatment area begins with an entrance vest and air seal area which keeps unwanted air particles out of the cleaning area. Following this, the vehicle enters a cleaning station that deluges the vehicle with cleaning solution and then spray cleans it. The next station dips the vehicle into a cleaning solution and then sprays it. Next, the vehicle enters two consecutive spray rinse stations. These consecutive cleaning solution and water rinse stations help to remove grease, dirt, and other contaminants from the vehicle's body before it can be pretreated in the rest of the pretreatment process area.

Following the water rinse, the vehicle goes through a series of pretreatment stations that ready the vehicle for the ELPO process area. First, the vehicle is dipped into a conditioning solution in one station, followed by a phosphating dip in another station. After this phosphating dip, the vehicle enters a passivating spray station and then a passivating dip station. Finally, the vehicle enters a station where it is tilted ("camel-backed") to drain excess solution and then blown off in order to better dry the vehicle. The vehicle then enters the ELPO stage.

Before each of these stations, a small "buffer" area is included in the simulation. In the actual pretreatment area, there are no buffers within the pretreatment line; however, very small buffer areas are included in this model in order to compensate for jobs entering and exiting each station. The table below lists the ten stations and their approximate rated speeds.

Table 4.2: Pretreatment Area Station List

Section	Station Description	Station Number	Rated Speed (parts/min)
Pretreatment	Entrance Vest & Air Seal	1	0.80
	Cleaner Deluge/Spray	2	0.57
	Cleaner Dip/Spray	3	0.56
	City Water Spray Rinse	4	0.82
	City Water Spray Rinse	5	0.64
	City Water (or Conditioner) Dip	6	0.57
	Thin Film (or Phosphate) Dip	7	0.57
	DI (or Passivation) Spray	8	0.98
	DI Dip	9	0.62
	Camel Back and Blow Off	10	0.62

4.5.2 ELPO Station Layout

The Electro Coat Primer Operation (ELPO) stage follows the pretreatment stage. During the ELPO process, the vehicle is coated with an electrically charged primer layer that aids the adherence of paint later in the paint shop. The ELPO station consists of 14 automated stations, the last of which is a very large job bank before the sealing line area. Between adjacent stations, there are buffer areas, for a total of 13 buffer areas in the ELPO process area.

The ELPO process begins with the ELPO immersion tank station. This tank contains a solution that becomes electrically-charged and adheres to the vehicle, forming a consistent electrocoated layer. Next, the vehicle enters a series of rinsing stations that remove any excess paint that has adhered to the electrocoat layer. The vehicle is first given rinse with a fresh ultrafiltrate (UF) solution, followed by a recirculated UF rinse spray. Then, the vehicle enters a full UF immersion rinse, followed by a second recirculated UF rinse spray. After this station, the vehicle enters a fresh UF rinse spray station, followed by a recirculated DI passivation spray rinse. Afterwards, the vehicle enters a fresh deionized water passivation spray rinse. In the following two stations, the vehicle is “camel backed” to drain excess solution and then is blown off to remove the remaining excess solution.

The second half of the ELPO process involves baking the ELPO layer onto the vehicle. This is done in three oven zones – the heat up zone (Zone 1), the equalization zone (Zone 2), and the convection hold zone (Zone 3). After leaving the oven, the vehicle enters a cooling tunnel that cools the vehicle to near room temperature. In order to simplify modeling of the ELPO oven and cooling tunnel, these stations are modeled with very large buffers before them to simulate the large number of jobs that are processed within them. For these zones, the rated speed of each station is set to closely match the approximate time interval between vehicles exiting each station.

After the cooling tunnel, the vehicle enters a large buffer station called the ELPO oven strip bank. The ELPO oven strip bank serves as a very large buffer that separates the ELPO process area from the sealing line area. It helps to allow the two areas to run separately in the event of random downtime events or differences in production schedules. The ELPO oven strip bank is modeled as a station because it has several conveyor systems that consume a significant amount of resource. If the strip bank equipment was modeled within another station (such as the cooling tunnel), this would skew resource consumption rates and suggest that the cooling tunnel uses resources at a significantly higher rate than it actually does. The buffer area within the ELPO oven strip bank is modeled evenly on both sides of the station; therefore, the buffers in the simulation around the ELPO strip bank have large capacities. The table below shows the fourteen stations and their rated speeds.

Table 4.3: ELPO Area Station List

Section	Station Description	Station Number	Rated Speed (parts/min)
ELPO	ELPO Immersion Tank	11	0.56
	1st UF Rinse	12	1.16
	2nd Rinse Recirc UF Spray	13	0.82
	3rd Rinse Full UF Immersion	14	0.62
	4th Rinse Recirc UF Spray	15	0.64
	5th Rinse Fresh UF Spray	16	2.79
	6th Rinse Recirc DI Spray	17	0.82
	7th Rinse Fresh DI Spray	18	2.79
	Camel Back/Blow Off	19	0.70
	Z1 - ELPO Oven - Heat Up	20	0.93
	Z2 - ELPO Oven - Equalization	21	1.32
	Z3 - ELPO Oven - Convection Hold	22	0.81
	Cooling Tunnel	23	0.70
	ELPO Oven Strip Bank	24	0.75

4.5.3 Sealing Line Station Layout

The sealing line seals the vehicle frame to fully protect it from the elements. Sealants are applied to the vehicle both manually and through automation. The sealing line contains 14 stations and 13 buffers in series.

The vehicle enters the sealing line from the ELPO area and enters a metal correction station. Next, protection aids and plugs are installed on the vehicle. The vehicle is then sanded to prepare the ELPO layer for additional sealing. The underbody of the vehicle is then sealed manually and robotically. Next, the interior and roof of the vehicle are sealed robotically. Following this station, the vehicle enters the automated liquid applied sound deadening (LASD) sealant station. Following LASD, the vehicle is then manually sealed. Following the manual seal, the vehicle undergoes manual hem sealing, automated rocker antichip sealing, and manual in-line PVC-based resin sealing.

After the vehicle is fully sealed, the vehicle enters the sealing line oven in order to fully cure sealants and adhere them to the vehicle. Similar to the ELPO oven, the sealing oven has three zones: the heat-up zone (Zone 1), the equalization zone (Zone 2), and the convection hold zone (Zone 3). The vehicle exits the oven and then enters the cooling tunnel before moving on to the sealing line oven strip bank and the paint booth.

The sealing line oven is modeled in the same way as the ELPO oven as several stations each holding one job and preceded by a large buffer. The sealing line oven strip bank is modeled similarly to the ELPO oven strip bank with a large buffer area on each side of the sealing oven strip bank "station". The table below shows the fourteen stations and their rated speeds.

Table 4.4: Sealing Line Area Station List

Section	Station Description	Station Number	Rated Speed (parts/min)
Sealing Line	Metal Repair	25	0.81
	Protection Aids/Plugs	26	0.75
	ELPO Sand	27	0.81
	Robotic UBS/UBS	28	0.92
	Robotic Interior & Roof	29	0.73
	LASD & Engine Robotic	30	0.73
	Manual Seal (Main Deck)	31	0.81
	Manual Sealer Hem Seal	32	0.81
	Robotic Rocker/PVC Roof Ditch	33	0.81
	Z1 - Seal Oven - Heat Up	34	0.80
	Z2 - Seal Oven - Equalization	35	1.00
	Z3 - Seal Oven - Hold	36	0.89
	Cooler	37	0.83
	Sealer Oven Strip Bank	38	0.76

4.5.4 Paint Booth Station Layout

The paint booth follows the sealing line and is the final area considered in this case study. The paint booth is where the basecoat and topcoats of paint are applied to the vehicle. The paint booth consists of 19 stations and 18 buffers in series.

The paint booth is a bit more difficult to model than the other paint shop areas because it contains two separate paint lines for much of the area. All of the other areas consist of single serial production lines, but the paint booth contains a section of parallel production lines. In order to compensate for these parallel lines without modifying the simulation code, these parallel lines were modeled as a single serial production line. Each station within this section is modeled with a higher rated speed to make up for the reduction of two lines to a single line. While this simplification will cause a loss of accuracy in cases where a station within this section breaks down, this inaccuracy is assumed to be minor for the purposes of this thesis. Future adaptations could implement the parallel lines separately in order to increase accuracy.

When the vehicle enters the paint booth from the sealing line, it enters a station that performs a high velocity blow off to remove contaminants such as dust from the vehicle. The vehicle is then manually prepped. After leaving a manual prep deck, the vehicle enters one of two lines. These two lines have identical stations and merely run in parallel. After entering one of the two lines, the vehicle is first feather dusted. Then, robots apply paint to the exterior of the vehicle. Following this, the vehicle is flash heated and then cooled. Next, robots spray paint the interior of the vehicle followed by the exterior of the vehicle. After this basecoat is applied, the vehicle is flash heated and cooled for a second time. Another set of robots then applies a topcoat to the interior of the vehicle. This is followed by robots applying the topcoat to the exterior. As stated previously, these two parallel painting lines are modeled as a single line with twice the speed.

After the topcoat is applied, the vehicle enters the paint booth oven. The paint booth oven is similar to the ELPO and sealing line ovens in that it also has separate zones. The paint booth oven, however, has five zones, not three. These five zones are the initial heat-up zone (Zone 1), the heat-up hold zone (Zone 2), the final heat-up zone (Zone 3), the equalization zone (Zone 4), and the convection hold zone (Zone 5). The vehicle enters a cooler after leaving the oven and then enters the topcoat strip bank buffer area before being released to the post-paint area. The topcoat oven, cooling tunnel, and oven strip bank are all modeled in the same fashion as their corresponding segments in the ELPO and sealing line process areas. The table below shows the stations within the paint booth and their rated speeds.

Table 4.5: Paint Booth Area Station List

Section	Station Description	Station Number	Rated Speed (parts/min)
Paint Booth	HV Blow Off	39	0.69
	Manual Prep Deck	40	0.68
	Feather Duster	41	0.63
	Basecoat #1 Exterior	42	0.78
	Heated Flash #1	43	0.75
	Cooling	44	0.75
	Basecoat #2 1st Coat Auto Int & Ext	45	0.52
	Basecoat #2 2nd Coat Auto Int & Ext	46	0.67
	Heated Flash #2	47	0.58
	Cooling	48	0.98
	Clearcoat Interior Robots	49	0.67
	Clearcoat Robots	50	0.72
	Initial Heat Up	51	0.71
	Heat Up Hold	52	1.00
	Final Heat Up	53	1.00
	Equalization	54	1.00
	Hold	55	0.94
	Cooler	56	0.57
	Topcoat Oven Strip Bank	57	0.57

4.6 Spreadsheet Model Setup

The costing model is setup in an Excel workbook with separate spreadsheets for different stages of the ABC structure. Some of these spreadsheets contain static data that does not change. Other sheets are dynamically updated by the simulation. The simulation updates these sheets for every simulated minute. This is done to take advantage of the increased speed of spreadsheet formulas over VBA executions during the simulation. This also allows the simulation to store less information and allows the model to be easily scaled. The cost allocation process is similar to the one used in the engine assembly line example in Section 3.4.2. The figures below present the two-phase allocation method. In the actual costing spreadsheet, the scalar consumption intensities are applied at the end of the allocation process in order to ease readability and promote the use of various consumption intensities and cost types like environmental costs.

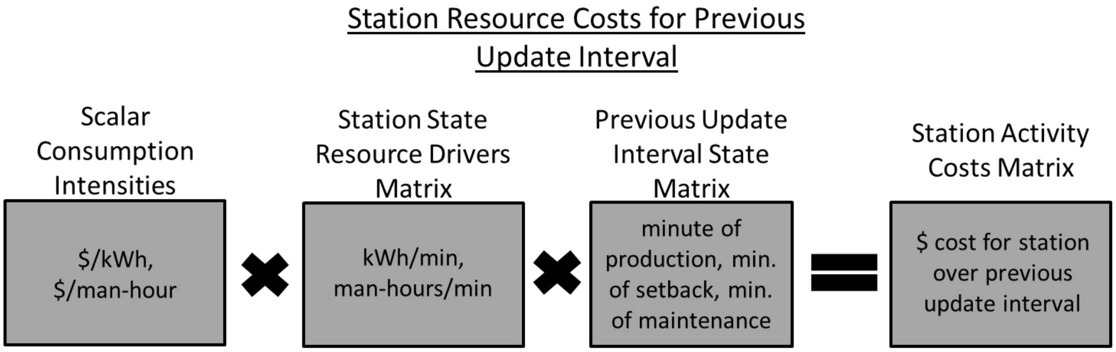


Figure 4.4: First Phase of Cost Allocation Process

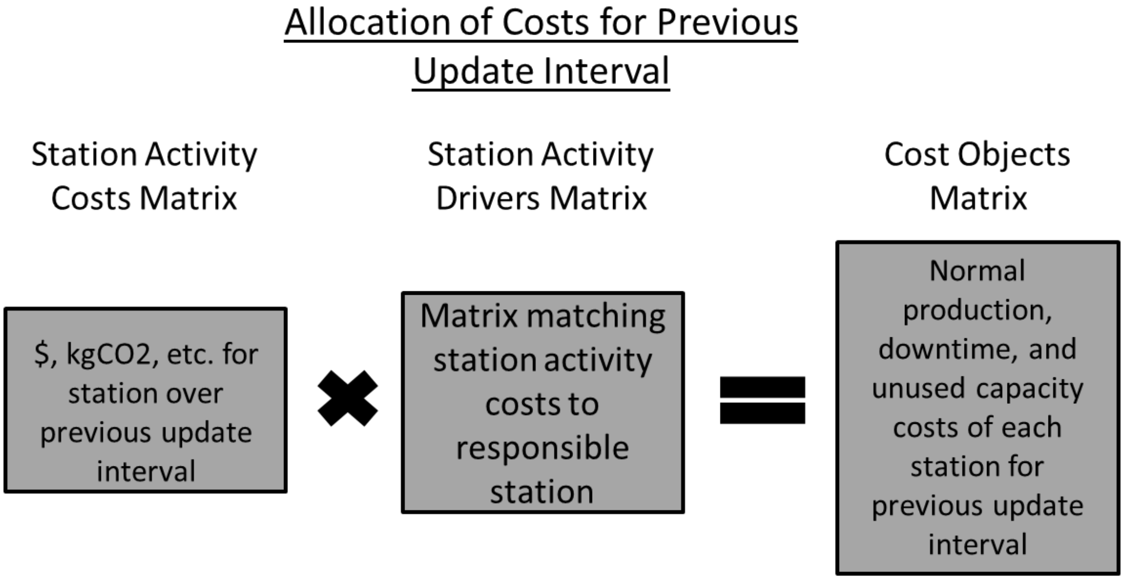
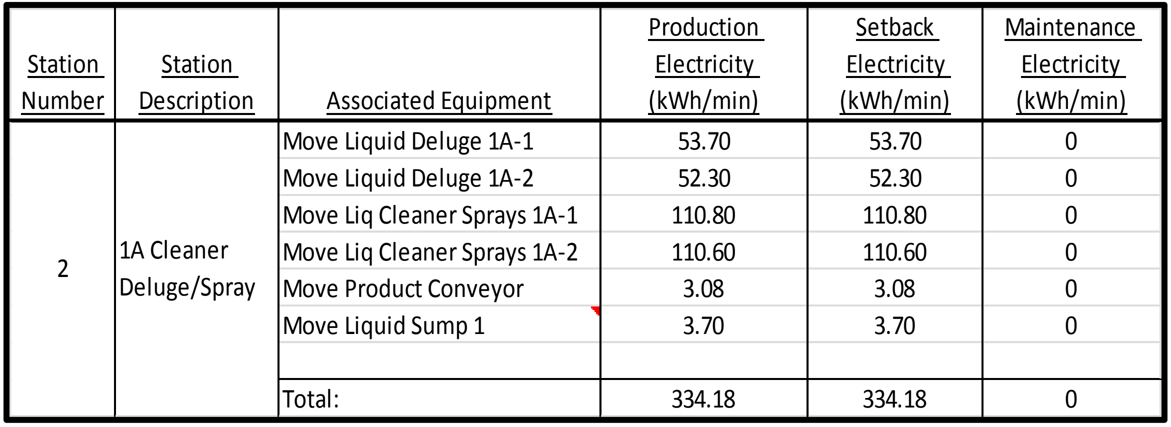


Figure 4.5: Second Phase of Cost Allocation Process

The “ResourceDrivers” worksheet contains a matrix of the resource usage of each station for every minute in each of the three possible states. This matrix is static and is based on real usage rates from Jurek's model. These equipment usage rates were allocated to each station to create a total resource usage rate for each individual station. The table below shows an equipment list of a single station. In addition to the electricity usage rates below, usage rates for the other four resources considered in this case study are also determined. The names of associated equipment are often listed by their function rather than the actual name of the piece of equipment.

Table 4.6: Station 2 Equipment List for Electricity Consumption



Station Number	Station Description	Associated Equipment	Production Electricity (kWh/min)	Setback Electricity (kWh/min)	Maintenance Electricity (kWh/min)
2	1A Cleaner Deluge/Spray	Move Liquid Deluge 1A-1	53.70	53.70	0
		Move Liquid Deluge 1A-2	52.30	52.30	0
		Move Liq Cleaner Sprays 1A-1	110.80	110.80	0
		Move Liq Cleaner Sprays 1A-2	110.60	110.60	0
		Move Product Conveyor	3.08	3.08	0
		Move Liquid Sump 1	3.70	3.70	0
		Total:	334.18	334.18	0

The "ResourceDrivers" matrix has three rows for every station (corresponding to the three possible station states: production, setback, and maintenance) and five columns (one for each resource). A subsection of this worksheet is provided in the table below. This subsection corresponds to the ten stations of the pretreatment area of the paint shop. Additional resource driver information is provided in Appendix C.

Table 4.7: Pretreatment Area Station Resource Drivers Per Minute Basis

Station	State	Electricity (kWh/min)	Natural Gas (mmBTU/min)	Compressed Air (CFM)	Hot Water (mmBTU/min)	Chilled Water (mmBTU/min)
1	Production	0.2011	0.0000	0.0000	0.0000	0.0000
	Setback	0.2011	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
2	Production	4.1494	0.0000	0.0000	0.1933	0.0000
	Setback	4.1494	0.0000	0.0000	0.0117	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
3	Production	2.3505	0.0000	0.0000	0.0000	0.0000
	Setback	2.3505	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
4	Production	0.5291	0.0000	0.0000	0.0000	0.0000
	Setback	0.5291	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
5	Production	1.3150	0.0000	0.0000	0.0000	0.0000
	Setback	1.3150	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
6	Production	1.2577	0.0000	0.0000	0.0300	0.0000
	Setback	1.2577	0.0000	0.0000	0.0117	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
7	Production	3.1738	0.0000	0.0000	0.0000	0.0000
	Setback	3.1738	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
8	Production	0.4569	0.0000	0.0000	0.0000	0.0000
	Setback	0.4569	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
9	Production	1.0679	0.0000	0.0000	0.0000	0.0000
	Setback	1.0679	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
10	Production	0.2831	0.0000	0.0000	0.0000	0.0000
	Setback	0.2831	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000

The resource drivers are defined on a per-minute basis with corresponding units. For instance, electricity use is presented in “kilowatt-hours per minute”. The hot water and chilled water resource drivers are dimensioned in “mmBTU per minute”. This unit was used because it was the unit given in Jurek’s model which provided resource usage numbers. This dimension characterizes the amount of energy used to heat or chill the water used in the operation. It does not characterize the amount of water used.

The “ResourceDrivers2” sheet contains another matrix. This matrix is updated dynamically by the simulation for every simulated minute and is called the station state update matrix. This matrix is a series of zeroes and ones, depending on the states of individual stations. It is diagonal with a one denoting the current state of the each station. This matrix is similar to an identity matrix, with three rows and three columns for each station. The matrix is created this way in order to allow matrix multiplication. The table below shows the matrix for the first three stations of the line and corresponds to a time when all three stations are in the production state.

Table 4.8: Diagonal Matrix Showing Current Station State

Station	State	1			2			3		
1	Production	**1**	0	0	0	0	0	0	0	0
	Setback	0	0	0	0	0	0	0	0	0
	Maintenance	0	0	0	0	0	0	0	0	0
2	Production	0	0	0	**1**	0	0	0	0	0
	Setback	0	0	0	0	0	0	0	0	0
	Maintenance	0	0	0	0	0	0	0	0	0
3	Production	0	0	0	0	0	0	**1**	0	0
	Setback	0	0	0	0	0	0	0	0	0
	Maintenance	0	0	0	0	0	0	0	0	0

The “ActivityTotal” sheet contains a matrix of the resource use of each station over the previously simulated minute. This matrix, called the station activity costs matrix, is created through matrix multiplication of the matrices on the “ResourceDrivers” sheet and “ResourceDrivers2” sheet. This matrix shows the resource use of each station for the last simulated minute in all three states. In order to save space in later worksheets, this matrix is summarized in a second matrix that eliminates rows by summing the three rows of each station. The following tables show subsections of each of these matrices from an example run of the model.

Table 4.9: Station Activity Costs Matrix Generated by Multiplication of ResourceDrivers and ResourceDrivers2 Matrices

Station	Electricity (kWh)	Natural Gas (mmBTU)	Compressed Air (CF)	Hot Water (mmBTU)	Chilled Water (mmBTU)
1	0.2011	0	0	0	0
	0	0	0	0	0
	0	0	0	0	0
2	4.1494	0	0	0.193333333	0
	0	0	0	0	0
	0	0	0	0	0
3	2.3505	0	0	0	0
	0	0	0	0	0
	0	0	0	0	0

Table 4.10: Summarized Version of Previous Matrix

Station	Electricity (kWh)	Natural Gas (mmBTU)	Compressed Air (CF)	Hot Water (mmBTU)	Chilled Water (mmBTU)
1	0.2011	0	0	0	0
2	4.1494	0	0	0.193333333	0
3	2.3505	0	0	0	0

The “ActivityDrivers” sheet contains a matrix that shows the station responsible for each station’s resource use over the previously simulated minute. This matrix, called the activity drivers matrix, is similar to the “ResourceDrivers2” matrix in that it is a matrix of zeros and ones that is updated every minute. In this case, the matrix contains a column and three rows for each station. The three rows separate the normal production costs, added downtime costs, and added unused capacity costs for each station. The matrix is updated so that a single one appears within each column, corresponding to that station’s resource use for the previous simulated minute. This one is placed within a row that corresponds to the station responsible for that station’s resource use depending on if this resource use was due to normal production, downtime, or unused capacity. The following tables show two examples of a subsection of this matrix. The first table corresponds to a time when all three stations are in the production state. The second table corresponds to a time when the second station is in the maintenance state with the other two stations in the setback state.

Table 4.11: Subset of Activity Drivers Matrix during Normal Production

Cost Type	Station	1	2	3
Normal	1	**1**	0	0
Downtime		0	0	0
Unused		0	0	0
Normal	2	0	**1**	0
Downtime		0	0	0
Unused		0	0	0
Normal	3	0	0	**1**
Downtime		0	0	0
Unused		0	0	0

Table 4.12: Subset of Activity Drivers Matrix with Broken Down Station 2

Cost Type	Station	1	2	3
Normal	1	0	0	0
Downtime		0	0	0
Unused		0	0	0
Normal	2	0	0	0
Downtime		**1**	**1**	**1**
Unused		0	0	0
Normal	3	0	0	0
Downtime		0	0	0
Unused		0	0	0

The “CostObjects” sheet contains two matrices. The first matrix shows the resource costs for each station after added downtime and excess capacity costs have been allocated for the previous simulated minute. This matrix is computed through matrix multiplication between the “ActivityTotal” summarized matrix and the “ActivityDrivers” matrix. The second matrix on the “CostObjects” sheet shows the total resource usage for the entire simulation. This matrix is computed by summing the results in the previous matrix for every simulated minute.

This second matrix in the “CostObjects” sheet can then be used to trace different cost parameters to specific stations. These costs could be monetary or environmental. This follows the framework developed by Emblemsvåg and Bras (2001) in their ABCEM method. After these costs are determined and allocated to the individual stations, the costs of each station in a section of the paint shop can be summed to determine the costs of the four considered process areas of the paint shop.

Table 4.13: Subset of Cost Objects Matrix for Allocated Total Resource Use

Station	Cost Type	Electricity (kWh)	Natural Gas (mmBTU)	Compressed Air (CF)	Hot Water (mmBTU)	Chilled Water (mmBTU)
1	Normal	69.58	0	0	0	0
	Downtime	0	0	0	0	0
	Unused Capacity	23.93	0	0	0	0
2	Normal	1904.57	0	0	88.74	0
	Downtime	0	0	0	0	0
	Unused Capacity	0	0	0	0	0
3	Normal	810.92	0	0	0	0
	Downtime	96.87	0	0	0.19	0
	Unused Capacity	239.75	0	0	0	0
4	Normal	182.54	0	0	0	0
	Downtime	0	0	0	0	0
	Unused Capacity	52.91	0	0	0	0
5	Normal	454.99	0	0	0	0
	Downtime	0	0	0	0	0
	Unused Capacity	127.56	0	0	0	0
6	Normal	435.16	0	0	10.38	0
	Downtime	750.73	2	2	0.18	0
	Unused Capacity	118.22	0	0	1.10	0
7	Normal	1098.13	0	0	0	0
	Downtime	0	0	0	0	0
	Unused Capacity	298.34	0	0	0	0
8	Normal	158.09	0	0	0	0
	Downtime	0	0	0	0	0
	Unused Capacity	47.52	0	0	0	0
9	Normal	369.49	0	0	0	0
	Downtime	0	0	0	0	0
	Unused Capacity	111.06	0	0	0	0
10	Normal	106.73	0	0	0	0
	Downtime	0	0	0	0	0
	Unused Capacity	20.67	0	0	0	0

Table 4.14: Example Matrix of Allocated Monetary Costs

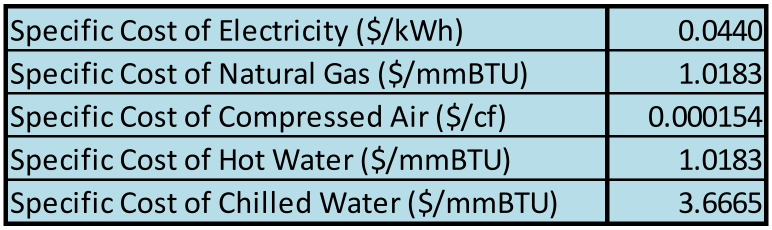
Station	Cost Type	Electricity	Natural Gas	Compressed Air	Hot Water	Chilled Water	Totals
1	Normal	$ 6.96	$ -	$ -	$ -	$ -	$ 6.96
	Downtime	$ -	$ -	$ -	$ -	$ -	$ -
	Unused Capacity	$ 2.39	$ -	$ -	$ -	$ -	$ 2.39
2	Normal	$ 190.46	$ -	$ -	$ 399.33	$ -	$ 589.79
	Downtime	$ -	$ -	$ -	$ -	$ -	$ -
	Unused Capacity	$ -	$ -	$ -	$ -	$ -	$ -
3	Normal	$ 81.09	$ -	$ -	$ -	$ -	$ 81.09
	Downtime	$ 9.69	$ -	$ -	$ 0.84	$ -	$ 10.53
	Unused Capacity	$ 23.98	$ -	$ -	$ -	$ -	$ 23.98
4	Normal	$ 18.25	$ -	$ -	$ -	$ -	$ 18.25
	Downtime	$ -	$ -	$ -	$ -	$ -	$ -
	Unused Capacity	$ 5.29	$ -	$ -	$ -	$ -	$ 5.29
5	Normal	$ 45.50	$ -	$ -	$ -	$ -	$ 45.50
	Downtime	$ -	$ -	$ -	$ -	$ -	$ -
	Unused Capacity	$ 12.76	$ -	$ -	$ -	$ -	$ 12.76
6	Normal	$ 43.52	$ -	$ -	$ 46.71	$ -	$ 90.23
	Downtime	$ 75.07	$ 9.00	$ 0.00	$ 0.79	$ -	$ 84.86
	Unused Capacity	$ 11.82	$ -	$ -	$ 4.94	$ -	$ 16.76
7	Normal	$ 109.81	$ -	$ -	$ -	$ -	$ 109.81
	Downtime	$ -	$ -	$ -	$ -	$ -	$ -
	Unused Capacity	$ 29.83	$ -	$ -	$ -	$ -	$ 29.83
8	Normal	$ 15.81	$ -	$ -	$ -	$ -	$ 15.81
	Downtime	$ -	$ -	$ -	$ -	$ -	$ -
	Unused Capacity	$ 4.75	$ -	$ -	$ -	$ -	$ 4.75
9	Normal	$ 36.95	$ -	$ -	$ -	$ -	$ 36.95
	Downtime	$ -	$ -	$ -	$ -	$ -	$ -
	Unused Capacity	$ 11.11	$ -	$ -	$ -	$ -	$ 11.11
10	Normal	$ 10.67	$ -	$ -	$ -	$ -	$ 10.67
	Downtime	$ -	$ -	$ -	$ -	$ -	$ -
	Unused Capacity	$ 2.07	$ -	$ -	$ -	$ -	$ 2.07

As one can guess, these various matrices grow to be very large with a large number of stations. This diminishes the readability of the different spreadsheets; however, it does provide all pertinent information. For several of the scenarios, the results will be presented in graph form in order to improve readability.

4.6.1 Monetary Costs

Monetary costs are based on electricity and natural gas utility rates for the area of the assembly plant in eastern Michigan. The cost of electricity was estimated using the "Special Manufacturing Supply Rate" from DTE Energy (2013). This gave an electricity monetary consumption intensity of 4.44 cents per kilowatt-hour. The cost of natural gas was estimated using the "GS-3General Service Rate" from Consumers Energy (2012). This gave a natural gas monetary consumption intensity of $1.0183 per mmBTU. Because the other three resources – compressed air, hot water, and chilled water – directly depend on electricity and natural gas, their monetary consumption intensities are derived from the monetary consumption intensities of electricity and natural gas and the amount of either that is used to produce a unit of the resource.

Table 4.15: Monetary Consumption Intensities



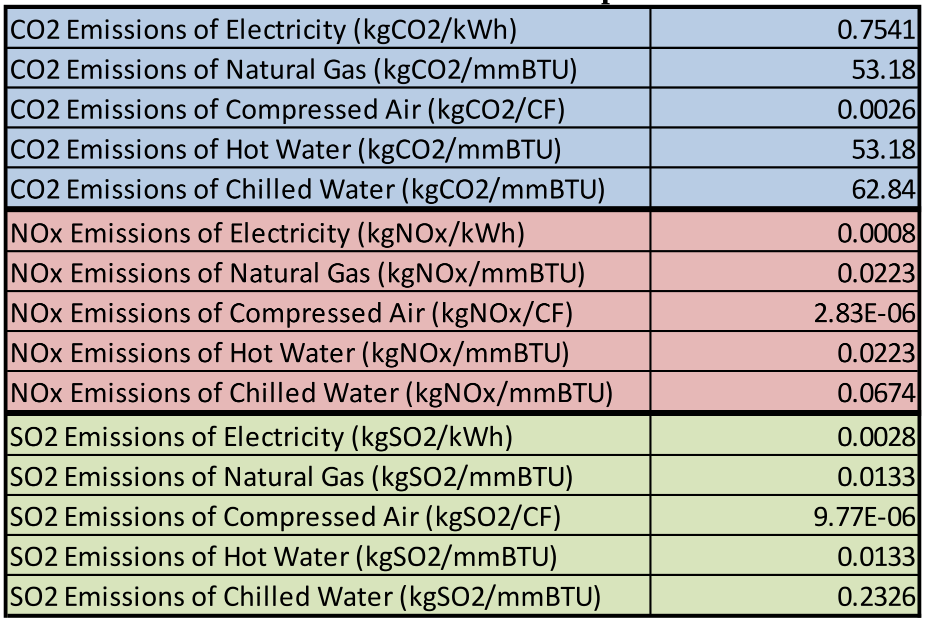
Specific Cost of Electricity ($/kWh)	0.0440
Specific Cost of Natural Gas ($/mmBTU)	1.0183
Specific Cost of Compressed Air ($/cf)	0.000154
Specific Cost of Hot Water ($/mmBTU)	1.0183
Specific Cost of Chilled Water ($/mmBTU)	3.6665

4.6.2 Environmental Costs

The costing spreadsheet also takes into account environmental costs of the paint shop operations. Specifically, the costing model looks at carbon dioxide emissions, sulfur dioxide emissions, and nitrogen dioxide emissions. The emission consumption intensities for electricity were based on the fuel mix of the electricity grid to determine emissions caused by electricity production. Data for emissions caused by electricity production was taken from the EPA's eGRID database (U.S. Environmental Protection Agency 2009) for the area of eastern Michigan where the assembly plant is located.

Natural gas emissions data was taken from several sources. Some assumptions were made depending on the type of emissions. The consumption intensity for natural gas carbon dioxide emissions was taken from the EIA's website and is equal to 117.0 lbCO2/mmBTU (U.S. Energy Information Administration 2013). Natural gas used by the production line is assumed to be combusted within small boilers with controlled low NOx burners. This provides a nitrogen oxide emissions consumption intensity for natural gas of 0.049 lbNOx/mmBTU (U.S. Environmental Protection Agency 1998). Sulfur emissions from natural gas used by the production line are assumed to be comparable to sulfur emissions from utility electricity generation using natural gas; therefore, the sulfur emissions consumption intensity for natural gas is 0.1 lbSO2/MWh, or 0.029 lbSO2/mmBTU (U.S. Environmental Protection Agency 2013).

Table 4.16: Environmental Consumption Intensities



CO2 Emissions of Electricity (kgCO2/kWh)	0.7541
CO2 Emissions of Natural Gas (kgCO2/mmBTU)	53.18
CO2 Emissions of Compressed Air (kgCO2/CF)	0.0026
CO2 Emissions of Hot Water (kgCO2/mmBTU)	53.18
CO2 Emissions of Chilled Water (kgCO2/mmBTU)	62.84
NOx Emissions of Electricity (kgNOx/kWh)	0.0008
NOx Emissions of Natural Gas (kgNOx/mmBTU)	0.0223
NOx Emissions of Compressed Air (kgNOx/CF)	2.83E-06
NOx Emissions of Hot Water (kgNOx/mmBTU)	0.0223
NOx Emissions of Chilled Water (kgNOx/mmBTU)	0.0674
SO2 Emissions of Electricity (kgSO2/kWh)	0.0028
SO2 Emissions of Natural Gas (kgSO2/mmBTU)	0.0133
SO2 Emissions of Compressed Air (kgSO2/CF)	9.77E-06
SO2 Emissions of Hot Water (kgSO2/mmBTU)	0.0133
SO2 Emissions of Chilled Water (kgSO2/mmBTU)	0.2326

4.7 Case Study Scenario Definitions

For this case study, several different scenarios were chosen. The chosen scenarios are meant to show different realistic scenarios to see the usefulness of the methodology with different system behaviors. In each scenario, the paint line is simulated for an entire eight-hour shift. Buffer capacities are fixed based on system information. For physical buffers, initial buffer levels are set to half the buffer capacity. For "buffer" areas between adjacent stations where there is not a physical job bank, initial buffer levels are set equal to the buffer capacity.

4.7.1 Scenario 1 Definition

Scenario 1 is designed to replicate a "good" shift for the paint line; therefore, the line does not experience any downtime events during the shift. Each station on the line operates at its rated speed as shown previously in Sections 4.5.1 through 4.5.4. Scenario 1 was simulated three times using different allocation methods.

The first simulation allocates costs in a “traditional” way. With this allocation method, all costs are allocated to the station where these costs were generated. This allocation method does not recognize a difference between costs due to normal production and costs due to downtime or unused capacity. Because of this, all station costs are allocated to the normal production cost object for each station.

The second and third simulations allocate costs based on the proposed methodology and split costs according to those caused by normal production, downtime, or unused capacity; however, they vary in the way in which unused capacity costs are allocated. The second simulation allocates costs according to the proposed methodology and illustrated in Figure 4.3 in Section 4.4.4. This method allocates unused capacity costs to the faster station to highlight individual stations that are often idle because they are starved or blocked by a slower station. The third simulation allocates unused capacity costs to the slower station to illustrate idling costs that are caused by the slower station. The results of each simulation will be discussed and compared in the Section 4.8.1.

4.7.2 Scenario 2 Definition

Scenario 2 is similar to Scenario 1 except that it models a shift where the paint line experiences several downtime events. These downtime events occur in different locations at different times for different durations. Downtime event information is presented in the table below. These downtime events are arbitrary and were chosen only to show the effect of downtime on total cost.

Table 4.17: Scenario 2 Downtime Event Information

Downtime Event	Station Affected	Event Time (minutes)	Event Duration (minutes)
1	7	50	30
2	45	125	30
3	29	200	45
4	49	325	25
5	14	400	60

Like Scenario 1, Scenario 2 is simulated three times with each simulation using a different cost allocation methodology as discussed in Scenario 1's definition. The results of these three simulations will be presented and discussed in Section 4.8.2.

4.7.3 Scenario 3 Definition

Scenario 3 is an example of how the methodology can be combined with simulation to prioritize preventative maintenance and replacement policies. For this scenario, each station within the ELPO process area is inspected to characterize how a significant failure at each station impacts production volume and total production cost. In order to inspect this impact, fourteen simulations were performed. For each simulation, one station within the ELPO process area fails in the middle of the shift. Each downtime event lasts for 100 minutes. The table below presents information for each simulation run. The results of this sensitivity analysis are provided in Section 4.8.3.

Table 4.18: Scenario 3 Simulation Information

Simulation Run Number	Failure Station Number	Downtime Event Time (minutes)	Downtime Event Duration (minutes)
1	11	200	100
2	12	200	100
3	13	200	100
4	14	200	100
5	15	200	100
6	16	200	100
7	17	200	100
8	18	200	100
9	19	200	100
10	20	200	100
11	21	200	100
12	22	200	100
13	23	200	100
14	24	200	100

4.8 Case Study Results

Results for each scenario are presented and discussed below. In most cases, only some results are shown in this section. Additional results are included in Appendix D.

4.8.1 Scenario 1 Results

Scenario 1 was created to replicate a "good" eight-hour shift where there are zero random downtime events. This scenario was simulated three times, each using a different cost allocation method, in order to compare results of the three methods. Considering that the only difference between the three simulations was how costs were allocated among the stations on the line, the production volume, total monetary costs, and total environmental costs were the same for each simulation. Table 4.19 shows these results. Table 4.20 shows per-unit costs for Scenario 1.

Table 4.19: Scenario 1 Total Cost Results

Production Volume (units):	266
Total Utility Cost ($):	$ 2,700.68
Total CO2 Emissions (kgCO2):	58316.60
Total NOx Emissions (kgNOx):	50.86
Total SO2 Emissions (kgSO2):	154.04

Table 4.20: Scenario 1 Costs Per Unit Produced

Utility Cost per Unit ($):	$ 10.15
CO2 Emissions per Unit (kgCO2):	219.24
NOx Emissions per Unit (kgNOx):	0.19
SO2 Emissions per Unit (kgSO2):	0.58

For the first simulation, a “traditional” cost allocation method was used. This method did not split costs into normal production costs, downtime costs, and unused capacity costs; therefore, all costs are allocated as normal production costs. The figure below shows how monetary costs were distributed across the 57 stations.

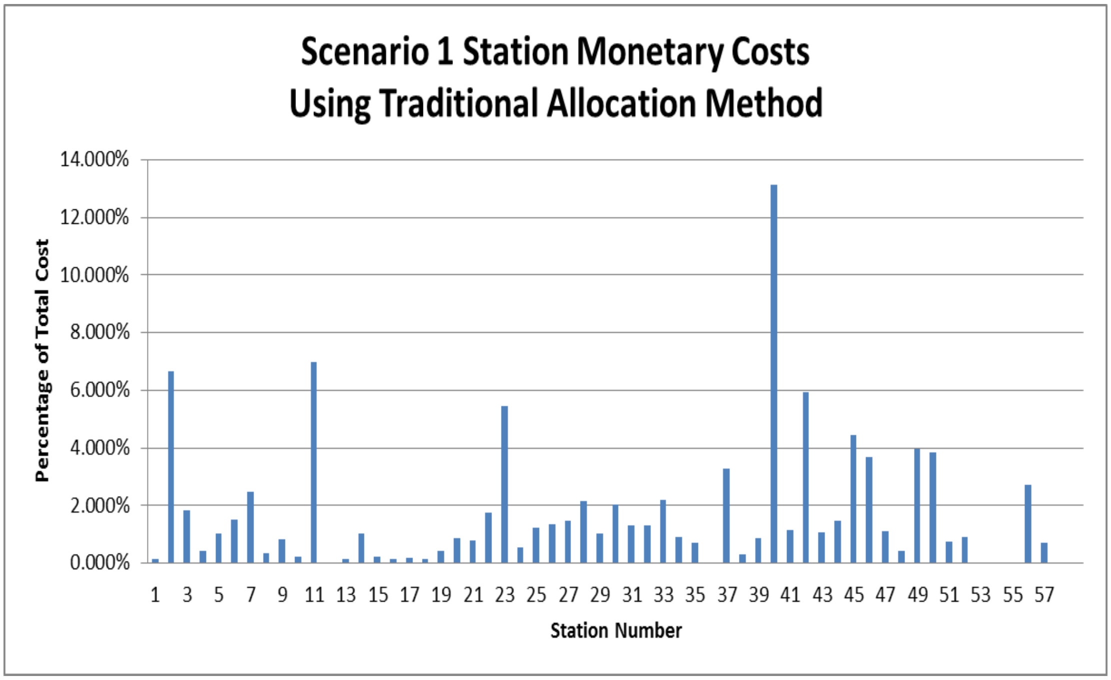


Figure 4.6: Distribution of Monetary Station Costs for Scenario 1 Using Traditional Cost Allocation Method

The second simulation used the first proposed methodology to allocate costs. For this simulation, costs were separated into normal production costs, downtime costs, and unused capacity costs. Normal production costs and downtime costs were allocated as discussed in Section 3.3. Unused capacity costs were allocated to the faster station. The figure below shows how costs were distributed between the stations for this cost allocation method.

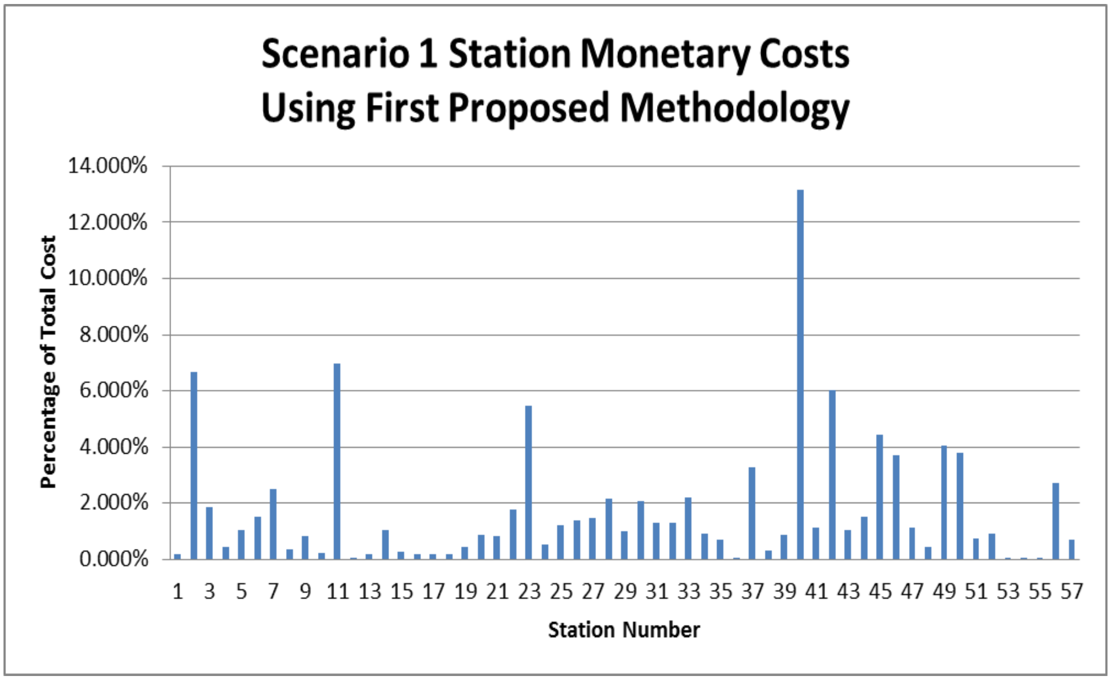


Figure 4.7: Distribution of Monetary Station Costs for Scenario 1 Using First Proposed Cost Allocation Method

The third simulation was identical to the second simulation except that unused capacity costs were allocated to the slower station, following the rules of the second proposed allocation method. The figure below shows the cost distribution over the 57 stations for this cost allocation method.

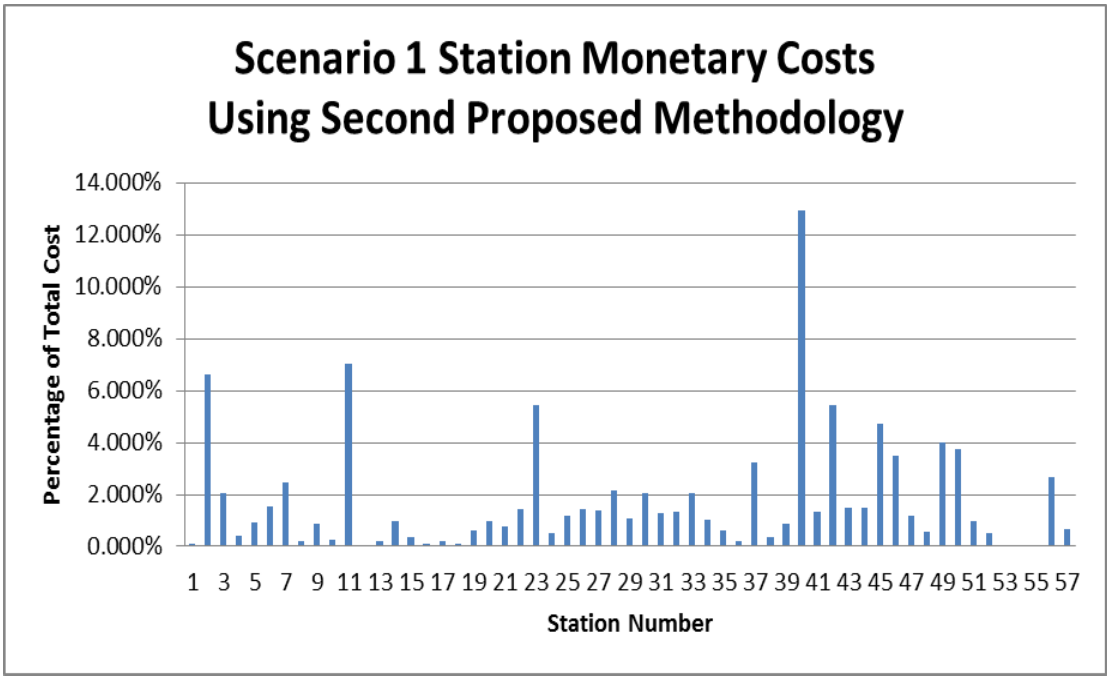


Figure 4.8: Distribution of Monetary Station Costs for Scenario 1 Using Second Proposed Cost Allocation Method

One can see that there are only small changes in the allocation of station costs between the three allocation methods. In most cases, the total station cost for a single station varies only a few tenths of a percent of the total simulation cost. The largest change occurred for stations 42 and 43. For these stations, the total cost changed about 0.5% of the total line cost between the three allocation methods (~$13). The difference is due to the allocation of unused capacity and the large resource drivers of Station 42. Station 42 is slightly faster than Station 43, requiring it to enter a setback state when it is blocked by Station 43. Because Station 42 has relatively high resource drivers, even for the setback state, this generates significantly high idling costs.

Table 4.21: Differences in Scenario 1 Station Costs between Allocation Methods

Allocation Method	Station 42	Station 43
Traditional	5.96%	1.07%
Unused Capacity Allocated to Faster	6.02%	1.05%
Unused Capacity Allocated to Slower	5.44%	1.50%

The tables below show the distribution of total costs between normal production costs, downtime costs, and unused capacity costs for each simulation and for each considered cost. For monetary costs, the amount of unused capacity per unit produced (car) is relatively low. This is due to the relatively low monetary cost of utilities. Nevertheless, unused capacity was responsible for approximately 6% of total monetary cost. This percentage is the same for environmental costs as well. This constitutes a fairly significant percentage of costs. With the inclusion of additional resource types that do not have lower resource usage rates during setback state (such as labor), this percentage is likely to grow.

Table 4.22: Scenario 1 Total Monetary Cost Distribution Across Cost Types by Allocation Method

Cost Type	Traditional Method	Proposed Method 1	Proposed Method 2
Total Normal Production Costs:	$ 2,700.68	$2,543.21	$2,539.68
Total Downtime Costs:	$ -	$ -	$ -
Total Unused Capacity Costs:	$ -	$160.17	$161.00
Normal Production Cost per Car:	$ 10.15	$9.60	$9.55
Downtime Cost per Car:	$ -	$ -	$ -
Unused Capacity Cost per Car:	$ -	$0.60	$0.61

Table 4.23: Scenario 1 Total CO2 Emissions Distribution Across Cost Types by Allocation Method

Cost Type	Traditional Method	Proposed Method 1	Proposed Method 2
Total Normal Production CO2 Emissions (kgCO2):	58316.62	54913.46	54820.77
Total Downtime CO2 Emissions (kgCO2):	0.00	0.00	0.00
Total Unused Capacity CO2 Emissions (kgCO2):	0.00	3479.02	3495.85
Normal Production CO2 Emissions per Car (kgCO2):	219.24	207.22	206.09
Downtime CO2 Emissions per Car (kgCO2):	0.00	0.00	0.00
Unused Capacity CO2 Emissions per Car (kgCO2):	0.00	13.13	13.14

Table 4.24: Scenario 1 Total NOx Emissions Distribution Across Cost Types by Allocation Method

Cost Type	Traditional Method	Proposed Method 1	Proposed Method 2
Total Normal Production NOx Emissions (kgNOx):	50.86	47.89	47.83
Total Downtime NOx Emissions (kgNOx):	0.00	0.00	0.00
Total Unused Capacity NOx Emissions (kgNOx):	0.00	3.02	3.03
Normal Production NOx Emissions per Car (kgNOx):	0.19	0.18	0.18
Downtime NOx Emissions per Car (kgNOx):	0.00	0.00	0.00
Unused Capacity NOx Emissions per Car (kgNOx):	0.00	0.01	0.01

Table 4.25: Scenario 1 Total SO2 Emissions Distribution Across Cost Types by Allocation Method

Cost Type	Traditional Method	Proposed Method 1	Proposed Method 2
Total Normal Production SO2 Emissions (kgSO2):	154.04	145.07	144.89
Total Downtime SO2 Emissions (kgSO2):	0.00	0.00	0.00
Total Unused Capacity SO2 Emissions (kgSO2):	0.00	9.11	9.16
Normal Production SO2 Emissions per Car (kgSO2):	0.58	0.55	0.54
Downtime SO2 Emissions per Car (kgSO2):	0.00	0.00	0.00
Unused Capacity SO2 Emissions per Car (kgSO2):	0.00	0.03	0.03

The graphs below show how each allocation method distributed the total monetary cost and total CO2 emissions among the four main process areas. Of the four process areas, the paint booth used the most resources during the eight-hour shift simulation; therefore, it bears the highest percentage of total monetary cost and total CO2 emissions. The two graphs differ slightly in the distribution of costs for the other three process areas. For monetary costs, the sealing line bears the second-highest responsibility with the ELPO area responsible for the third-highest percentage. Conversely, the pretreatment area is responsible for the second-highest percentage of total CO2 emissions. This is due to the large usage of hot water in the pretreatment stage. Hot water usage in the pretreatment area is responsible for 5585 kgCO2 emissions alone. This hot water usage is only responsible for $107 in monetary costs. Additional graphs for NOx and SO2 emissions are included in Appendix D.

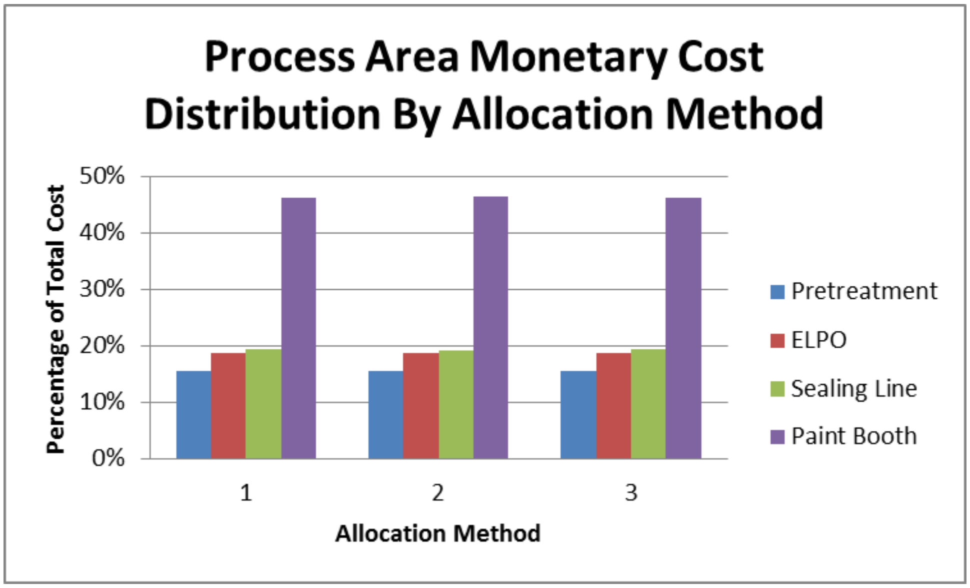


Figure 4.9: Scenario 1 Monetary Cost Distribution between Process Areas by Allocation Method

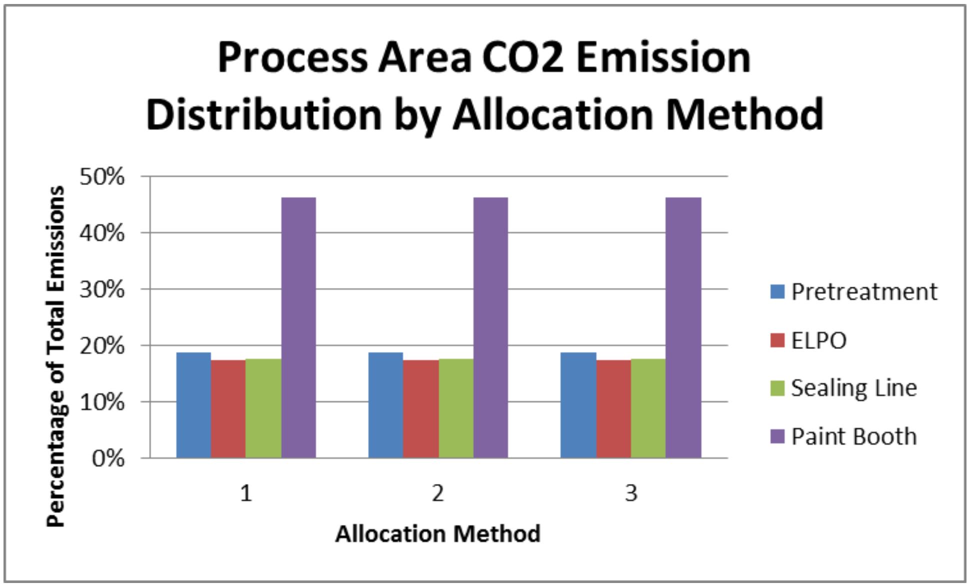


Figure 4.10: Scenario 2 CO2 Emission Distribution between Process Areas by Allocation Method

Each allocation method allocates station costs slightly differently; however, these differences can be relatively small when one looks at the differences between the cost allocation methods for an individual station, especially for monetary costs. This is due to three main factors: 1) the large number of slow workstations at similar speeds, 2) the relatively low cost of utilities, and 3) the exclusion of resource types outside of the five chosen utility resources.

Because there are a large number of workstations, the total cost of production is allocated across a large set of stations. Many of these stations are close in rated speed, limiting the cost effects of unused capacity due to very slow stations relative to the rest of the line. Additionally, these workstations are all relatively slow, mitigating the propagation of downtime and unused capacity effects throughout the production line.

There are only five resources modeled for this case study: the utility resources of electricity, natural gas, compressed air, hot water, and chilled water. Because of the relatively low cost of these resources, the total cost for this scenario is fairly low (under <$3000) for an entire eight-hour shift. While this aspect is particularly important when determining why there are only slight differences in monetary station costs (as well as NOx and SO2 emissions) between the three allocation methods, this aspect is less important when looking at CO2 emissions.

By excluding other resource types, the model has a lower total cost and does not capture the full cost effects of downtime and unused capacity. The modeled utility resources have greatly different resource drivers for each station state. Because only utility resources are modeled and utility resource usage lowers during a setback period, the cost effects of downtime and unused capacity are mitigated in the simulation costing results. Other resource types, such as labor, have constant resource drivers between station states; therefore, downtime events and unused capacity effects are more greatly “punished” and bear a higher percentage of total cost. One can look at the results from the implementation example in Section 3.4.2 to see the higher impact of downtime and unused capacity costs when labor resources are included in the costing model. Additional results for the engine assembly line example in Section 3.4.2 are included in Appendix A.

4.8.2 Scenario 2 Results

Scenario 2 differs from Scenario 1 by including several downtime events in its simulations. These downtime events (presented in Table 4.17) had a large effect on the total costs accrued over the course of the simulated eight-hour shift when compared to Scenario 1. Table 4.26 shows the production volume, total monetary cost, and total environmental costs of Scenario 2. Because of downtime, the production volume (and indirectly absolute costs) of Scenario 2 are lower than the absolute costs of Scenario 1; however, the per-unit costs of Scenario 2 are higher. Table 4.27 shows the per-unit costs for Scenario 2. These per-unit costs are compared to the per-unit costs of Scenario 1 in Table 4.28. One can see that there is a 5% increase in monetary and environmental per-unit costs between the two scenarios.

Table 4.26: Scenario 2 Total Cost Results

Production Volume (units):	238
Total Utility Cost ($):	$ 2,540.99
Total CO2 Emissions (kgCO2):	54826.80
Total NOx Emissions (kgNOx):	47.85
Total SO2 Emissions (kgSO2):	144.99

Table 4.27: Scenario 2 Costs per Unit Produced

Utility Cost per Unit ($):	$ 10.68
CO2 Emissions per Unit (kgCO2):	230.37
NOx Emissions per Unit (kgNOx):	0.20
SO2 Emissions per Unit (kgSO2):	0.61

Table 4.28: Comparison of Per-Unit Costs of Scenarios 1 and 2

Cost Type	Scenario 2	Scenario 1	Difference	Percent Change
Utility Cost per Unit ($):	$ 10.68	$ 10.15	$ 0.53	5%
CO2 Emissions per Unit (kgCO2):	230.37	219.24	$ 11.13	5%
NOx Emissions per Unit (kgNOx):	0.20	0.19	$ 0.01	5%
SO2 Emissions per Unit (kgSO2):	0.61	0.58	$ 0.03	5%

Like Scenario 1, Scenario 2 was simulated three times with three different cost allocation methods. The figures below show the distribution of monetary costs among the stations for each of the cost allocation methods. As discussed with Scenario 1, these changes are often fairly small for an individual station due to the use of only utility resources and the large number of stations. Similar to Scenario 1, stations 42 and 43 changed significantly between the three allocation methods. However the largest change came for Station 7. Station 7 was allocated an additional 1.12% and 1.21% of total monetary cost for the first proposed allocation method (unused capacity allocated to faster stations) and second proposed allocation method (unused capacity allocated to slower stations), respectively.

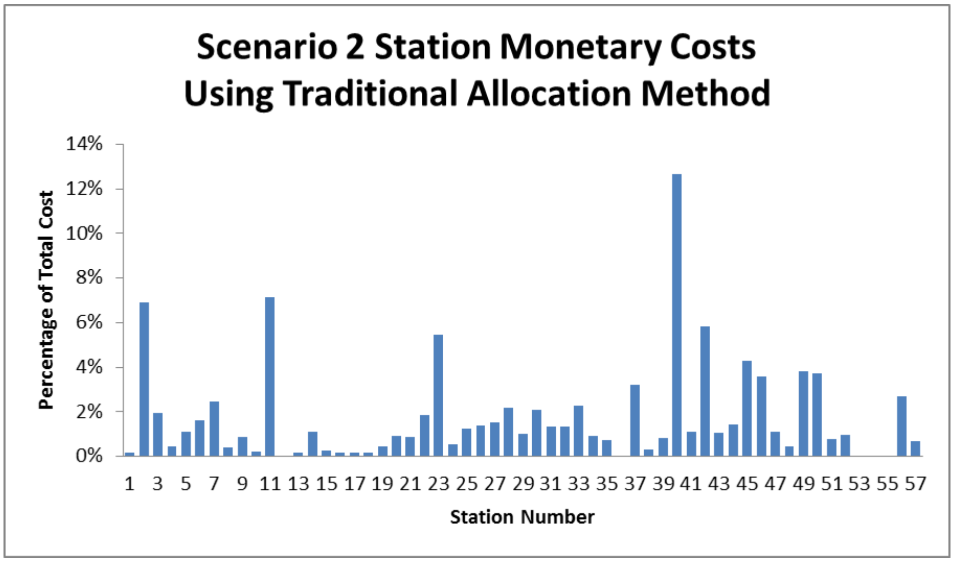


Figure 4.11: Distribution of Monetary Station Costs for Scenario 2 Using Traditional Cost Allocation Method

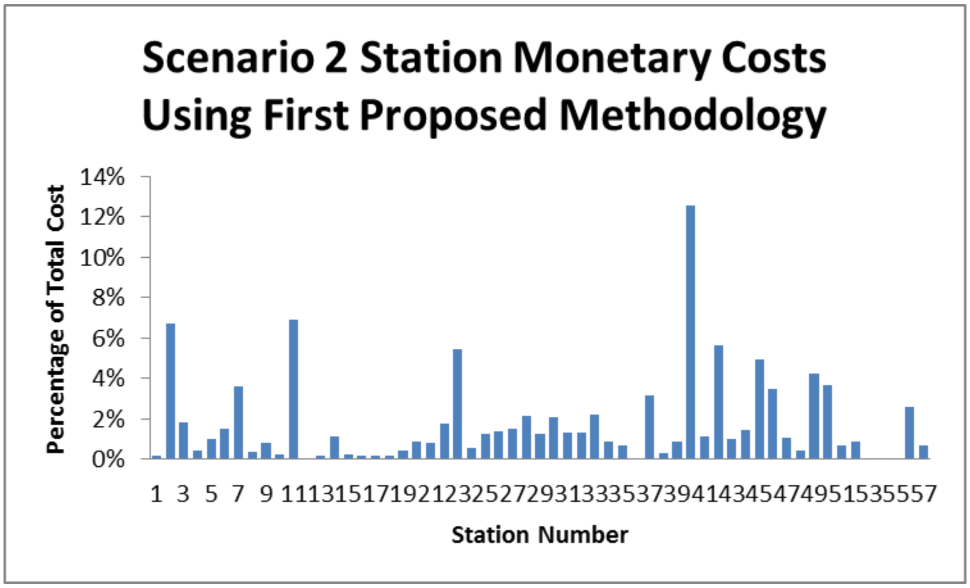


Figure 4.12: Distribution of Monetary Station Costs for Scenario 2 Using First Proposed Cost Allocation Method

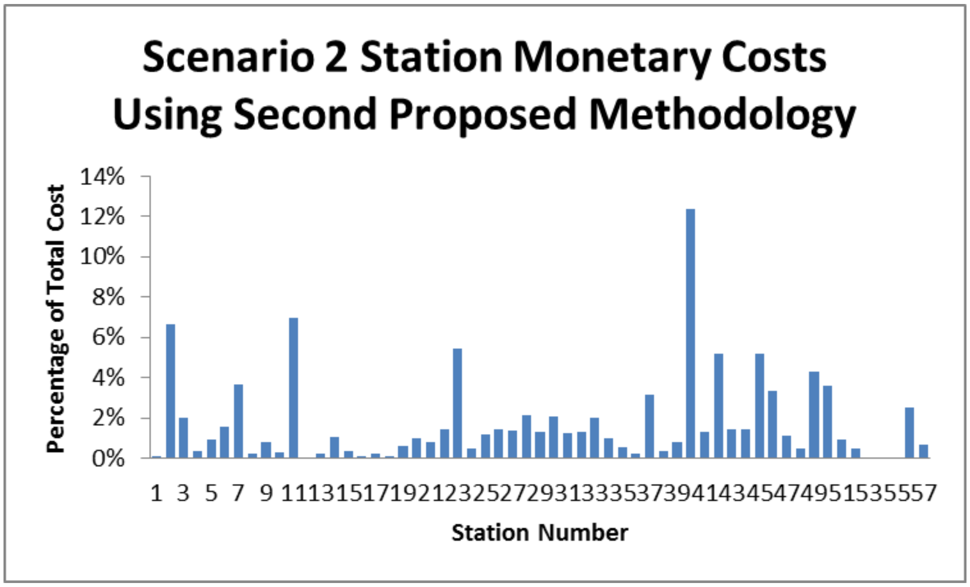


Figure 4.13: Distribution of Monetary Station Costs for Scenario 2 Using Second Proposed Cost Allocation Method

Table 4.29: Differences in Station Costs between Allocation Methods

Allocation Method	Station 7
Traditional	2.47%
Unused Capacity Allocated to Faster	3.59%
Unused Capacity Allocated to Slower	3.68%

The tables below present the allocation of total costs to normal production, downtime, and unused capacity between the three allocation methods for monetary and environmental costs. For this scenario, unused capacity was responsible for approximately 5.6% of total cost for monetary and environmental costs. Downtime was responsible for approximately 2.5% of total cost for monetary and environmental costs. With the inclusion of additional resources, these percentages are likely to increase.

Table 4.30: Scenario 2 Total Monetary Cost Distribution Across Cost Types by Allocation Method

Cost Type	Traditional Method	Proposed Method 1	Proposed Method 2
Total Normal Production Costs:	$2,540.99	$2,330.45	$2,330.45
Total Downtime Costs:	$ -	$67.39	$65.95
Total Unused Capacity Costs:	$ -	$143.15	$144.58
Normal Production Cost per Car:	$ 10.68	$9.79	$9.79
Downtime Cost per Car:	$ -	$0.28	$0.28
Unused Capacity Cost per Car:	$ -	$0.60	$0.61

Table 4.31: Scenario 2 Total CO2 Emissions Distribution Across Cost Types by Allocation Method

Cost Type	Traditional Method	Proposed Method 1	Proposed Method 2
Total Normal Production CO2 Emissions (kgCO2):	54826.81	50337.04	50337.04
Total Downtime CO2 Emissions (kgCO2):	0.00	1369.91	1343.13
Total Unused Capacity CO2 Emissions (kgCO2):	0.00	3119.86	3146.64
Normal Production CO2 Emissions per Car (kgCO2):	230.36	211.50	211.50
Downtime CO2 Emissions per Car (kgCO2):	0.00	5.76	5.64
Unused Capacity CO2 Emissions per Car (kgCO2):	0.00	13.11	13.22

Table 4.32: Scenario 2 Total NOx Emissions Distribution Across Cost Types by Allocation Method

Cost Type	Traditional Method	Proposed Method 1	Proposed Method 2
Total Normal Production NOx Emissions (kgNOx):	47.85	43.89	43.89
Total Downtime NOx Emissions (kgNOx):	0.00	1.26	1.23
Total Unused Capacity NOx Emissions (kgNOx):	0.00	2.70	2.73
Normal Production NOx Emissions per Car (kgNOx):	0.20	0.18	0.18
Downtime NOx Emissions per Car (kgNOx):	0.00	0.01	0.01
Unused Capacity NOx Emissions per Car (kgNOx):	0.00	0.01	0.01

Table 4.33: Scenario 2 Total SO2 Emissions Distribution Across Cost Types by Allocation Method

Cost Type	Traditional Method	Proposed Method 1	Proposed Method 2
Total Normal Production SO2 Emissions (kgSO2):	144.99	132.90	132.90
Total Downtime SO2 Emissions (kgSO2):	0.00	3.97	3.88
Total Unused Capacity SO2 Emissions (kgSO2):	0.00	8.12	8.21
Normal Production SO2 Emissions per Car (kgSO2):	0.61	0.56	0.56
Downtime SO2 Emissions per Car (kgSO2):	0.00	0.02	0.02
Unused Capacity SO2 Emissions per Car (kgSO2):	0.00	0.03	0.03

The allocation of costs to the four main process areas yielded similar results to Scenario 1. The paint booth area was responsible for the largest percentage of total cost for monetary and environmental costs. The ranking of the other three process areas is different for monetary and environmental costs. The figures below show the distribution of monetary costs and CO2 emissions, respectively, for the four process areas. Additional results are included in Appendix D.

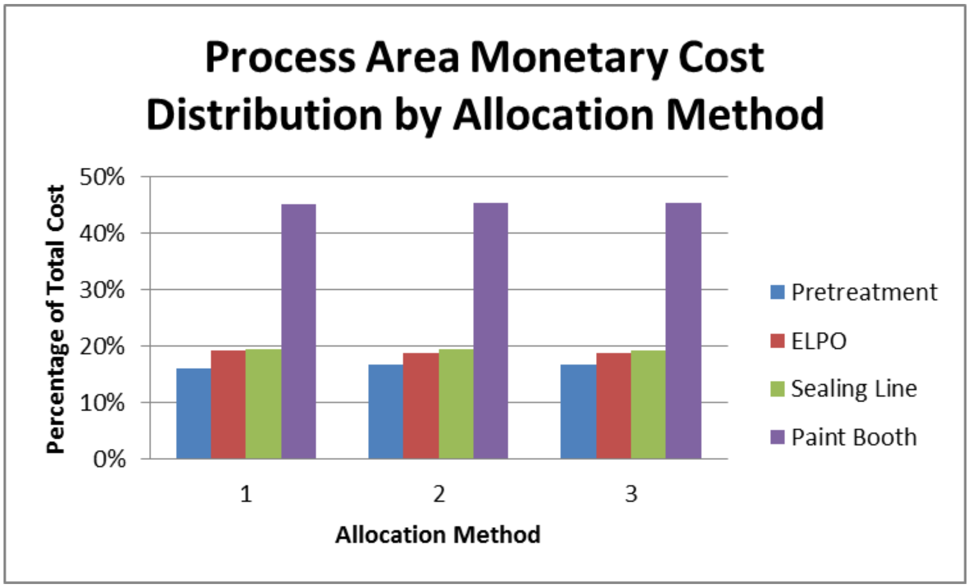


Figure 4.14: Scenario 2 Monetary Cost Distribution between Process Areas by Allocation Method

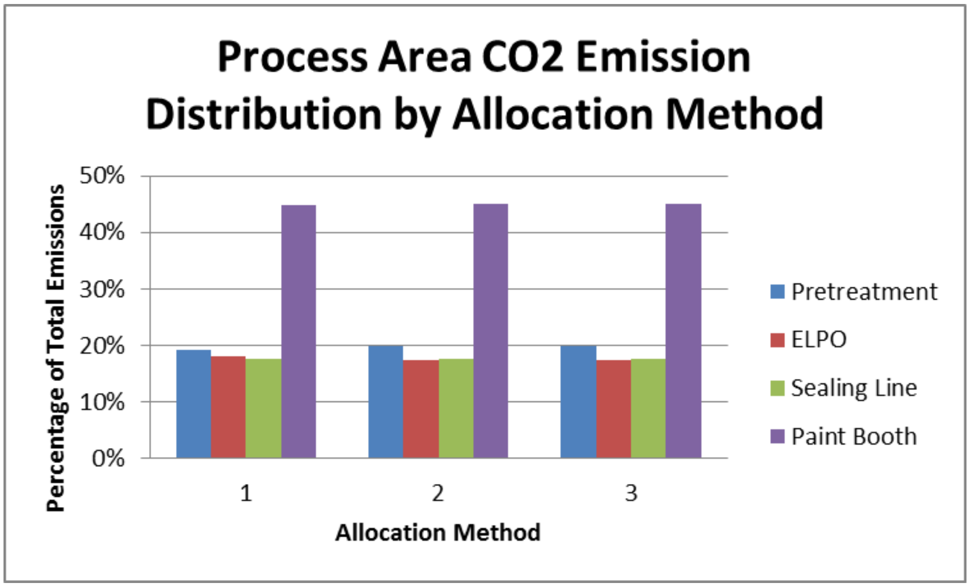


Figure 4.15: Scenario 2 CO2 Emission Distribution between Process Areas by Allocation Method

4.8.3 Scenario 3 Results

Scenario 3 was effectively a sensitivity analysis of the paint line to see how a significant downtime event would impact production volume and total cost depending on the location of the downtime event. For this scenario, only the fourteen stations located in the ELPO process area experienced a downtime event, one failed station for each run as described in Table 4.18. The table below shows the results of these simulation runs.

Table 4.34: Scenario 3 Production Volume and Total Cost Results

Run Number	Failed Station	Production Volume	Utility Cost ($)	CO2 Emissions (kgCO2)	NOx Emissions (kgNOx)	SO2 Emissions (kgSO2)
1	11	266	$ 2,598.39	55748.6	48.90	148.72
2	12	266	$ 2,656.85	57175.1	50.01	151.82
3	13	266	$ 2,607.05	55917.1	49.06	149.24
4	14	266	$ 2,607.01	55937.8	49.06	149.21
5	15	266	$ 2,608.51	55956.2	49.09	149.32
6	16	266	$ 2,610.28	56007.6	49.12	149.40
7	17	266	$ 2,612.62	56066.6	49.17	149.52
8	18	266	$ 2,614.66	56116.9	49.20	149.63
9	19	266	$ 2,616.10	56159.8	49.23	149.69
10	20	266	$ 2,623.16	56340.2	49.37	150.06
11	21	266	$ 2,643.68	56788.6	49.76	151.22
12	22	266	$ 2,646.23	56964.9	49.82	151.19
13	23	266	$ 2,661.39	57376.8	50.11	151.93
14	24	266	$ 2,699.21	58289.2	50.83	153.95

One can immediately see that the production volume did not change between runs. None of the downtime events were long enough in duration to alter production volume. It should be noted that production volume, in this case, only considers units finished by the final station. While each station that was forced into setback state during a downtime event would have individually processed fewer units than in the absence of a downtime event, that individual station production volume is not examined here.

These constant production volume levels are due to a combination of the length of the paint line, the presence of large buffers between the ELPO, sealing line, and paint booth areas, and the relatively slow nature of the line. Because the line consists of many stations, it takes a reasonably long time (compared to the length of a shift) a stoppage in the middle of the line to propagate far enough along the line to reduce production volume. Large buffers at the end of the ELPO and sealing line areas also help to mitigate the effects of a downtime event on production volume during an individual shift. Lastly, the relatively low rated speeds of each station in the paint line mean that product moves slowly through the line; therefore, the effects of a lack of product also move slowly through the line.

When one examines only Table 4.34, one would suggest that Station 24 is the station that most effects production line costs for a significant downtime event because it generated the highest total monetary and environment costs. However, this table does not tell the full story behind the generation of costs. Table 4.35 breaks the total monetary cost of each simulation down into the costs of normal production, downtime, and unused capacity.

Table 4.35: Scenario 3 Monetary Costs for Each Cost Type

Run Number	Failed Station	Total Normal Production Cost	Total Downtime Cost	Total Unused Capacity Cost
1	11	$ 2,337.56	$ 119.07	$ 141.75
2	12	$ 2,437.93	$ 65.68	$ 153.24
3	13	$ 2,343.42	$ 119.91	$ 143.72
4	14	$ 2,345.21	$ 121.41	$ 140.39
5	15	$ 2,346.50	$ 121.03	$ 140.98
6	16	$ 2,350.96	$ 113.13	$ 146.19
7	17	$ 2,355.52	$ 115.91	$ 141.18
8	18	$ 2,359.92	$ 109.08	$ 145.66
9	19	$ 2,365.00	$ 111.25	$ 139.85
10	20	$ 2,389.08	$ 93.31	$ 140.77
11	21	$ 2,420.89	$ 85.47	$ 137.33
12	22	$ 2,451.80	$ 53.57	$ 140.87
13	23	$ 2,465.34	$ 56.20	$ 139.86
14	24	$ 2,538.22	$ 12.12	$ 148.87

Contrary to conclusions made when examining only Table 4.34, Table 4.35 suggests that Station 24 is not the most important station for downtime costs. In fact, the simulation where Station 24 failed had the lowest total downtime cost of all of the simulations, despite having the highest total cost. This can be explained by information about the stations and buffers around Station 24. Station 24 is surrounded by adjacent buffer areas with very large buffer inventories and capacities. Because of this, the cost effects of a downtime event at Station 24 take longer to propagate through the rest of the system. This leads to fewer stations entering a setback state because of Station 24's failure, leading to fewer downtime costs caused by idling. If plant management uses a cost allocation methodology which does not separate normal production costs and downtime costs, decision-making may be adversely affected.

The results in Table 4.35 suggest that Station 14 and Station 15 may be the most important stations for minimizing downtime costs; therefore, these two stations should receive the highest priority for preventative maintenance and repair activities. Station 11 and Station 13 should also receive high priority for these activities. By using an allocation method that separates normal production, downtime, and unused capacity costs, plant management can better determine areas for improvement projects concerning maintenance and capacity levels.

The results in Table 4.35 show slight changes in the total unused capacity cost. Some variation is expected due to changing system dynamics caused by downtime events. For instance, a downtime event may exhaust a buffer's inventory level. If the station after this buffer is faster than the station before this buffer, the faster station will experience more starvation events than usual because the slower station cannot replenish the buffer quickly enough. Because of this, the faster station will enter a setback state more often than usual; therefore, total unused capacity costs will increase. This causes a coupling between rising downtime costs and unused capacity costs. Depending on production line station information and dynamics, this coupling could potentially distort decision making. The distortion caused by this coupling is larger in situations where station speeds are similar. For instance, assume there is a production line of two stations where the second station has a slightly higher rated speed. If the first station breaks down and starves the second station, the second station may enter a setback state more often due to the diminished buffer inventory level. For Scenario 3 of this case study, this coupling proved to be relatively minor with unused capacity costs not directly following downtime costs in terms of trending upward and downward. In some situations, this coupling may have a larger effect.

Additional work is needed to help quantify this coupling and to address situations where production line operators may forcibly idle stations in order to improve line dynamics (e.g. stopping a faster station to replenish buffer inventory). Ideally, refinement of this methodology would account for this coupling in order to fully separate any correlation between downtime costs and unused capacity costs; however, this may prove to be difficult due to changing system dynamics and lingering effects of downtime events. It is recommended that future work look to quantify these lingering effects by comparing cost effects to a baseline situation in the absence of downtime events.

CHAPTER 5

FINAL SUMMARY AND CONCLUSIONS

5.1 Chapter Overview

This chapter provides a final summary of this thesis and conclusions pertaining to this thesis. This chapter revisits the research questions originally presented in Section 1.5 and discusses how well this thesis answered these research questions. While discussing these research questions, this chapter also provides a quick discussion of the validity of the methodology. Lastly, a discussion of possible future work is presented, followed by some closing remarks.

5.2 Research Questions

In Chapter 1, Section 1.5, several research questions were posed that helped to guide this work. These research questions are presented again below.

1. **Can an activity-based costing methodology be developed to accurately capture the effects of dynamic events that occur during manufacturing?**
2. **Can the proposed methodology separate manufacturing costs into normal production costs and added costs due to downtime events and unused capacity?**
3. **Can this methodology be implemented within a realistic case study of an industrial facility to model an actual activity-based costing model using spreadsheet software?**

4. **Does this model produce results and insights that can be used to aid short-term and long-term decision-making to ultimately help the company's bottom line?**

Each of these research questions will be discussed and answered separately to show how well this thesis answers each question.

5.2.1 First Research Question

The first research question asked, "Can an activity-based costing methodology be developed to accurately capture the effects of dynamic events that occur during manufacturing?"

This question is difficult to answer quantitatively; however, qualitatively, the answer is yes. The proposed methodology relies on regularly updated, automated production line data. Assuming that this production line data is correct, the proposed methodology can capture cost effects of changing system behavior.

In the case of utility usage, the methodology provides a reasonable approximation of utility usage. The proposed methodology uses static resource drivers that correspond to each system state (as discussed in Section 3.3.1) and will not be perfectly accurate because it will not capture erratic behavior like power spikes. However, the methodology will be able to reasonably approximate this resource use and still show cost trends due to system behavior. This allows the methodology to be used without additional expensive utility meters at the station level.

Ultimately, a costing model based on the methodology presented in this thesis is only as accurate as its input information. If the costing model is given faulty data, it has no hope of being accurate.

5.2.2 Second Research Question

The second research question asked, “Can the proposed methodology separate manufacturing costs into normal production costs and added costs due to downtime events and unused capacity?”

The answer to this question is yes. The methodology separates manufacturing costs into normal production costs and added downtime and unused capacity costs. The methodology does this by relying on automated production line data regarding station state and production line buffer levels to capture system dynamics.

The methodology uses this information to allocate station activity costs for the previous update interval to the responsible cost center. Normal production costs are allocated to the station where the costs were generated. Downtime costs are allocated to the malfunctioning station that is responsible for those costs. Downtime costs may be due to stations entering a setback state during the downtime event (e.g. idling costs), or they may be connected with a permanent loss of production during a downtime event (e.g. costs of lost sales). Unused capacity costs in this methodology are connected to idling costs from stations that enter a setback state due to blockage or starvation caused by a slower station. These unused capacity costs can either be allocated to the idling, faster station or to the slower station, depending on user preference and project goals.

5.2.3 Third Research Question

The third research question asked, “Can this methodology be implemented within a realistic case study of an industrial facility to model an actual activity-based costing model using spreadsheet software?”

The work presented in Chapter 4 answers this question affirmatively. The proposed methodology was implemented within a case study of a paint shop within an automotive assembly plant. The methodology was used to capture resource use corresponding to five resources: electricity, natural gas, compressed air, hot water, and chilled water. The methodology was implemented in conjunction with simulation code that mimicked paint line system behavior. The case study proved that the proposed methodology can be useful for separating the costs connected to use of the five examined resources into normal production costs, downtime costs, and unused capacity costs and allocating these costs to the responsible stations in the paint line system.

5.2.4 Fourth Research Question

The fourth research question asked, “Does this model produce results and insights that can be used to aid short-term and long-term decision-making to ultimately help the company’s bottom line?”

The proposed methodology could be used in various ways to aid decision makers with short-term and long-term decisions. Scenario 3 in Section 4.7.3 illustrated one possible use of the methodology in conjunction with simulation code to prioritize station preventative maintenance. If the proposed methodology is used on a production line using automated data acquisition, it can alert plant management of changing manufacturing system behavior in a short time frame. Depending on the flexibility of the system, this updated view of station behavior could aid plant management with the distribution of plant resources, such as labor force or buffer space, in the short term.

The proposed methodology can be useful for aiding long-term decisions by providing a more accurate view of costs and by highlighting specific stations and areas for possible improvement projects. This is done by splitting station costs into normal production costs and added costs due to downtime and unused capacity and allocating these costs to responsible cost centers. By using historical downtime cost data captured by a costing system based on the proposed methodology, plant management can better prioritize and justify line improvement projects such as installing new machinery, altering preventative maintenance policies, or hiring additional maintenance workers. By using historical unused capacity cost data captured by the costing system, plant management can also identify possible improvement projects to diminish this unused capacity, such as altering production schedules or adding buffer space. All possible improvements, specifically short-term improvements, are dependent on some flexibility in the manufacturing system in order to most easily and effectively minimize costs.

5.3 Suggested Future Work

Additional work is needed to fully develop and improve the dynamic activity-based costing methodology presented in this work. Specifically, work should be performed regarding 1) the inclusion of more resource types within the implementation of this costing method, 2) additional work to further refine the method of calculating downtime costs from permanent production loss, 3) the logistics of implementing this methodology using actual production line data acquisition systems, and 4) additional work to ease implementation of this methodology with commercial discrete event simulation software.

The inclusion of more resource types within the costing model would give users a better understanding of the true costs of unused capacity and downtime. The costing model implementation for the case study did not include several resource types that would have better highlighted the added costs of downtime and unused capacity. In the case study costing model, only utility resources were included. These resources are still used when a station enters a setback state due to downtime or unused capacity; however, they are often used at a much lower rate during this setback state. The reduction in resource drivers due to this setback state causes the representation of downtime and unused capacity costs to be lower than if other resources that have consistent resource drivers, such as labor or amortization costs of machinery, were included. For example, labor resource drivers remain constant during a downtime event. As such, the cost of labor per unit time remains relatively high, leading to higher costs of downtime.

The calculation of downtime costs stemming from permanent production loss was well-defined and examined by Liu et al (2012) for a continuous flow model. This calculation method was modified slightly in order to calculate these costs within a discrete flow model. Additional work should be done to refine this modified calculation method to improve its definition and accuracy.

Additional work should be performed to examine the logistics of implementing an actual costing system based on the proposed methodology using actual production line data acquisition systems. This would further validate the methodology and highlight possible improvements to the method. Work by Duncan (2003)and Wilgenbusch (2001) has discussed the implementation of similar methods; however, a proof of concept for the proposed methodology is needed in order to further validate and verify its importance.

Likewise, additional work should be performed to ease the implementation of this costing methodology with commercially-available discrete event simulation software. This would allow plant management to run faster, more realistic simulations in order to test various scenarios. Simulation experiments with the proposed costing methodology included could be useful for determining maintenance plans, production schedules, and other decisions. Additionally, this simulation work could use stochastic events instead of deterministic events that were used in the case study and example implementations. This would provide a more realistic and accurate view of production line costs, specifically downtime costs, because downtime events are inherently random. Additional work could be done to pair the proposed costing methodology with stochastic programming and simulation to provide better decision-making support. The work in this thesis mainly looks at the cost effects of downtime events and unused capacity, and additional work, such as this stochastic simulation, could be done to use the methodology to predict these cost effects and aid decision makers with determining methods for decreasing these cost effects. The proposed costing methodology merely relies as station state and buffer information when allocating costs; therefore, it may be used in simulations that use stochastic events as well as simulations that use deterministic events.

5.4 Closing Remarks

The work presented in this thesis examined a new methodology for assessing manufacturing costs using real-time production line data. It aims to build upon existing methodologies in the areas of activity-based costing, downtime costing, and unused capacity costing to provide a framework for allocating production costs within a short time frame.

The proposed methodology was implemented in a small example of an engine assembly line in Section 3.4.2 and in a large case study of a paint shop at an automotive assembly plant in Chapter 4. These two example implementations illustrated how the proposed methodology allocates costs differently than a “traditional” dynamic activity-based costing system. The example implementations were not meant to capture the full costs of the production lines in these examples and did not model all associated costs and resources of the modeled production lines; however, the framework of the methodology presented allows for scalability by using large matrices with matrix multiplication to include additional resources and costs.

Additional work is needed to further refine the proposed methodology for implementation within an actual production line using automated data from actual production line data acquisition systems. Specifically, the logistics of fully implementing a costing system based on the proposed methodology need to be explored. Nevertheless, the work presented in this thesis has presented the framework on which a new costing system can be constructed. This new framework provides a method that can capture the effects of changing system behavior, determine the monetary and environmental costs of this changing behavior, and allocate these costs to responsible stations and line segments. This new allocation method will better highlight areas of possible improvement, specifically areas where downtime costs and unused capacity costs can be minimized. It is hoped that this new methodology can be further explored and provide useful insights when fully implemented on the production floor.

APPENDIX A

ENGINE ASSEMBLY LINE EXAMPLE RESULTS

Table A. 1: Monetary Cost Objects Table Using Traditional Methodology

Station	Cost Type	Electricity	Labor	Lost Sales Costs	Station State Cost Totals	Totals
1	Normal	$ 3.46	$ 200.00	$ 183.33	$ 203.45	$ 386.79
	Downtime	$ -	$ -		$ -	$ -
	Unused Capacity	$ -	$ -		$ -	$ -
2	Normal	$ 0.89	$ 200.00	$ 183.33	$ 200.89	$ 384.23
	Downtime	$ -	$ -	$ -	$ -	$ -
	Unused Capacity	$ -	$ -	$ -	$ -	$ -
3	Normal	$ 0.50	$ 200.00	$ 183.33	$ 200.50	$ 383.83
	Downtime	$ -	$ -		$ -	$ -
	Unused Capacity	$ -	$ -	$ -	$ -	$ -
4	Normal	$ 1.71	$ 200.00	$ 183.33	$ 201.70	$ 385.04
	Downtime	$ -	$ -		$ -	$ -
	Unused Capacity	$ -	$ -	$ -	$ -	$ -
5	Normal	$ 0.90	$ 200.00	$ 183.33	$ 200.90	$ 384.23
	Downtime	$ -	$ -	$ -	$ -	$ -
	Unused Capacity	$ -	$ -	$ -	$ -	$ -
6	Normal	$ 1.75	$ 200.00	$ 183.33	$ 201.75	$ 385.09
	Downtime	$ -	$ -		$ -	$ -
	Unused Capacity	$ -	$ -	$ -	$ -	$ -
Repair	Unused Capacity	$ -	$ 400.00	$ -	$ 400.00	$ 400.00
Totals		**$ 9.20**	**$ 1,600.00**	**$ 1,100.00**	**$ 1,609.20**	**$ 2,709.20**

Table A. 2: Monetary Cost Objects Table Using Proposed Methodology

Station	Cost Type	Electricity	Labor	Lost Sales	State Totals	Totals
1	Normal	$ 2.44	$ 101.67	$ -	$ 104.11	$ 104.11
	Downtime	$ 0.03	$ 50.00	$ 155.06	$ 50.03	$ 205.08
	Unused Capacity	$ 0.82	$ 68.75	$ -	$ 69.57	$ 69.57
2	Normal	$ 0.63	$ 104.17	$ -	$ 104.79	$ 104.79
	Downtime	$ 0.08	$ 26.67	$ -	$ 26.75	$ 26.75
	Unused Capacity	$ 0.19	$ 61.67	$ -	$ 61.85	$ 61.85
3	Normal	$ 0.41	$ 137.08	$ -	$ 137.49	$ 137.49
	Downtime	$ 0.09	$ 25.83	$ 147.00	$ 25.92	$ 172.92
	Unused Capacity	$ 0.06	$ 41.67	$ -	$ 41.73	$ 41.73
4	Normal	$ 1.24	$ 102.92	$ -	$ 104.15	$ 104.15
	Downtime	$ 0.20	$ 110.42	$ 633.89	$ 110.62	$ 744.51
	Unused Capacity	$ 0.40	$ 66.67	$ -	$ 67.07	$ 67.07
5	Normal	$ 0.62	$ 103.75	$ -	$ 104.37	$ 104.37
	Downtime	$ 0.02	$ 15.00	$ -	$ 15.02	$ 15.02
	Unused Capacity	$ 0.18	$ 61.25	$ -	$ 61.43	$ 61.43
6	Normal	$ 1.25	$ 104.58	$ -	$ 105.84	$ 105.84
	Downtime	$ 0.19	$ 68.75	$ 164.37	$ 68.94	$ 233.31
	Unused Capacity	$ 0.36	$ 60.00	$ -	$ 60.36	$ 60.36
Repair	Unused Capacity	$ -	$ 289.17	$ -	$ 289.17	$ 289.17
Totals		**$ 9.20**	**$ 1,600.00**	**$ 1,100.31**	**$ 1,609.20**	**$ 2,709.52**

APPENDIX B

CASE STUDY SIMULATION FLOWCHARTS

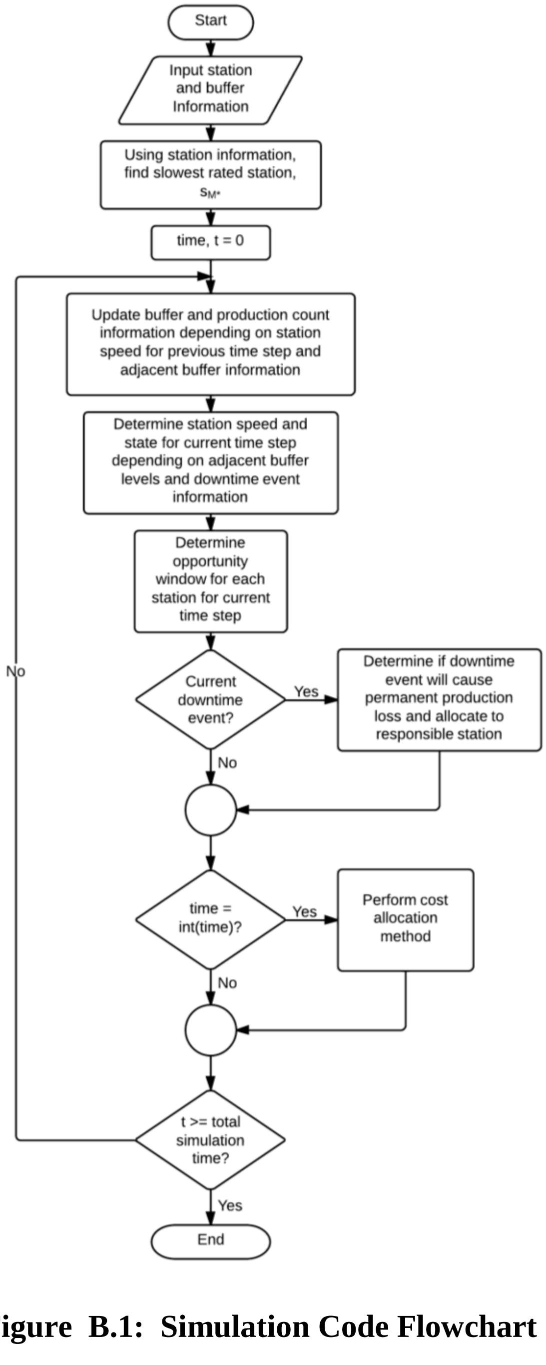


Figure B.1: Simulation Code Flowchart

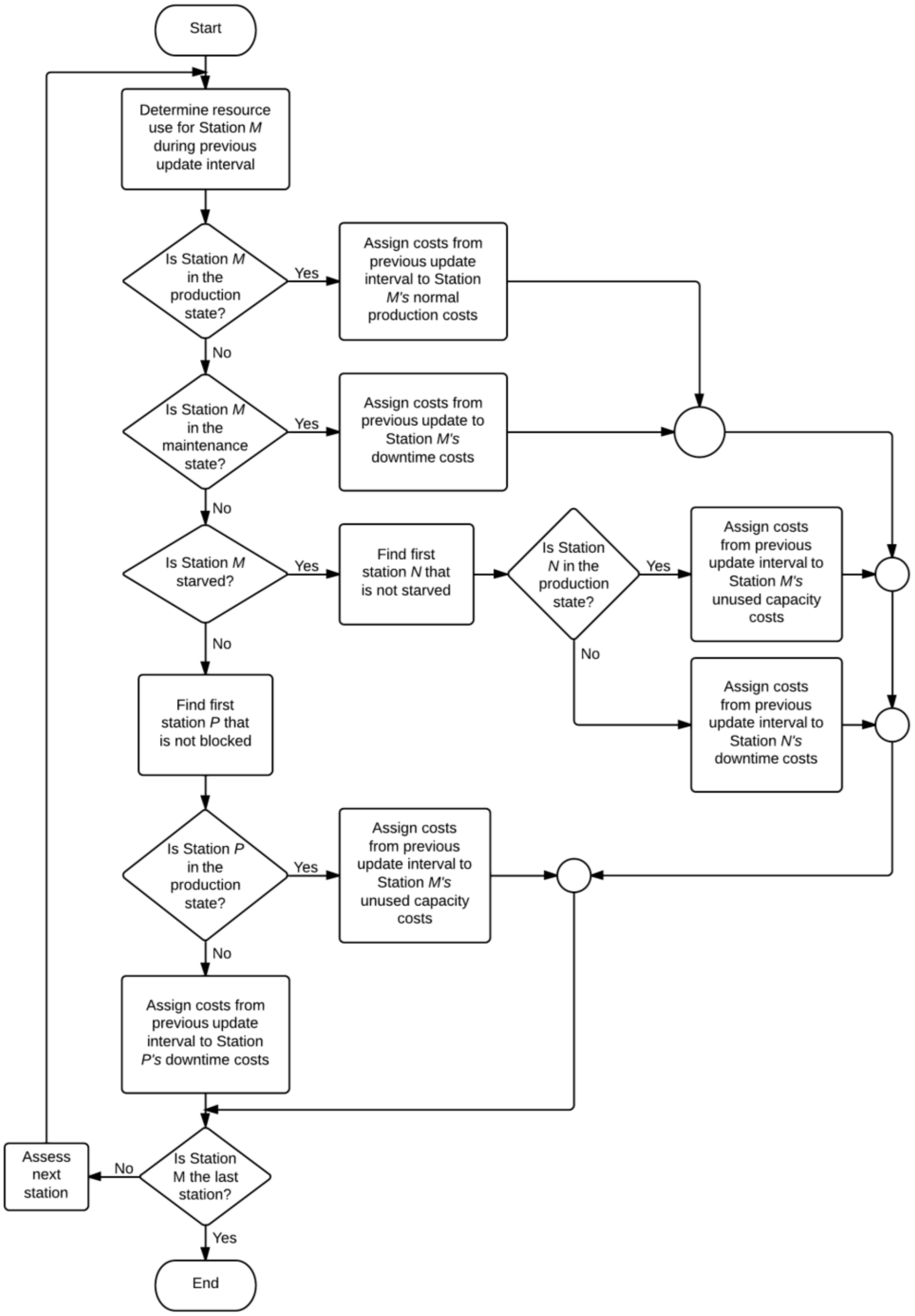


Figure B.2: Flowchart for Cost Allocation Logic when Allocating Unused Capacity Costs to Faster Stations

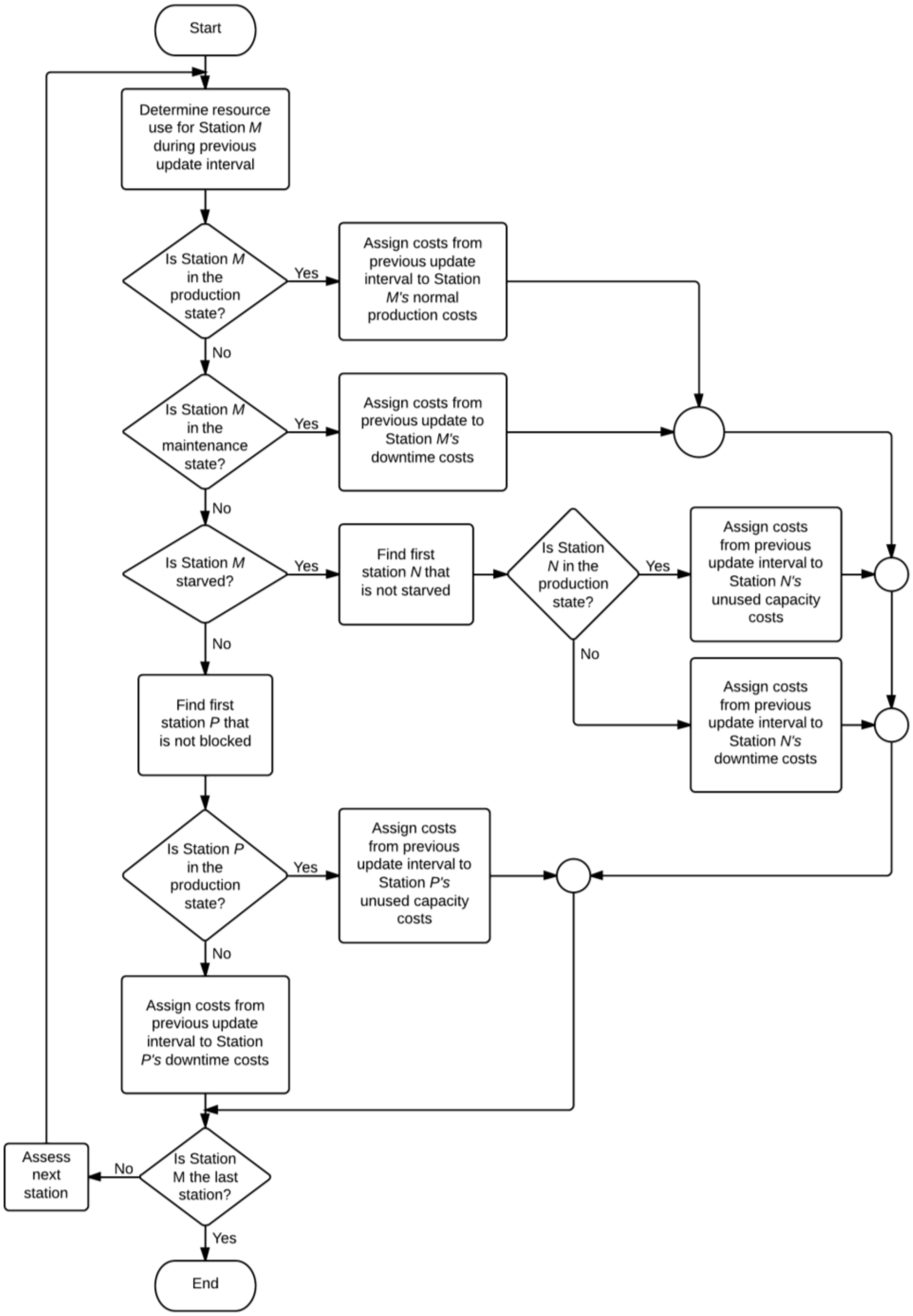


Figure B.3: Flowchart for Cost Allocation Logic when Allocating Unused Capacity Costs to Slower Stations

APPENDIX C

CASE STUDY STATION RESOURCE DRIVERS

C.1 Pretreatment Area Station Resource Drivers

Table C.1: Pretreatment Area Station Resource Drivers

Station	State	Electricity (kWh/min)	Natural Gas (mmBTU/min)	Compressed Air (CFM)	Hot Water (mmBTU/min)	Chilled Water (mmBTU/min)
1	Production	0.2011	0.0000	0.0000	0.0000	0.0000
	Setback	0.2011	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
2	Production	4.1494	0.0000	0.0000	0.1933	0.0000
	Setback	4.1494	0.0000	0.0000	0.0117	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
3	Production	2.3505	0.0000	0.0000	0.0000	0.0000
	Setback	2.3505	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
4	Production	0.5291	0.0000	0.0000	0.0000	0.0000
	Setback	0.5291	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
5	Production	1.3150	0.0000	0.0000	0.0000	0.0000
	Setback	1.3150	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
6	Production	1.2577	0.0000	0.0000	0.0300	0.0000
	Setback	1.2577	0.0000	0.0000	0.0117	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
7	Production	3.1738	0.0000	0.0000	0.0000	0.0000
	Setback	3.1738	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
8	Production	0.4569	0.0000	0.0000	0.0000	0.0000
	Setback	0.4569	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
9	Production	1.0679	0.0000	0.0000	0.0000	0.0000
	Setback	1.0679	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
10	Production	0.2831	0.0000	0.0000	0.0000	0.0000
	Setback	0.2831	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000

C.2 ELPO Area Station Resource Drivers

Table C.2: ELPO Area Station Resource Drivers

Station	State	Electricity (kWh/min)	Natural Gas (mmBTU/min)	Compressed Air (CFM)	Hot Water (mmBTU/min)	Chilled Water (mmBTU/min)
11	Production	3.9400	0.0000	0.0000	0.0000	0.0600
	Setback	3.6395	0.0000	0.0000	0.0000	0.0000
	Maintenance	2.3703	0.0000	0.0000	0.0000	0.0000
12	Production	0.0320	0.0000	0.0000	0.0000	0.0000
	Setback	0.0320	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
13	Production	0.2173	0.0000	0.0000	0.0000	0.0000
	Setback	0.2173	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.2036	0.0000	0.0000	0.0000	0.0000
14	Production	1.3260	0.0000	0.0000	0.0000	0.0000
	Setback	1.3260	0.0000	0.0000	0.0000	0.0000
	Maintenance	1.2677	0.0000	0.0000	0.0000	0.0000
15	Production	0.3105	0.0000	0.0000	0.0000	0.0000
	Setback	0.3105	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.2843	0.0000	0.0000	0.0000	0.0000
16	Production	0.2024	0.0000	0.0000	0.0000	0.0000
	Setback	0.2024	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
17	Production	0.2230	0.0000	0.0000	0.0000	0.0000
	Setback	0.2230	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
18	Production	0.2024	0.0000	0.0000	0.0000	0.0000
	Setback	0.2024	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
19	Production	0.5285	0.0000	0.0000	0.0000	0.0000
	Setback	0.5285	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
20	Production	0.6299	0.0250	0.0000	0.0000	0.0000
	Setback	0.5641	0.0167	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
21	Production	0.6044	0.0250	0.0000	0.0000	0.0000
	Setback	0.5349	0.0167	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
22	Production	1.2663	0.0500	0.0000	0.0000	0.0000
	Setback	1.0354	0.0333	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
23	Production	3.6158	0.0000	0.0000	0.0000	0.0550
	Setback	0.3353	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
24	Production	0.7549	0.0000	0.0000	0.0000	0.0000
	Setback	0.2918	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.1863	0.0000	0.0000	0.0000	0.0000

C.3 Sealing Line Area Station Resource Drivers

Table C.3: Sealing Line Area Station Resource Drivers

Station	State	Electricity (kWh/min)	Natural Gas (mmBTU/min)	Compressed Air (CFM)	Hot Water (mmBTU/min)	Chilled Water (mmBTU/min)
25	Production	0.3179	0.0071	0.0000	0.0000	0.0179
	Setback	0.3179	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
26	Production	0.3807	0.0071	0.0000	0.0000	0.0179
	Setback	0.3179	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
27	Production	0.6556	0.0071	0.0000	0.0000	0.0179
	Setback	0.6556	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
28	Production	2.1833	0.0071	2.2500	0.0000	0.0179
	Setback	0.4213	0.0000	0.0167	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
29	Production	1.4407	0.0000	2.2500	0.0000	0.0000
	Setback	0.3803	0.0000	0.0167	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
30	Production	1.3215	0.0071	8.5000	0.0000	0.0179
	Setback	0.3803	0.0000	0.0167	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
31	Production	0.4218	0.0071	0.0000	0.0000	0.0179
	Setback	0.4218	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
32	Production	0.4359	0.0071	0.0000	0.0000	0.0179
	Setback	0.3574	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
33	Production	1.7411	0.0071	4.4167	0.0000	0.0179
	Setback	1.1874	0.0000	0.0167	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
34	Production	0.6015	0.0328	0.0000	0.0000	0.0000
	Setback	0.5444	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
35	Production	0.7125	0.0145	0.7333	0.0000	0.0000
	Setback	0.7125	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
36	Production	0.0301	0.0000	0.0000	0.0000	0.0000
	Setback	0.0301	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
37	Production	1.8111	0.0000	0.0000	0.0000	0.0500
	Setback	0.2180	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
38	Production	0.5625	0.0000	0.0000	0.0000	0.0000
	Setback	0.0000	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000

C.4 Paint Booth Area Station Resource Drivers

Table C.4: Paint Booth Area Station Resource Drivers

Station	State	Electricity (kWh/min)	Natural Gas (mmBTU/min)	Compressed Air (CFM)	Hot Water (mmBTU/min)	Chilled Water (mmBTU/min)
39	Production	1.4105	0.0000	0.0000	0.0000	0.0000
	Setback	0.0658	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
40	Production	1.1441	0.1173	0.0000	0.0000	0.2100
	Setback	1.1441	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.6978	0.0000	0.0000	0.0000	0.0000
41	Production	1.7289	0.0000	0.3333	0.0000	0.0000
	Setback	0.0725	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
42	Production	2.4695	0.0677	3.2500	0.0015	0.0765
	Setback	1.9840	0.0000	0.1333	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
43	Production	1.0642	0.0317	0.0000	0.0000	0.0000
	Setback	0.0336	0.0133	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
44	Production	0.2692	0.0000	0.0000	0.0000	0.0283
	Setback	0.2692	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
45	Production	1.6863	0.0338	3.2500	0.0008	0.0383
	Setback	1.1567	0.0000	0.1417	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
46	Production	1.6836	0.0338	3.2500	0.0008	0.0383
	Setback	1.1540	0.0000	0.1417	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
47	Production	0.9979	0.0250	0.0000	0.0000	0.0000
	Setback	0.0294	0.0117	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
48	Production	0.2650	0.0000	0.0000	0.0000	0.0067
	Setback	0.2650	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
49	Production	1.5648	0.0088	2.7000	0.0092	0.0518
	Setback	1.1091	0.0000	0.1333	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
50	Production	1.5728	0.0088	2.7000	0.0092	0.0518
	Setback	1.1171	0.0000	0.1333	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
51	Production	0.4368	0.0250	0.0000	0.0000	0.0000
	Setback	0.4368	0.0167	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
52	Production	0.6864	0.0250	0.7333	0.0000	0.0000
	Setback	0.6864	0.0167	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
53	Production	0.0060	0.0000	0.0000	0.0000	0.0000
	Setback	0.0060	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
54	Production	0.0060	0.0000	0.0000	0.0000	0.0000
	Setback	0.0060	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
55	Production	0.0203	0.0000	0.0000	0.0000	0.0000
	Setback	0.0203	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
56	Production	1.1553	0.0000	0.0000	0.0000	0.0300
	Setback	1.1553	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000
57	Production	0.9015	0.0000	0.0000	0.0000	0.0000
	Setback	0.4507	0.0000	0.0000	0.0000	0.0000
	Maintenance	0.0000	0.0000	0.0000	0.0000	0.0000

APPENDIX D

CASE STUDY ADDITIONAL SCENARIO RESULTS

D.1 Scenario 1 Additional Results

D.1.1 Traditional Allocation Method

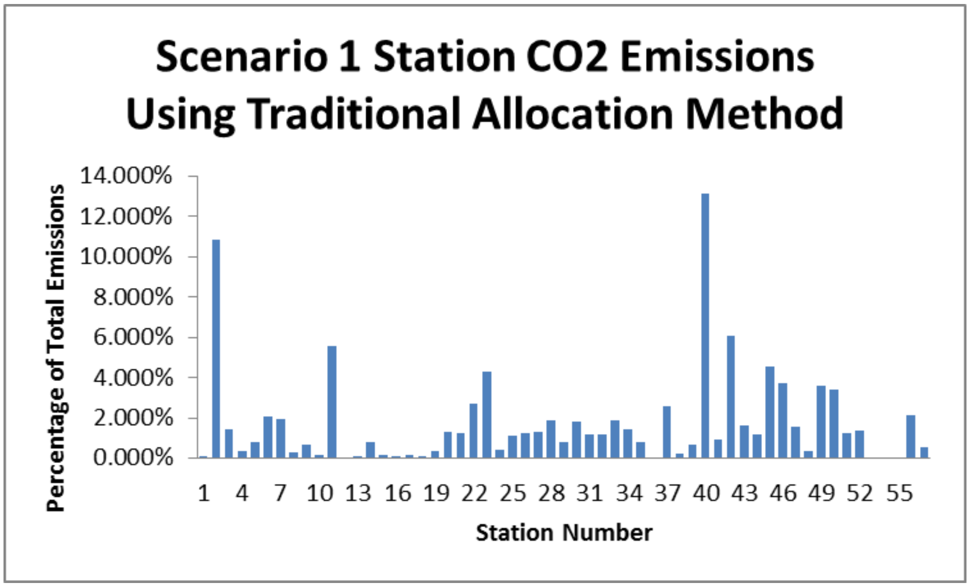


Figure D.1: Distribution of Station CO2 Emissions for Scenario 1 Using Traditional Cost Allocation Method

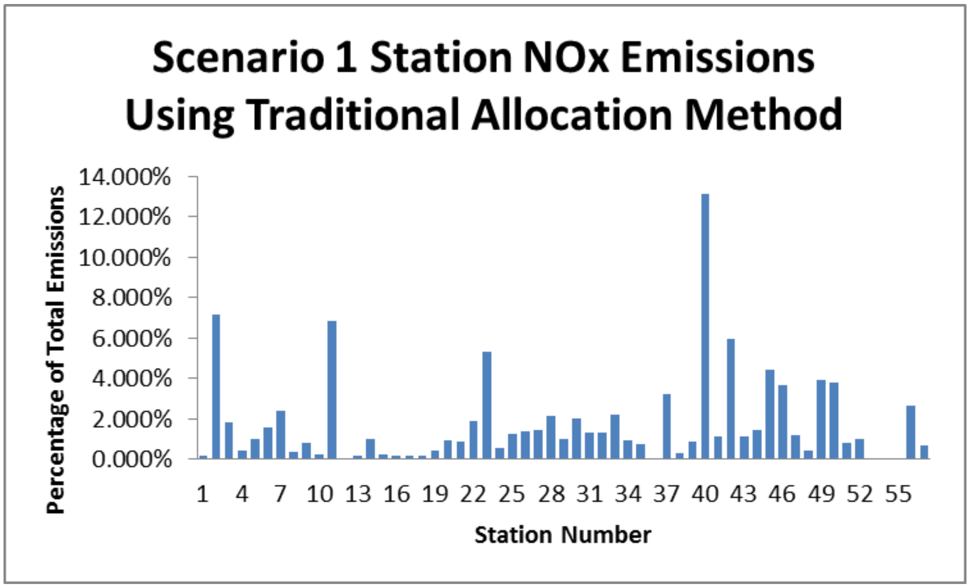


Figure D.2: Distribution of Station NOx Emissions for Scenario 1 Using Traditional Cost Allocation Method

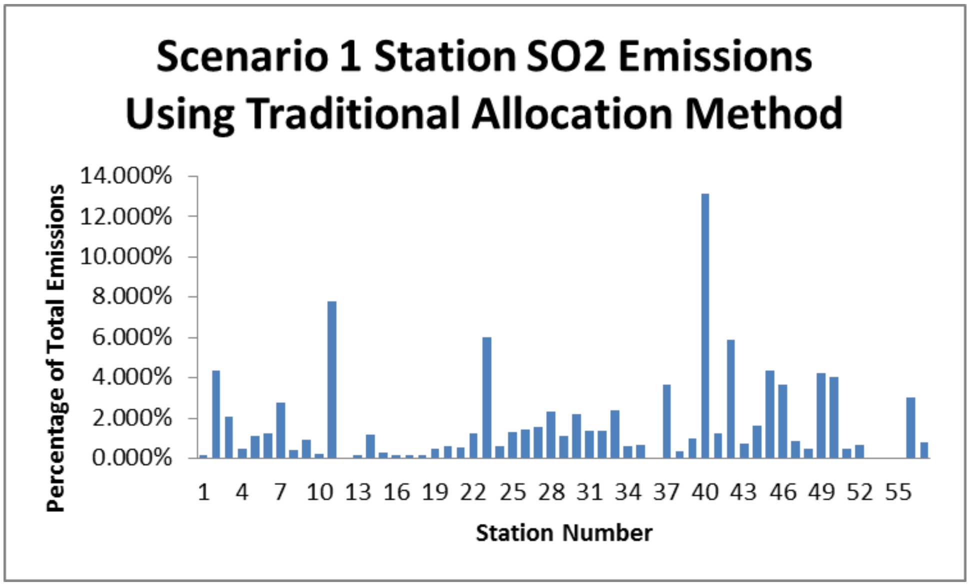


Figure D.3: Distribution of Station SO2 Emissions for Scenario 1 Using Traditional Cost Allocation Method

D.1.2 First Proposed Allocation Method

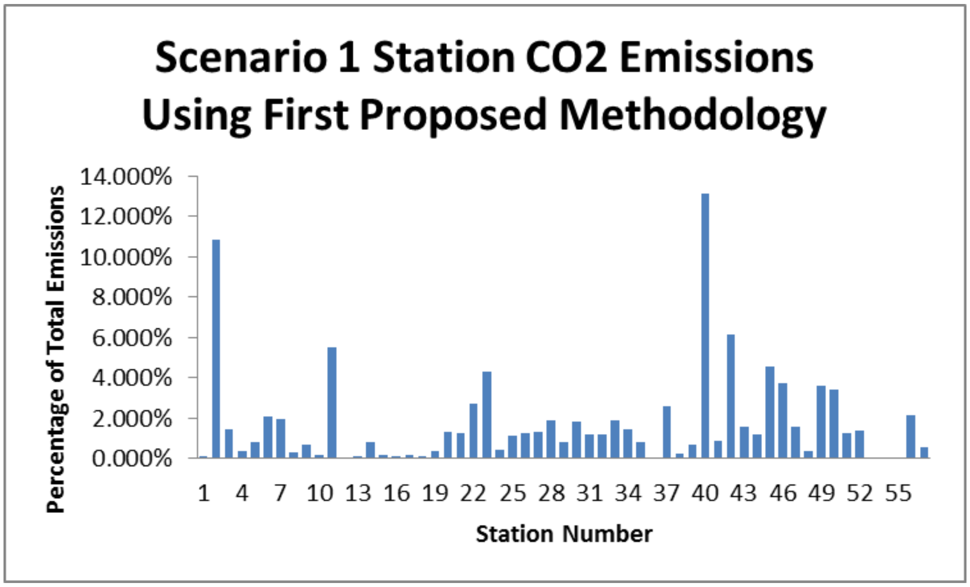


Figure D.4: Distribution of Station CO2 Emissions for Scenario 1 Using First Proposed Cost Allocation Method

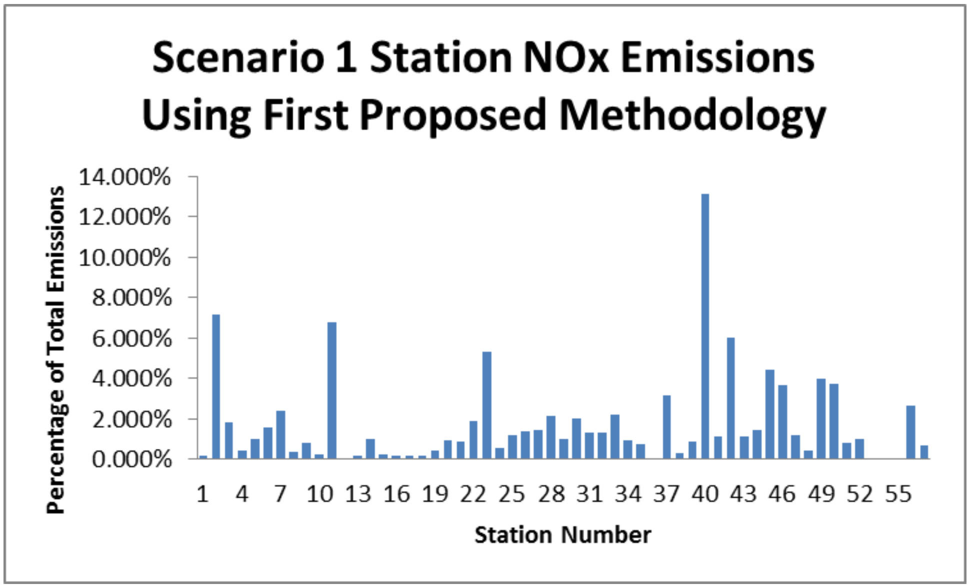


Figure D.5: Distribution of Station NOx Emissions for Scenario 1 Using First Proposed Cost Allocation Method

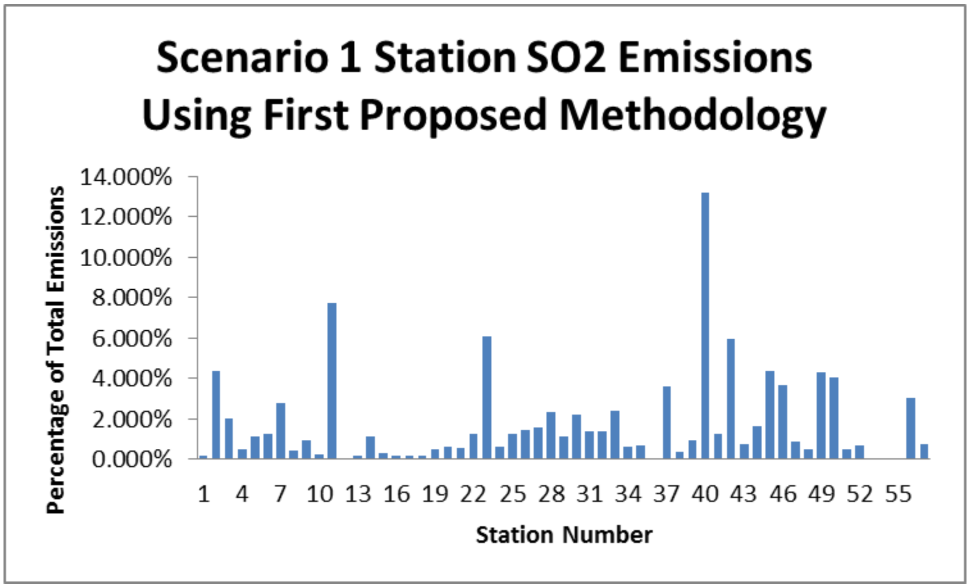


Figure D.6: Distribution of Station SO2 Emissions for Scenario 1 Using First Proposed Cost Allocation Method

D.1.3 Second Proposed Allocation Method

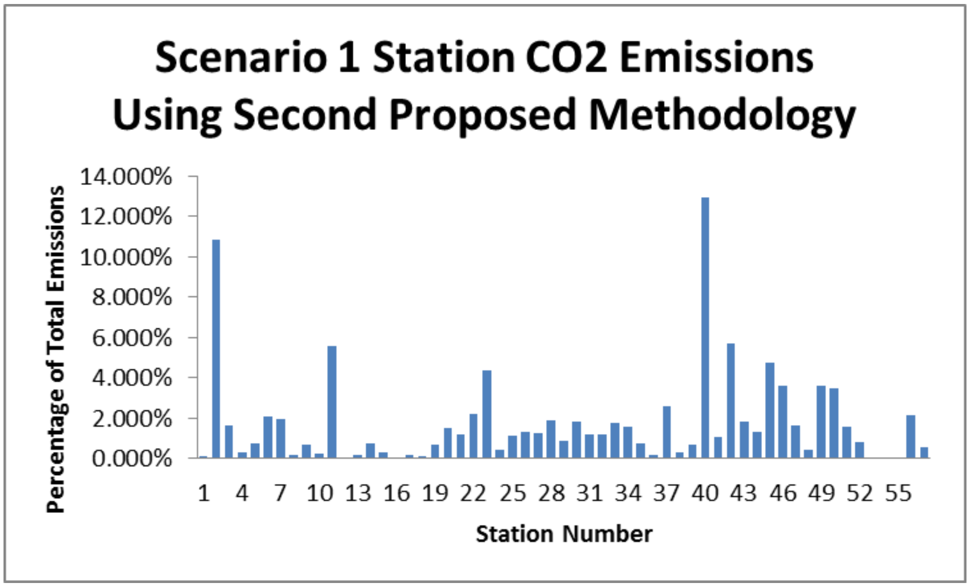


Figure D.7: Distribution of Station CO2 Emissions for Scenario 1 Using Second Proposed Cost Allocation Method

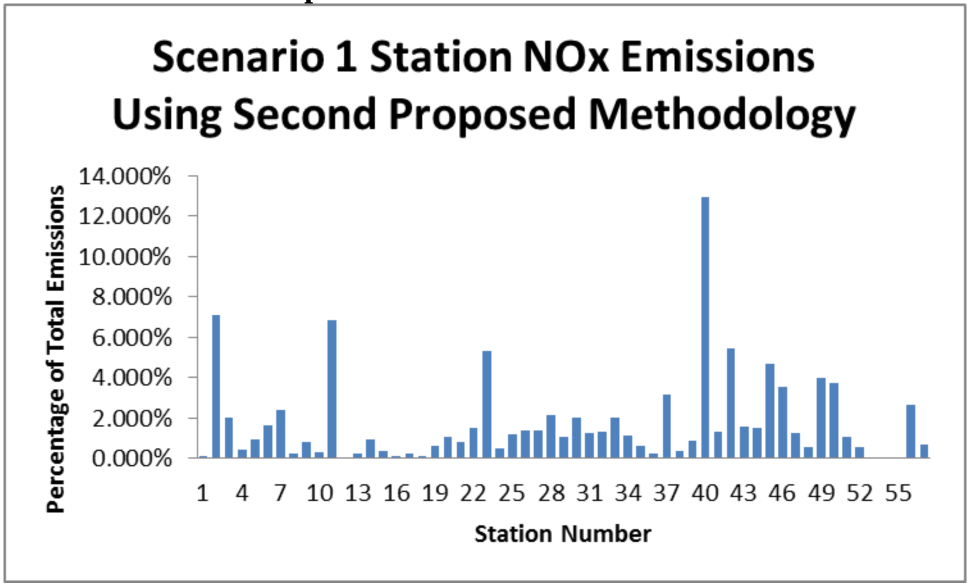


Figure D.8: Distribution of Station NOx Emissions for Scenario 1 Using Second Proposed Cost Allocation Method

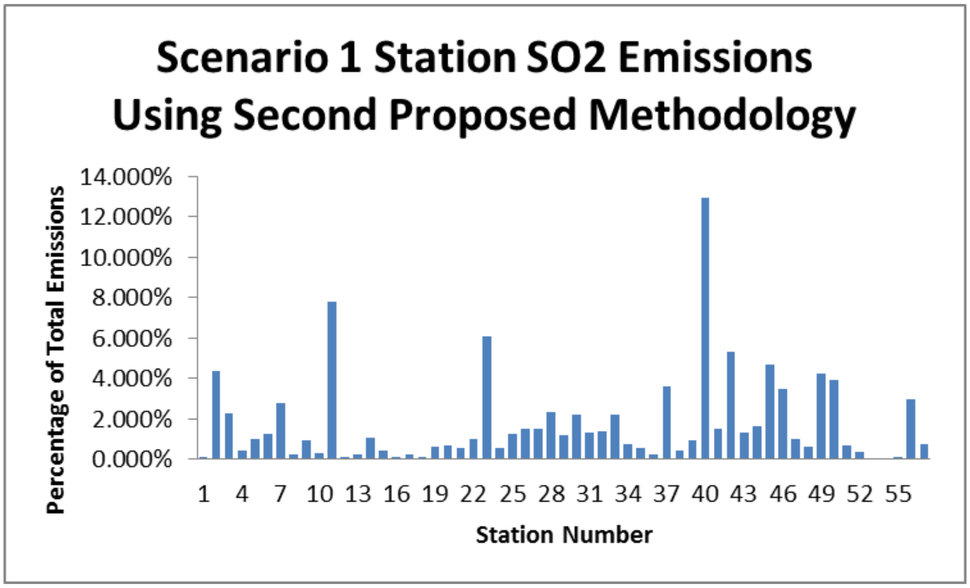


Figure D.9: Distribution of Station SO2 Emissions for Scenario 1 Using Second Proposed Cost Allocation Method

D.1.4 Comparison between Allocation Methods

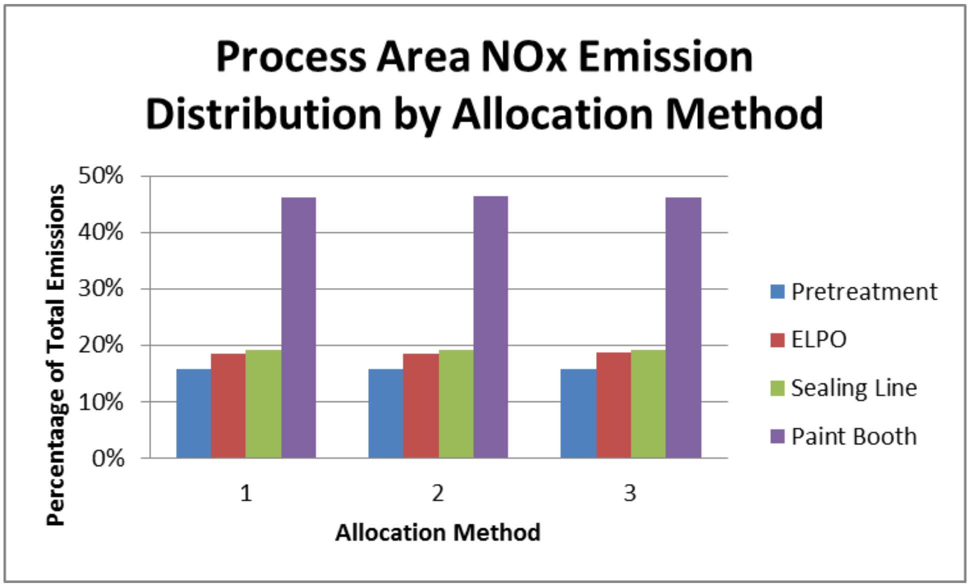


Figure D.10: Scenario 1 NOx Emission Distribution between Process Areas by Allocation Method

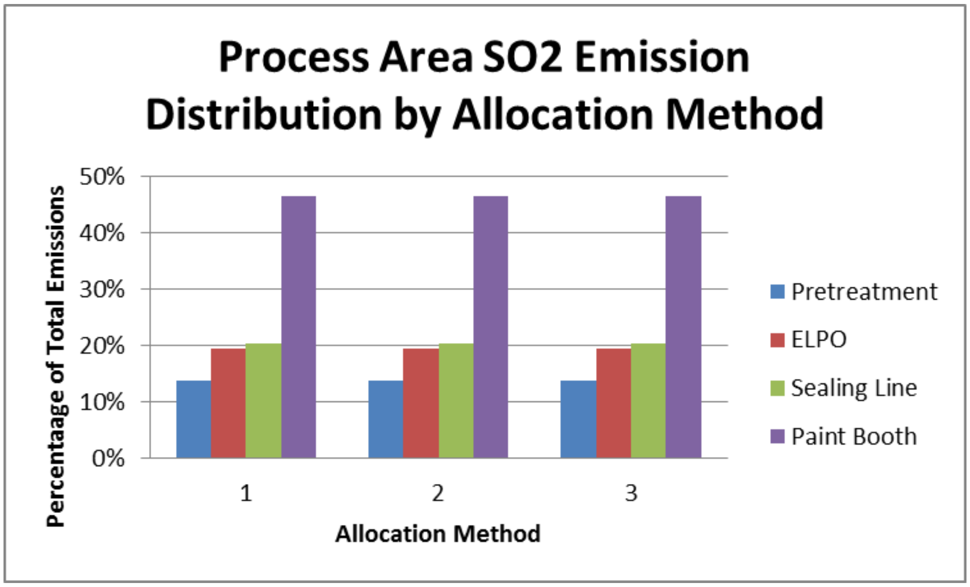


Figure D.11: Scenario 1 SO2 Emission Distribution between Process Areas by Allocation Method

D.2 Scenario 2 Additional Results

D.2.1 Traditional Allocation Method

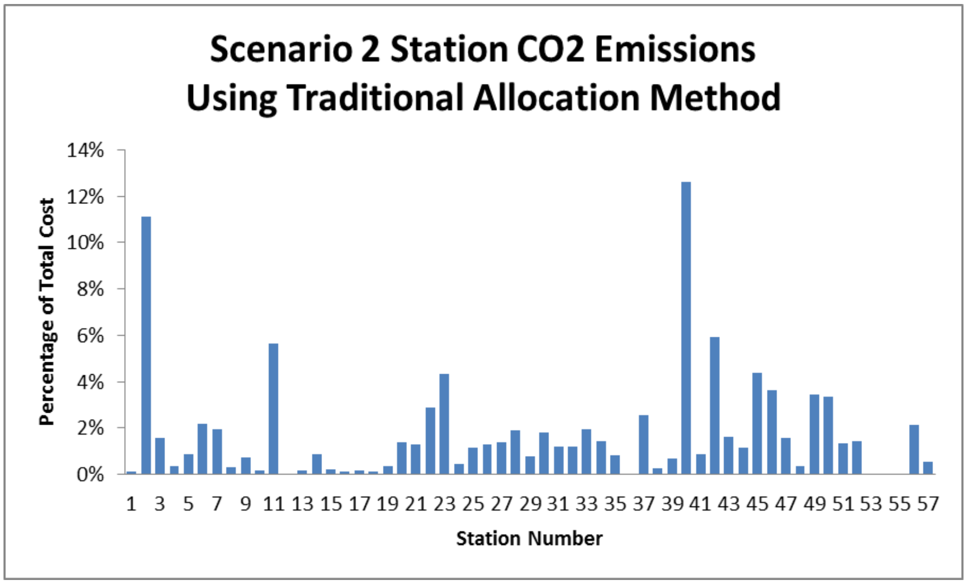


Figure D.12: Distribution of Station CO2 Emissions for Scenario 2 Using Traditional Cost Allocation Method

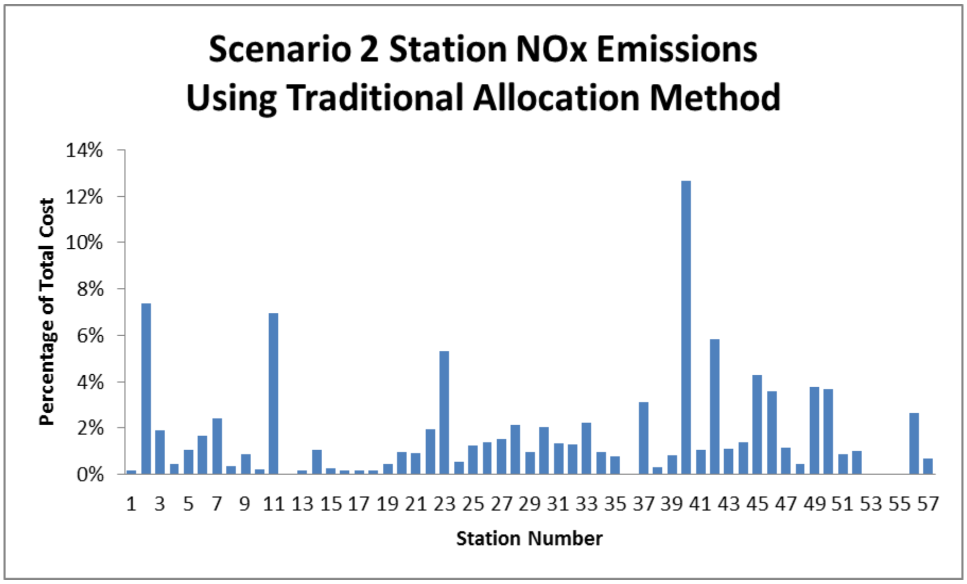


Figure D.13: Distribution of Station NOx Emissions for Scenario 2 Using Traditional Cost Allocation Method

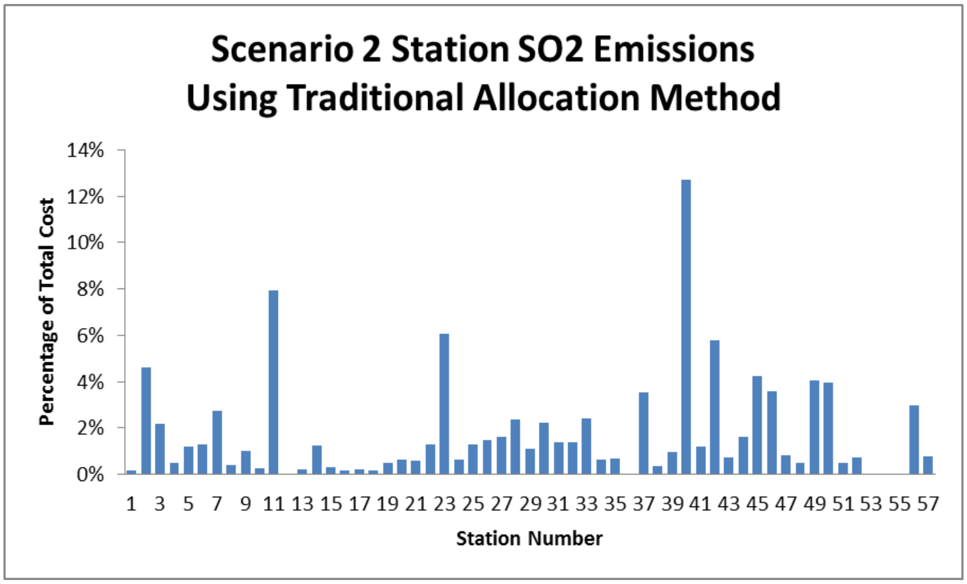


Figure D.14: Distribution of Station SO2 Emissions for Scenario 2 Using Traditional Cost Allocation Method

D.2.2 First Proposed Allocation Method

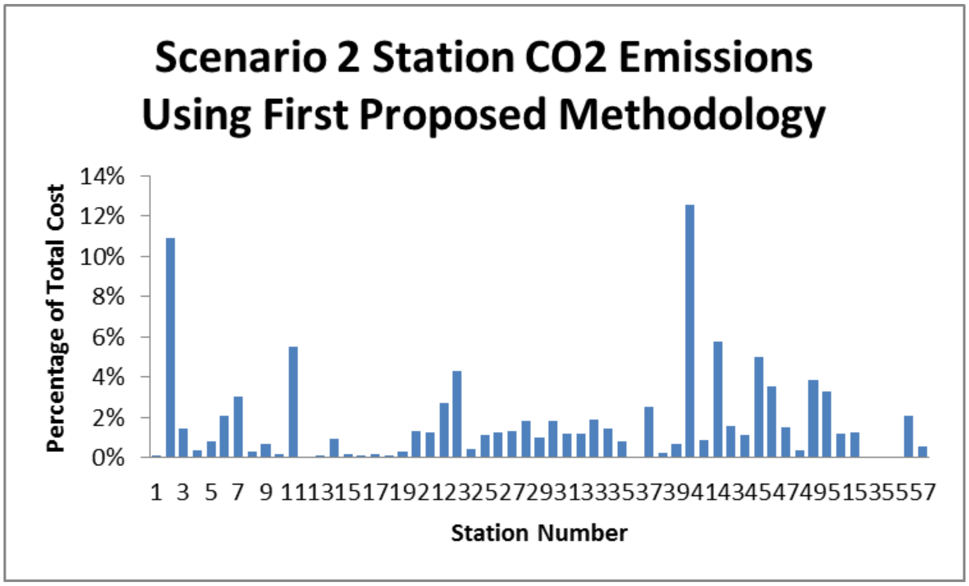


Figure D.15: Distribution of Station CO2 Emissions for Scenario 2 Using First Proposed Cost Allocation Method

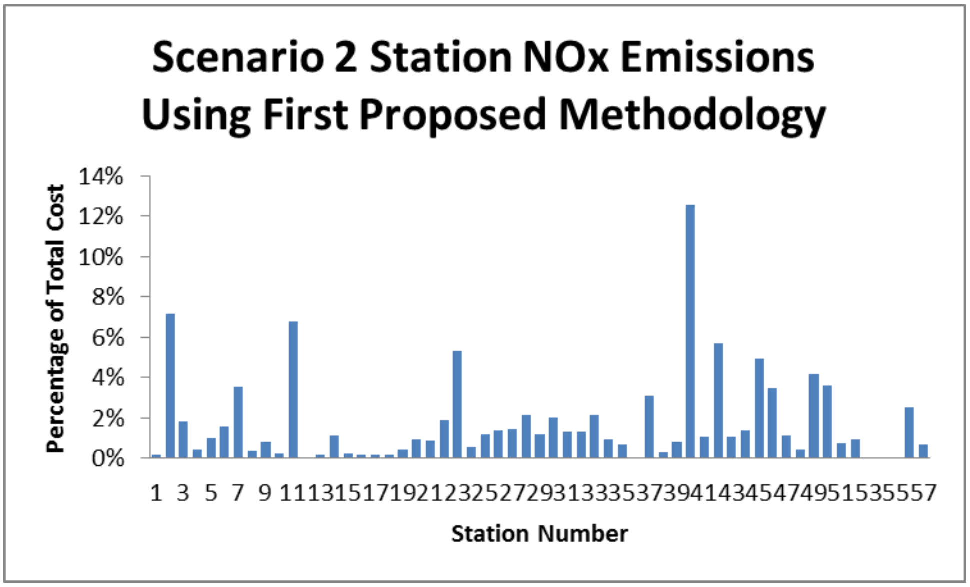


Figure D.16: Distribution of Station NOx Emissions for Scenario 2 Using First Proposed Cost Allocation Method

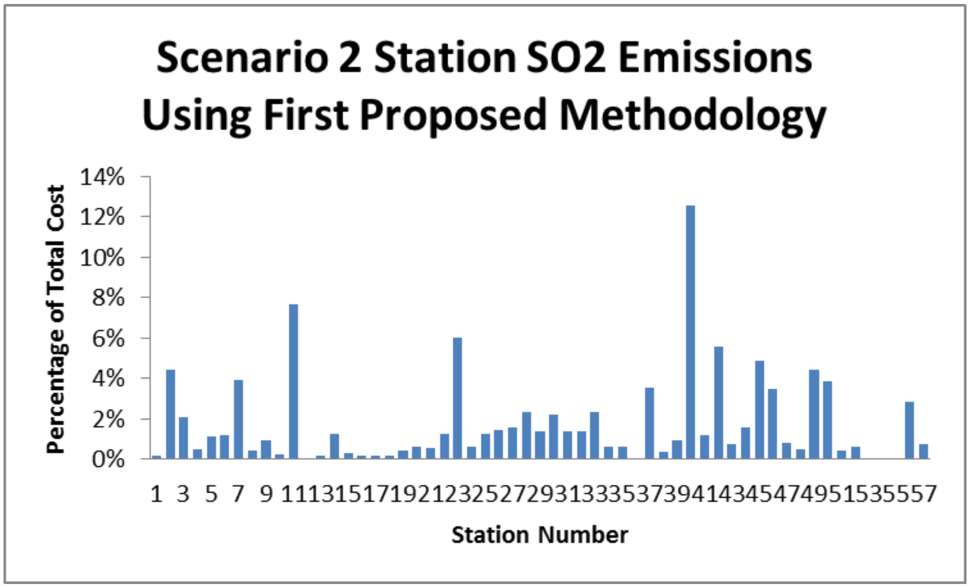


Figure D.17: Distribution of Station SO2 Emissions for Scenario 2 Using First Proposed Cost Allocation Method

D.2.3 Second Proposed Allocation Method

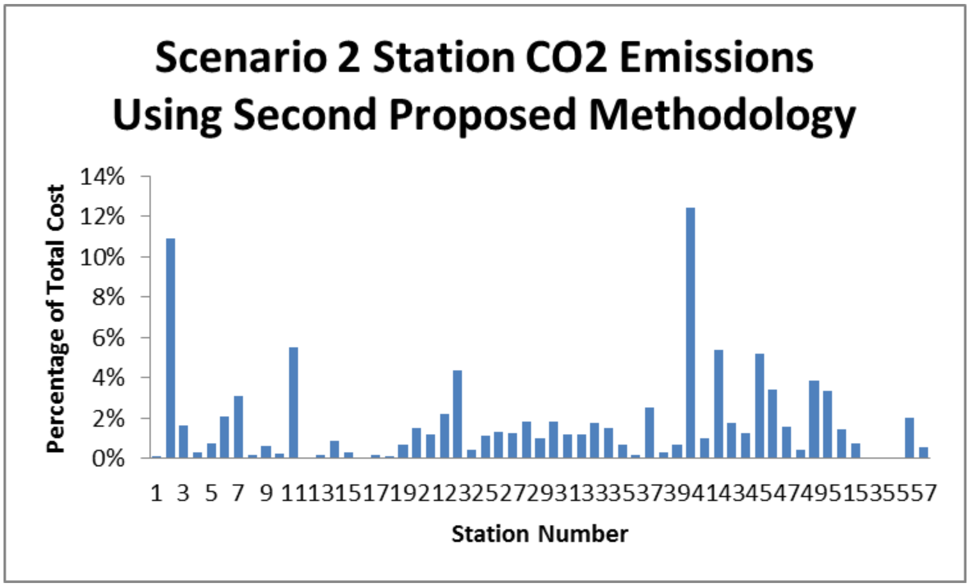


Figure D.18: Distribution of Station CO2 Emissions for Scenario 2 Using Second Proposed Cost Allocation Method

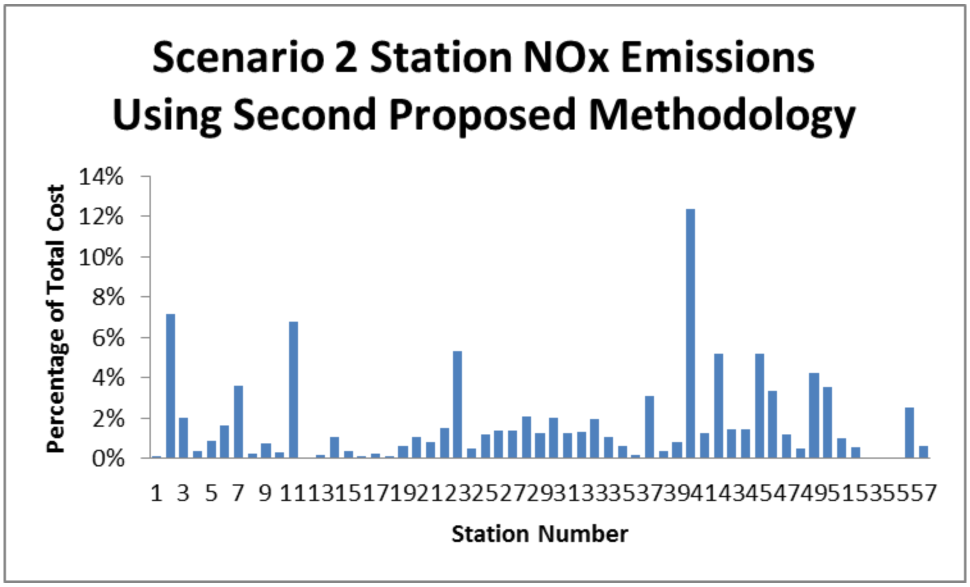


Figure D.19: Distribution of Station NOx Emissions for Scenario 2 Using Second Proposed Cost Allocation Method

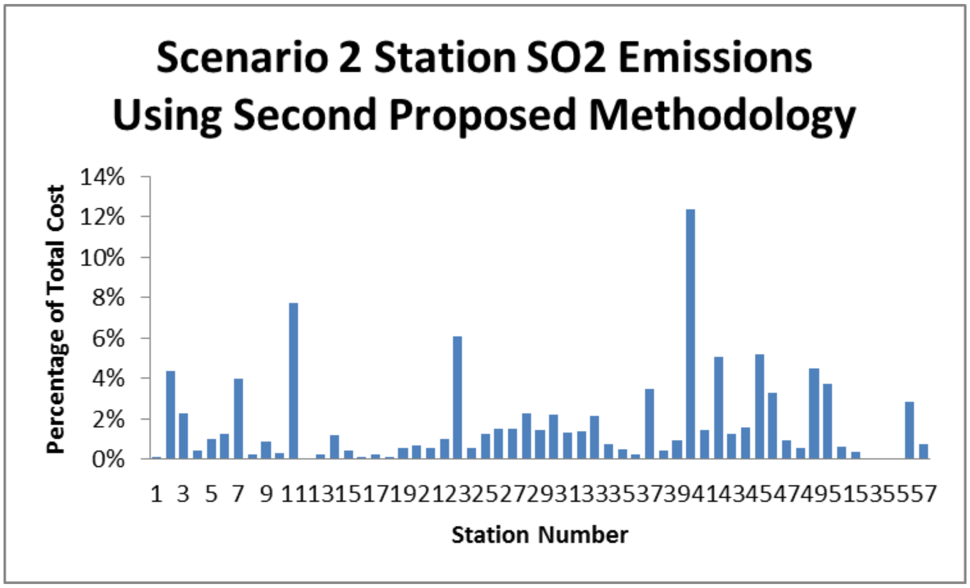


Figure D.20: Distribution of Station SO2 Emissions for Scenario 2 Using Second Proposed Cost Allocation Method

D.2.4 Comparison between Allocation Methods

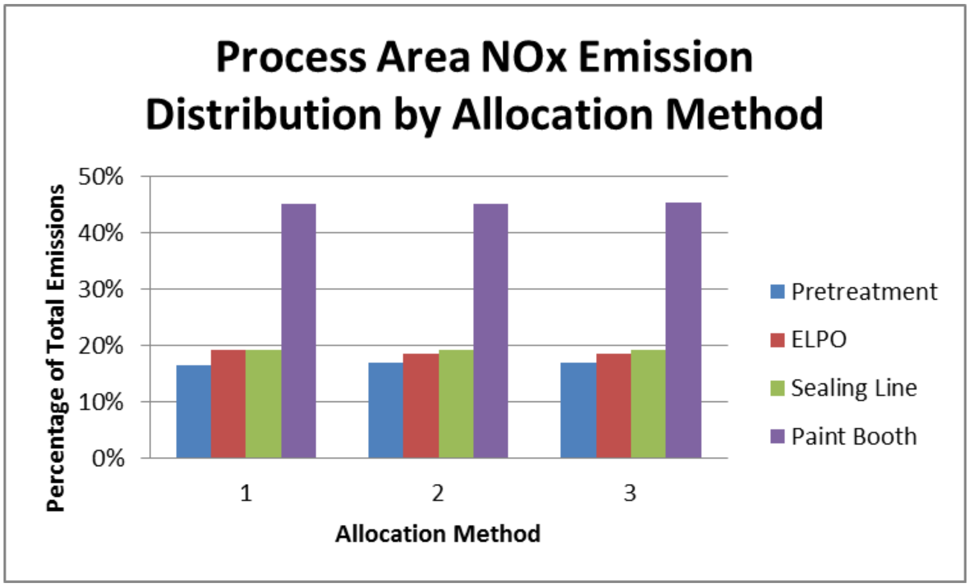


Figure D.21: Scenario 2 NOx Emission Distribution between Process Areas by Allocation Method

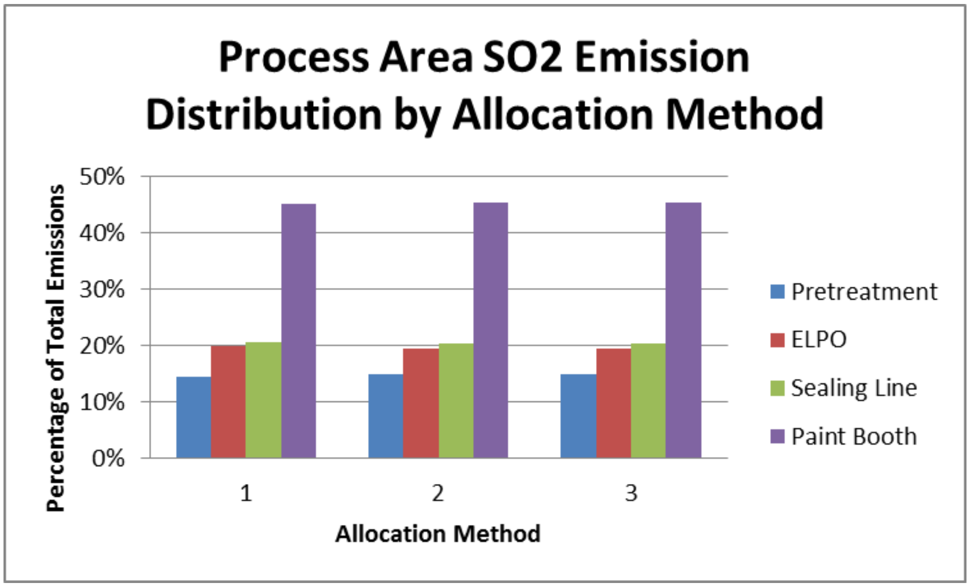


Figure D.22: Scenario 2 SO2 Emission Distribution between Process Areas by Allocation Method

REFERENCES

Afonso, P. S. and A. M. Paisana (2009). "An algorithm for activity based costing based on matrix multiplication." 2009 IEEE International Conference on Industrial Engineering & Engineering Management: 920.

Bargmann, M. A. (2002). Development of a Tool to Support Environmental Management Within Small- and Medium-Sized Enterprises. Master of Science in Mechanical Engineering, Georgia Institute of Technology.

Becker, J., P. Bergener, et al. (2009). Process-Based Governance in Public Administrations Using Activity-Based Costing. LECTURE NOTES IN COMPUTER SCIENCE, Germany, SPRINGER-VERLAG**:** 176-187.

Bras, B., S. Duncan, et al. (2001). Real-time Integrated Economic and Environmental Performance Monitoring of a Production Facility. SAE 2001 World Congress, Detroit, MI, USA, SAE.

Brooks, P. L., L. J. Davidson, et al. (1993). Environmental compliance: you better know your ABCs. Occupational Hazards. **55:** 41-46.

Brüggen, A., R. Krishnan, et al. (2011). "Drivers and Consequences of Short-Term Production Decisions: Evidence from the Auto Industry." Contemporary Accounting Research **28**(1): 83-123.

Buchheit, S. (2003). "Reporting the cost of capacity." Accounting, Organizations and Society **28**(6): 549-565.

Chang, Q., S. Biller, et al. (2010). "Transient Analysis of Downtimes and Bottleneck Dynamics in Serial Manufacturing Systems." Journal of Manufacturing Science and Engineering **132**(5).

Chea, A. C. (2011). "Activity-Based Costing System in the Service Sector: A Strategic Approach for Enhancing Managerial Decision Making and Competitiveness." International Journal of Business & Management **6**(11): 3-10.

Consumers Energy Company. (2012). "General Service Rate (Rates GS-1, GS-2 and GS-3)." from http://www.consumersenergy.com/tariffs.nsf/ELECTRIC_TARIFFS/265F40D0F99C3E9A85257A38004D06A0/$FILE/elerates.pdf?Open.

Cooper, R. and R. S. Kaplan (1988). "Measure Costs Right: Make the Right Decision." Harvard Business Review **66**(5): 96-103.

Cooper, R. and R. S. Kaplan (1992). "Activity-Based Systems: Measuring the Costs of Resource Usage." Accounting Horizons **6**(3): 1-13.

Cooper, R. and R. S. Kaplan (1998). The Promise and Peril of Integrated Cost Systems. Harvard Business Review. Boston, Harvard Business Review. **76:** 109-119.

Crumrine, D. and D. Post (2006). When True Cost of Downtime Is Unknown, Bad Decisions Ensue. Intech. **53:** 55-55.

DTE Energy. (2013). "Special Manufacturing Supply Agreement." from http://www.dteenergy.com/pdfs/specialManufacturingSupplyRate.pdf.

Duncan, S. J. (2003). A Mass and Energy Data Collection System to Support Environmental and Economic Assessment of a Coating Line in Carpet Manufacturing. Master of Science in Mechanical Engineering, Georgia Institute of Technology.

Edwards, D. J., G. D. Holt, et al. (2002). "Predicting downtime costs of tracked hydraulic excavators operating in the UK opencast mining industry." Construction Management & Economics **20**(7): 581.

Elkington, J. (1994). "Towards the Sustainable Corporation: Win-Win-Win Business Strategies for Sustainable Development." California Management Review **36**(2): 90-100.

Emblemsvåg, J. and B. Bras (2001). Activity-Based Cost and Environmental Management: A Different Approach to ISO 14000 Compliance. Boston, Kluwer Academic Publishers.

Faria, J. A., E. Nunes, et al. (2010). "Cost and quality of service analysis of production systems based on the cumulative downtime." International Journal of Production Research **48**(6): 1653-1684.

Ittner, C. and D. Larckner (2000). Non-financial Performance Measures: What Works and What Doesn't. Financial Times. **Mastering Management**.

Jones, R. L. (1998). Activity-based costing (ABC) in army garrisons. Armed Forces Comptroller, American Society of Military Comptrollers. **43:** 11-15.

Jurek, P., B. Bras, et al. (2012). Activity-Based Costing applied to automotive manufacturing. 2012 IEEE Power & Energy Society General Meeting. New Energy Horizons - Opportunities and Challenges, San Diego, CA, USA., IEEE.

Kaplan, R. S. and S. R. Anderson (2004). "Time-Driven Activity-Based Costing." Harvard Business Review **82**(11): 131-138.

Karlsson, F. (2007). The power of real-time costing. Paper 360, TAPPI. **2:** 22-23.

Khataie, A. H., A. A. Bulgak, et al. (2010). Advanced decision support tool by integrating activity-based costing and management to system dynamics. 2010 Portland International Conference on Management of Engineering & Technology

(PICMET 2010), Place of Publication: Piscataway, NJ, USA; Phuket, Thailand. Country of Publication: USA., IEEE.

Latshaw, C. A. and T. M. Cortese-Danile (2002). "Activity-based costing: Usage and pitfalls." Review of Business **23**(1): 30-32.

Liu, J., Q. Chang, et al. (2012). "The Costs of Downtime Incidents in Serial Multistage Manufacturing Systems." Journal of Manufacturing Science & Engineering **134**(2): 021016-021011-021016-021010.

Macedo, J., R. Ruiz Usano, et al. (1997). A real time cost monitoring system for business process reengineering. Manufacturing Systems: Modelling, Management and Control (MIM'97). Proceedings from IFAC Workshop, Vienna, Austria.

Mintel Group (2009) "Mintel predicts global consumer trends for 2010."

Nachtmann, H. and M. H. Al-Rifai (2004). "An Application of Activity Based Costing in the Air Conditioner Manufacturing Industry." Engineering Economist **49**(3): 221-236.

Oh, S.-C. and A. J. Hildreth (2013). "Decisions on Energy Demand Response Option Contracts in Smart Grids Based on Activity-Based Costing and Stochastic Programming." Energies (19961073) **6**(1): 425-443.

Öker, F. and H. Adigüzel (2010). "Time-driven activity-based costing: An implementation in a manufacturing company." Journal of Corporate Accounting & Finance (Wiley) **22**(1): 75-92.

Paranko, J. (1996). "Cost of free capacity." International Journal of Production Economics **46/47**(3): 469-476.

Pascual, R., V. Meruane, et al. (2007). "On the effect of downtime costs and budget constraint on preventive and replacement policies." Reliability Engineering and System Safety **93**: 144-151.

Romaniw, Y. A. (2010). An Activity Based Method for Sustainable Manufacturing Modeling and Assessments in SysML. Master of Science in Mechanical Engineering, Georgia Institute of Technology.

Savitz, A. W. and K. Weber (2006). The Triple Bottom Line : How Today's Best-Run Companies Are Achieving Economic, Social, and Environmental Success-And How You Can Too. San Francisco, CA, Jossey-Bass.

Simmons, T. (2005). "Dynamic costing: ABC for a new generation." Accountancy SA: 27-29.

Slaper, T. F. and T. J. Hall (2011) "The Triple Bottom Line: What Is It and How Does It Work?" Indiana Business Review **86**.

Tanış, V. N. and H. Özyapıcı (2012). "The Measurement and Management of Unused Capacity in a Time Driven Activity Based Costing System." Journal of Applied Management Accounting Research **10**(2): 43-55.

Tse, M. S. C. and M. Z. Gong (2009). "Recognition of Idle Resources in Time-Driven Activity-Based Costing and Resource Consumption Accounting Models." Journal of Applied Management Accounting Research **7**(2): 41-54.

U.S. Energy Information Administration. (2013). "How much carbon dioxide (CO2) is produced when different fuels are burned?", from http://www.eia.gov/tools/faqs/faq.cfm?id=73&t=11.

U.S. Environmental Protection Agency. (1998). "Natural Gas Combustion." from http://www.epa.gov/ttnchie1/ap42/ch01/final/c01s04.pdf.

U.S. Environmental Protection Agency. (2009). "How clean is the electricity I use? - Power Profiler." from http://www.epa.gov/cleanenergy/energy-and-you/how-clean.html.

U.S. Environmental Protection Agency. (2013). "Clean Energy: Natural Gas." from http://www.epa.gov/cleanenergy/energy-and-you/affect/natural-gas.html.

Wilgenbusch, B. (2001). Developing an Information Management System for an Environmental and Economic Monitoring System. Master of Science in Mechanical Engineering, Georgia Institute of Technology.

Zeng, B., R. Wang, et al. (2012). "Cost estimation model based on improved spreadsheet algorithm for assembly line manufacturing systems." Advanced Materials Research **490-495**(490-495): 2173-2177.