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The Costs and Benefits of Advanced Maintenance in Manufacturing

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National Institute of
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Applied Economics Office
Engineering Laboratory

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U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
Walter Copan, NIST Director and Under Secretary of Commerce for Standards and Technology

Photo Credit: The Chrysler 200 Factory Tour, an interactive online experience using Google Maps Business View technology, takes consumers inside the new 5-million-square-foot Sterling Heights Assembly Plant for a behind-the-scenes peek at how the 2015 Chrysler 200 is built.
http://media.fcanorthamerica.com/homepage.do?mid=1

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Executive Summary

The manufacturing atmosphere is continually changing with new technologies and standards being swiftly developed. Firms create competitive advantages using their knowledge, skills, supply chains, and processes to create superior products at lower prices. In such a competitive environment, efficient machinery maintenance methods can mean the difference between a thriving profitable firm and one that loses money and sales. Currently, at the national level there is limited understanding of the costs and losses associated with machinery maintenance or the different machinery maintenance techniques. This report examines the literature and data available for estimating the costs and losses relevant to different manufacturing maintenance techniques. It extends further to identify the data needed for making such estimates and the feasibility of collecting the relevant data. This report focuses on, but is not limited to, four categories of manufacturing: machinery, computer and electronic products, electrical equipment, and transportation equipment manufacturers.

Census data estimates that $50 billion was spent on maintenance and repair in 2016; however, this represents outsourcing of maintenance and repair, including that for buildings. It excludes internal expenditures on labor and materials. Estimates for maintenance costs made in journals and articles use a wide range of metrics. For instance, some articles discuss the percent of cost of goods sold, percent of sales, cost of ownership, or cost of manufacturing. Additionally, the values provided have a wide range. For example, maintenance is estimated to be between 15 % and 70 % of the cost of goods sold. The estimates are made using data from various countries, which may or may not have similarities to the US. A rough estimate of machinery maintenance costs might be made using a combination of datasets from the US Census Bureau and Bureau of Economic Analysis. This would include labor and material costs for maintenance and repair of machinery but would exclude items such as losses and downtime.

The potential effect on maintenance costs from adopting predictive maintenance techniques is not well documented at the national level. The estimates that have been made at the firm level show the impacts of predictive maintenance have a wide range of metrics and, within each metric, a wide range of values. These studies originate from various countries. There are estimates for the reduction in maintenance costs, defects, breakdowns, accidents, and downtime along with estimates of the increase in productivity and output. The reduction in maintenance cost can range from 15 % to 98 % and the return on investment is, generally, estimated to be favorable.

A number of data items would need to be collected to estimate the costs and losses associated with maintenance at the national level, including the following:

- Direct maintenance and repair costs (discussed in Section 3.1)
    - Labor (discussed in Section 3.1)
    - Materials (discussed in Section 3.1)
- Indirect costs (discussed in Section 3.2 through 3.4)
    - Downtime (discussed in Section 3.2)

    - Lost sales due to quality/delays (discussed in Section 3.3)
    - Rework/defects (discussed in Section 3.4)
- Separating maintenance types (i.e., predictive, preventive, and reactive) (discussed in Section 3.5)
- Sample size needed for data collection (discussed in Section 3.6)

Direct maintenance and repair costs include the cost of labor and materials, along with cascading effects, which refers to subsequent damage caused by a breakdown of a machine (i.e., repair). Downtime includes the capital and labor costs that are the result of downtime related to maintenance. Rework/defects is the lost revenue or additional expenditures associated with defects that result from maintenance issues. Downtime due to maintenance issues might have an impact on inventory costs, which are not examined in this study. Each of the costs and losses must be separated into the different maintenance techniques utilizing the insight of maintenance personnel.

Data collection requires that manufacturers are willing and able to provide data and that there is a sufficient survey sample size that represents the manufacturing sectors as a whole. Depending on the standard deviation, confidence interval, and accepted margin of error, a sample size of 77 is estimated, but could reasonably range from 14 to 140. Discussions with manufacturing maintenance personnel suggested that they are willing and able to provide estimates or approximations of the data needed for estimating the manufacturing costs/losses relevant to advanced maintenance techniques. However, some discussants expressed uncertainty about the willingness to provide some of the data. Some items were not tracked; however, most believed that an approximation could be provided in these cases.

1. Introduction

Trade associations and public research efforts in manufacturing have benefits to both producers and consumers. That is, research efforts improve the efficiency in both the production and use of products. Costs and losses are reduced for manufacturers (i.e., efficiency in production) while consumers have reliable long-lasting energy efficient products at lower prices (i.e., efficiency in product function). Manufacturing research efforts can and often are described in varying ways, such as improving quality, reliability, improving the quality of life, or even competitiveness, but these descriptors, generally, amount to reducing resource consumption for producers and consumers. In addition to resources in the form of inputs, there are also unintended negative impacts of producing and using products, such as air pollution, which affect third-parties. These negative impacts are often referred to as negative externalities and efforts to improve efficiency (both in production and use) frequently aim to reduce these impacts.

Figure 1.1 illustrates the potential areas of efficiency improvement in the production economy, both in product production and function. Inputs and negative externalities are represented in red with down arrows indicating an intended decrease in these items. Inputs for production can include items such as electricity to operate machinery. Inputs for the function of a product include items such as fuel for an automobile or electricity for a computer. Output and product function are represented in green with up arrows indicating an intended increase. Output includes

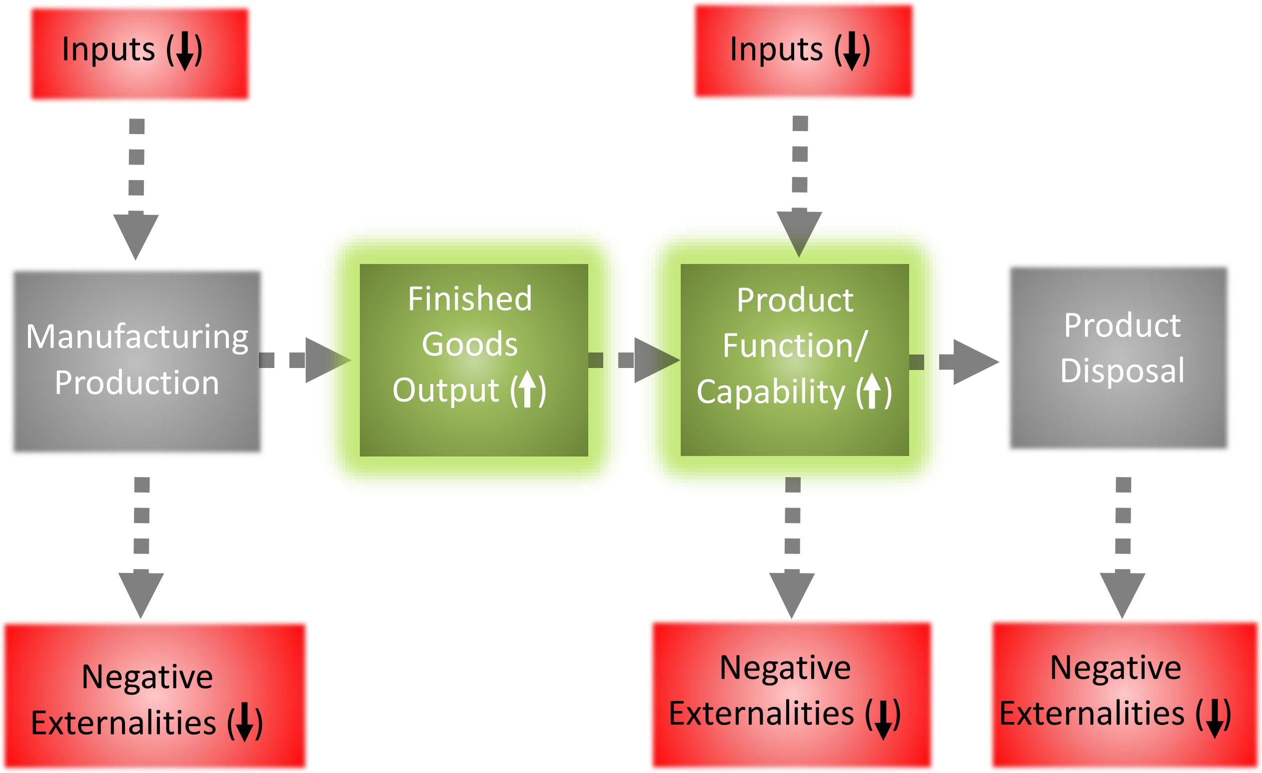

Figure 1.1: Mechanisms to Improve Efficiency in the Life-Cycle of a Product

the volume of finished goods. Product function/capability includes product reliability and longevity. The envisioned result of efficiency improvements is an increase in the quality and quantity of production at lower per unit costs and environmental impacts that benefits both producers and consumers. These types of productivity advancements facilitate sustained economic growth that increases average personal income (e.g., profit and/or compensation).[1]

An enabling research effort to advance manufacturing process efficiency is ongoing at the National Institute of Standards and Technology (NIST) where personnel are engaged in creating standards that ultimately reduce the costs and losses associated with maintenance within manufacturing environments. This effort aims to promote the adoption of advanced maintenance techniques that harness data analytics. In 2016, US manufacturers spent $50 billion on reported maintenance and repair, making it a significant part of total operating costs. Maintenance is also associated with equipment downtime and other losses including lost productivity. Currently, there is limited data on the total cost of manufacturing equipment maintenance at the national level. National data collected by the Census Bureau and Bureau of Labor Statistics does not create a complete accounting of maintenance costs.[2,3] Additionally, there is very limited data on the extent of downtime at the national level, such as the downtime caused by reactive maintenance.

Manufacturing environments are continually changing with new technologies and standards being developed rapidly. Firms create competitive advantages using their knowledge, skills, supply chains, and processes to create superior products at lower prices. In such a competitive environment, efficient maintenance methods can mean the difference between a thriving profitable firm and one that loses money and sales. Maintenance can affect product quality, capital costs, labor costs, and even inventory costs amounting to efficiency losses to both the producer and consumer. Understanding these costs and investing in advanced maintenance methods can advance the competitiveness of US manufacturers. NIST efforts in maintenance research seeks to create standards that reduce the costs and losses associated with maintenance in manufacturing environments. It aims to facilitate the adoption of advanced maintenance techniques, including determining the most advantageous balance between predictive, preventive, and reactive maintenance methods. Reactive maintenance occurs when a manufacturer runs their machinery until it breaks down or needs repairs and preventive maintenance is scheduled based upon pre-determined units (e.g., machine run time or cycles). Predictive maintenance is scheduled based on predictions of failure made using observed data such as temperature, noise, and vibration.

This report investigates the data available from public sources and in the literature on the total cost of manufacturing maintenance, including data on separating those costs into planned and unplanned maintenance. It also investigates the feasibility of collecting data to measure maintenance costs and separate costs by firm size. This area of investigation includes identifying whether manufacturers can provide information to estimate and separate maintenance costs. This effort requires consulting literature on the data collected at manufacturing facilities and consulting industry experts.

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[1] Weil, David N. Economic Growth. United States: Pearson Education Inc., 2005. 181

[2] Census Bureau. “Economic Census.” https://www.census.gov/EconomicCensus

[3] Census Bureau. “Annual Survey of Manufactures.” https://www.census.gov/programs-surveys/asm/about.html

2. Literature and Data Overview

2.1. Literature on Predictive Maintenance Economics

A number of terms have been used to discuss the use of digital technologies in manufacturing, including smart manufacturing, digital manufacturing, cloud manufacturing, cyber-physical systems, the industrial internet-of-things, and Industry 4.0.[4,5,6] One of the applications of digital technologies is in the area of maintenance, which appears to have a significant amount of terminology for discussing similar activities. The three maintenance types that are, generally, referenced in this report include the following:

- **Predictive maintenance**, which is analogous to condition-based maintenance, is initiated based on predictions of failure made using observed data such as temperature, noise, and vibration.
- **Preventive maintenance**, which is related to scheduled maintenance and planned maintenance, is scheduled, timed, or based on a cycle
- **Reactive maintenance**, which is related to run-to-failure, corrective maintenance, failure-based maintenance, and breakdown maintenance, is maintenance done, typically, after equipment has failed or stopped.

In addition to these maintenance strategies, there are other maintenance strategy terms, including maintenance prevention, reliability centered maintenance, productive maintenance, computerized maintenance, total predictive maintenance, and total productive maintenance, each with their own characteristics and focus. Some of the terms are not used consistently in the literature. For instance, Wang et al. discuss time-based, condition-based, and predictive maintenance as subcategories of preventive maintenance while others tend to discuss predictive and condition-based maintenance as being separate.[7] This report will primarily rely on the terms predictive, preventive, and reactive maintenance; however, other terms are occasionally discussed in relation to the maintenance literature being referenced.

Maintenance Costs: Manufacturing maintenance costs are estimated to be between 15 % and 70 % of the cost of goods produced, as shown in Table 2-1; however, some portion of these costs include non-maintenance expenditures such as modifications to capital systems.[8,9] Alsyouf estimates that in Sweden 37 % of the manufacturing maintenance budget is salaries for

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[4] Helu, Moneer and Brian Weiss. “The Current State of Sensing, Health Management, and Control for Small-to-Medium-Sized Manufacturers.” Proceedings of the ASME 2016 International Manufacturing Science and Engineering Conference. (June 27 – July 1, 2016). Blacksburg, VA: 1-9. http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=2558727

[5] Jin, Xiaoning, David Siegel, Brian A. Weiss, Ellen Gamel, Wei Wang, and Ni Jun. “The Present Status and Future Growth of Maintenance in US Manufacturing: Results from a Pilot Survey.” Manufacturing Review. 3 (2016): 1-10.

[6] Jin, Xiaoning, Brian A. Weiss, David Siegel, Jay Lee, Jun Ni. “Present Status and Future Growth of Advanced Maintenance Technology Strategy in US Manufacturing. 7, Issue 12 (2016): 1-18.

[7] Wang, Ling, Jian Chu, Jun Wu. “Selection of Optimum Maintenance Strategies Based on a Fuzzy Analytic Hierarchy Process.” International Journal of Production Economics. 107, no 1 (2007): 151-163.

[8] Mobley, R. Keith. An Introduction to Predictive Maintenance. (Woburn, MA: Elsevier Science, 2002). 1.

[9] Bevilacqua, M. and M. Braglia. “The Analytic Hierarchy Process Applied to Maintenance Strategy Selction.” Reliability Engineering and System Safety. 70, no 1 (2000): 71-83.

maintenance staff with spare parts being another 32 %, as seen in Figure 2.1. Komonen estimates that industrial maintenance is 5.5 % of company turnover (i.e., sales); however, it varies from 0.5 % to 25 %, as shown in Table 2-1.[10,11] Another paper showed that maintenance is 37.5 % of the total cost of ownership, which is also in the table.[12] Eti et al. estimates that in the chemical industry annual maintenance cost is approximately 1.8 % to 2.0 % of the replacement value of the plant and in "poorly managed" operations it could be as high as 5 %.[13] It is estimated that, approximately, one third of maintenance costs are unnecessary or improperly carried out.[14] For instance, preventive maintenance is estimated to be applied unnecessarily up to 50 % of the time in manufacturing.[15] Tabikh estimates from survey data in Sweden that downtime costs amount to 23.9 % of the total cost of manufacturing.[16] He also estimates that the percent of planned production time that is downtime amounts to 13.3 %.[17]

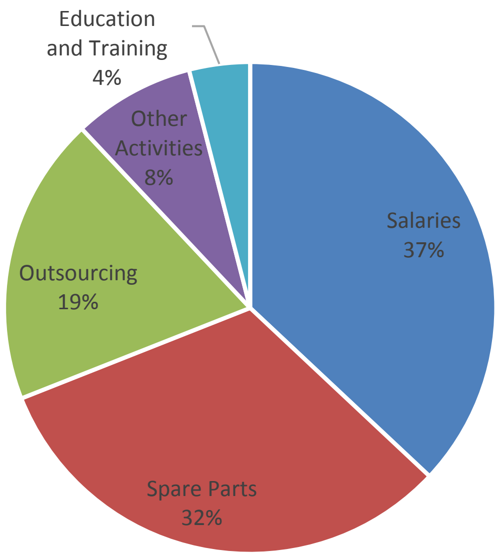

Figure 2.1: Manufacturing Maintenance Budget Distributions, Sweden

Source: Alsyouf, Imad. Cost Effective Maintenance for Competitive Advantages. Phd Thesis. Växjö University Press. 2004. https://www.diva-portal.org/smash/get/diva2:206693/FULLTEXT01.pdf

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[10] Komonen, Kari. "A Cost Model of Industrial Maintenance for Profitability Analysis and Benchmarking." International Journal of Production Economics. 79 (2002): 15-31.

[11] Komonen, "A Cost Model," 15-31.

[12] Herrmann, C., S. Kara, S. Thiede. "Dynamic Life Cycle Costing Based on Lifetime Prediction." International Journal of Sustainable Engineering. 4, no 3 (2011): 224-235.

[13] Eti, M.C., S.O.T. Ogaji, and S.D. Probert. "Reducing the Cost of Preventive Maintenance (PM) through Adopting a Proactive Reliability-Focused Culture." Applied Energy. 83 (2006): 1235-1248.

[14] Mobley, An Introduction to Predictive Maintenance, 1.

[15] Vogl, Gregory, Brian Weiss, Moneer Helu. "A Review of Diagnostic and Prognostic Capabilities and Best Practices for Manufacturing." Journal of Intelligent Manufacturing. (2016): 1-17. https://doi.org/10.1007/s10845-016-1228-8

[16] Tabikh, Mohamad. "Downtime Cost and Reduction Analysis: Survey Results." Master Thesis. KPP321. Mälardalen University. (2014). http://www.diva-portal.org/smash/get/diva2:757534/FULLTEXT01.pdf

[17] Tabikh, "Downtime Cost and Reduction."

Table 2-1: Characteristics of Maintenance Costs from a Selection of Articles, Various Countries/Industries

	Maintenance	
Description	Low	High
Cost of Goods Sold[a,b]	15.0%	70.0%
Sales[c]	0.5%	25.0%
Cost of Ownership[d]	37.5%	
Replacement Value of Plant[e]	1.8%	5.0%
Cost of Manufacturing[f]	23.9%	
Percent of Planned Production Time that is Downtime[f]	13.3%	

Sources: [a]Mobley, R. Keith. An Introduction to Predictive Maintenance. (Woburn, MA: Elsevier Science, 2002). 1.
[b]Bevilacqua, M. and M. Braglia. "The Analytic Hierarchy Process Applied to Maintenance Strategy Selection." Reliability Engineering and System Safety. 70, no 1 (2000): 71-83.
[c]Komonen, Kari. "A Cost Model of Industrial Maintenance for Profitability Analysis and Benchmarking." International Journal of Production Economics. 79 (2002): 15-31.
[d]Herrmann, C., S. Kara, S. Thiede. "Dynamic Life Cycle Costing Based on Lifetime Prediction." International Journal of Sustainable Engineering. 4, no 3 (2011): 224-235.
[e]Eti, M.C., S.O.T. Ogaji, and S.D. Probert. "Reducing the Cost of Preventive Maintenance (PM) through Adopting a Proactive Reliability-Focused Culture." Applied Energy. 83 (2006): 1235-1248.
[f]Tabikh, Mohamad. "Downtime Cost and Reduction Analysis: Survey Results." Master Thesis. KPP321. Mälardalen University. (2014). http://www.diva-portal.org/smash/get/diva2:757534/FULLTEXT01.pdf

Benefits of Predictive Maintenance: Total productive maintenance (TPM) is a program that aims for zero breakdowns and zero defects and focuses on eliminating six losses: equipment breakdown, setup and adjustment slowdowns, idling and short-term stoppages, reduced capacity, quality-related losses, and startup/restart losses. Generally, TPM tends to include predictive maintenance strategies. Overall equipment effectiveness (OEE) is a metric commonly used by manufacturers and for TPM. OEE is defined as[18,19]:

$$OEE = Availability \times Performance\ Rate \times Quality\ Rate$$

where

$$Availability = \frac{Required\ Availability - Downtime}{Required\ Availability} \times 100$$

$$Performance\ Rate = \frac{Design\ Cycle\ Time \times Output}{Operating\ Time} \times 100$$

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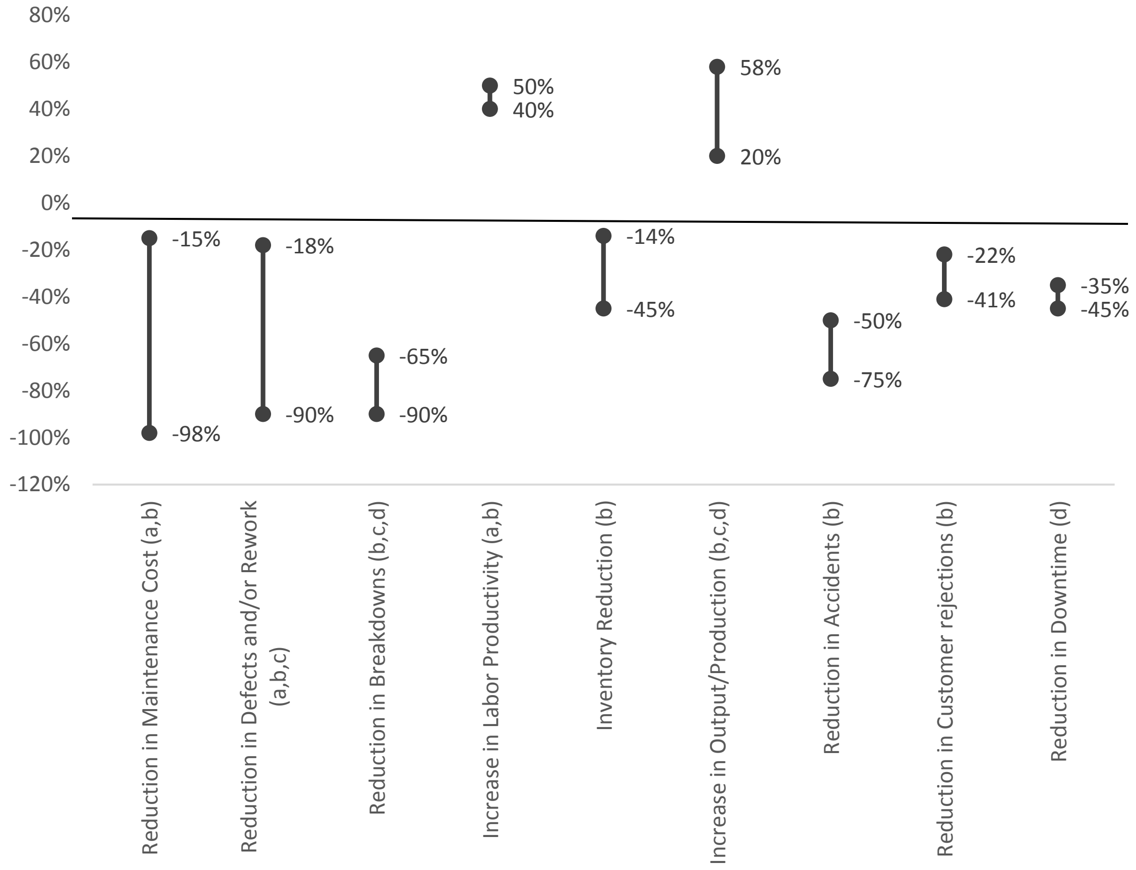
[18] Mobley, An Introduction to Predictive Maintenance, 6-7.
[19] International Organization for Standardization. ISO 22400-2:2014(E). Automation Systems and Integration – Key Performance Indicators (KPIs) for Manufacturing Operations Management – Part 2: Definitions and Descriptions.

$$Quality\ Rate = \frac{Production\ Input - Quality\ Defects}{Production\ Input} \times 100$$

Some implementations of advanced maintenance techniques have been shown to have a range of impacts on a number of areas, as shown in Figure 2.2.[20,21,22] Ahuja and Khamba suggest that most companies can reduce their maintenance costs by a third through advanced maintenance.

Figure 2.2: Range of Impacts Identified in Various Publications for Implementing Advanced Maintenance Techniques, Percent Change



Sources: [a]Nakajima, S. Introduction to Total Productive Maintenance (TPM). (Portland, OR: Productivity Press, 1988).

[b]Ahuja, I.P.S. and J.S. Khamba. "Total Productive Maintenance: Literature Review and Directions." International Journal of Quality and Reliability Management. 25, no 7 (2008): 709-756.

[c]Chowdhury, C. "NITIE and HINDALCO give a new dimension to TPM." Udyog Pragati, Vol. 22 No. 1, (1995): 5-11.

[d]Federal Energy Management Program. Operations and Maintenance Best Practices: A Guide to Achieving Operational Efficiency. (2010). https://energy.gov/sites/prod/files/2013/10/f3/omguide_complete.pdf

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[20] Nakajima, S. Introduction to Total Productive Maintenance (TPM). (Portland, OR: Productivity Press, 1988).

[21] Ahuja, I.P.S. and J.S. Khamba. "Total Productive Maintenance: Literature Review and Directions." International Journal of Quality and Reliability Management. 25, no 7 (2008): 709-756.

[22] Federal Energy Management Program. Operations and Maintenance Best Practices: A Guide to Achieving Operational Efficiency. (2010). https://energy.gov/sites/prod/files/2013/10/f3/omguide_complete.pdf

techniques.[23] Barajas and Srinivasa identify that investment in advanced maintenance techniques has had a return on investment of 10:1.[24,25] The cost characteristics of different maintenance types is characterized in Table 2-2, which is drawn from Barajas and Srinivasa and two papers by Jin et al. Reactive maintenance has high labor and parts cost. It is considered not cost effective. Predictive maintenance has relatively low maintenance labor and medium parts costs along with having significant costs savings.[26]

Table 2-2: Characteristics of Maintenance by Type

	Maintenance Type		
	Reactive	Preventive	Predictive
Frequency	On Demand	Scheduled, Timed, or Cycle Based	Condition Based
Labor Cost	High	High	Low
Labor Utilization	High	Low	Low
Parts Cost	High	Medium	Medium
Throughput Impact	High	Medium	Very Low
Urgency	High	Low	Low
ROI	Low	Medium	High
Initial Investment	Low	Medium	High
Profitability	Not cost effective	Satisfactory cost-effectiveness	Significant cost savings
Cost effectiveness	Labor intensive	Costly due to potential over maintenance or ineffective & inefficient maintenance	Cost-effective due to extended life and less failure-induced costs

Sources: Barajas, Leandro and Narayan Srinivasa. "Real-Time Diagnostics, Prognostics and Health Management for Large-Scale Manufacturing Maintenance Systems" Proceedings of the 2008 International Manufacturing Science and Engineering Conference. October 7-10, 2008. Evanston IL.
Jin, Xiaoning, David Siegel, Brian A. Weiss, Ellen Gamel, Wei Wang, and Ni Jun. "The Present Status and Future Growth of Maintenance in US Manufacturing: Results from a Pilot Survey." Manufacturing Review. 3 (2016): 1-10.
Jin, Xiaoning, Brian A. Weiss, David Siegel, Jay Lee, Jun Ni. "Present Status and Future Growth of Advanced Maintenance Technology Strategy in US Manufacturing. 7, Issue 12 (2016): 1-18.

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[23] Ahuja, "Total Productive Maintenance," 709-756.

[24] Barajas, Leandro and Narayan Srinivasa. "Real-Time Diagnostics, Prognostics and Health Management for Large-Scale Manufacturing Maintenance Systems" Proceedings of the 2008 International Manufacturing Science and Engineering Conference. Evanston IL. (October 7-10, 2008): 85-94.

[25] Federal Energy Management Program. Operations and Maintenance Best Practices.

[26] Barajas, "Real-Time Diagnostics," 85-94

A case study by Feldman et al. estimated a return on investment ratio of 3.5:1 for moving from reactive maintenance to predictive maintenance on an electronic multifunctional display system within a Boeing 737.[27] Although this is not maintenance on manufacturing machinery, it is a piece of equipment where there is regular use and reliability is important. An examination of train car wheel failures showed a potential cost savings of up to 56 % of the associated costs when switching from a reactive maintenance approach to a predictive maintenance approach.[28,29] Again, this is not maintenance on manufacturing machinery, but it is a piece of machinery that is expected to perform regularly and there are significant losses when it fails.

Piotrowski estimates that for pumps, reactive maintenance costs $18 per horsepower per year while preventive maintenance was $13, predictive was $9, and reliability centered maintenance was $6, which combines predictive techniques with other methods.[30] Additionally, the EPA estimates that predictive maintenance can result in 15 % to 25 % increase in equipment efficiency.[31]

A different case study, where advanced manufacturing maintenance techniques were adopted along with revising changeover standards, had a total investment cost of $1.35 million[32]:

- Production consulting services = $400 000
- Maintenance consulting services = $800 000
- Skills training = $150 000

A team was developed by the plant manager to address reliability problems. Before the implementation of the project, quality losses were 9 % of production and the plant was operating at 57 % of its true capacity. After adopting advanced maintenance techniques, maintenance costs increased in the first year by 10 % but decreased in the following years. The project increased capacity to 94 % and quality losses were brought down to 4 %. This project resulted in a $17.22 million increase in revenue in the first two years. Another case study at a paper mill in Sweden, invested in advanced maintenance where annual costs increased by $45 500 on average per year. The savings from this effort amounted to $3 million in addition to $358 000 in additional profit on average annually.[33]

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[27] Feldman, Kiri, Peter Sandborn, and Taoufik Jazouli. “The Analysis of Return on Investment for PHM Applied to Electronic Systems.” Proceedings of the International Conference on Pronostics and Health Management. Denver, CO. (October 2008). http://ieeexplore.ieee.org/document/4711415/

[28] Drummond, Chris and Chunsheng Yang. “Reverse-Engineering Costs: How much will a Prognostic Algorithm Save.” (2008). https://www.semanticscholar.org/paper/Reverse-Engineering-Costs-How-much-will-a-Prognost-Drummond-Yang/d276695f10ed041e0c43f08f668019a81cd757b3

[29] Yang, Chunsheng and Sylvain Letourneau. “Model Evaluation for Prognostics: Estimating Cost Saving for the End Users.” Sixth International Conference on Machine Learning and Applications. (Dec 13-15, 2007). http://ieeexplore.ieee.org/document/4457248/

[30] Piotrowski, John. “Effective Predictive and Pro-Active Maintenance for Pumps.” Maintenance World. (January 29, 2007). http://www.maintenanceworld.com/effective-predictive-and-pro-active-maintenance-for-pumps/

[31] EPA. “Lean Thinking and Methods – TPM.” (2011). https://www.epa.gov/lean/lean-thinking-and-methods-tpm

[32] Smith, Ricky and R. Keith Mobley. Rules of Thumb for Maintenance and Reliability Engineers. (Burlington, MA: Elsevier, 2008), 20.

[33] Al-Najjar, Basim and Imad Alsyouf. “Enhancing a Company’s Profitability and Competitiveness using Integrated Vibration-Based Maintenance: A Case Study.” European Journal of Operational Research. 157. (2004): 643-657.

Bo et al identify a number of benefits of prognostics and health management, a component related to predictive maintenance, which include[34]:

- Safety: Advance warning of failure and avoiding a catastrophic failure
- Maintainability: Eliminating redundant inspections, minimizing unscheduled maintenance, and decreasing test equipment requirement
- Logistics: Improving and assisting in the design of logistical support system
- Life-cycle costs: reducing operational and support costs
- System design and analysis: Improving design and qualifications along with improving reliability prediction accuracy
- Reliability: Making products more reliable

Jin et al identified through surveys that safety, availability, and reliability are the most highly rated maintenance objectives while productivity and quality were also considered important.[35,36]

Barriers to Adoption: Although there are many instances where investment in advanced maintenance techniques has a high return on investment, it is not cost effective in all instances.[37] An estimate for the ideal level of reactive maintenance has been considered to be 30 % to 40 % of the total maintenance time (both planned and unplanned maintenance).[38,39] A survey of manufacturers in Sweden suggested that in practice it is about 50 %, albeit that this estimate is from 1997.[40] When compared to large plants, small plants tend to face unique constraints that impede substantial investment in labor, tools and training.[41]

A survey of barriers to adopting advanced maintenance strategies identified cost as the most prevalent barrier (92 % of respondents), as seen in Figure 2.3.[42,43] Technology support (69 % of respondents), human resource (62 %), and organizational readiness (23 %) were also cited. Safety and environment (92 %), availability and reliability (77 %), productivity (69 %), and quality (69 %) were cited as potential objectives for adopting advanced maintenance techniques. However, when asked what the criteria is for prioritizing which assets need prognostics and health management, ‘impact/cost of failure’ was selected more frequently over others, including safety concerns. An additional complication to the adoption of advanced maintenance techniques, is the tracking of the relevant cost factors such as breakdowns, downtime, defective

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[34] Sun, BO, Shengkui Zeng, Rui Kang, and Michael Pecht. Benefits Analysis of Prognostics in Systems. Prognostics & System Health Management Conference. 2010. http://ieeexplore.ieee.org/document/5413503/

[35] Jin, “Present Status and Future Growth.”

[36] Jin, “The Present Status and Future Growth of Maintenance in US Manufacturing,” 1-10.

[37] Wang, “Selection of Optimum Maintenance Strategies,” 151-163.

[38] Tomlingson, P.D. Effective Maintenance – The Key to Profitability. (New York, NY: Van Nostrand Reinhold Company, 1993).

[39] Wireman, T. World Class Maintenance Management. (New York, NY: Industrial Press Inc., 1990).

[40] Jonsson, Patrik. “The Status of Maintenance Management in Swedish Manufacturing Firms.” Journal of Quality in Maintenance Engineering. 3, no 4 (1997): 233-258.

[41] Mobley, An Introduction to Predictive Maintenance, 20-21.

[42] Jin, “The Present Status and Future Growth of Maintenance,” 1-10.

[43] Jin, Xiaoning, Brian Weiss, David Siegel, and Jay Lee. “Present Status and Future Growth of Advanced Maintenance Technology and Strategy in US Manufacturing.” International Journal of Prognostics and Health Management. Special Issue on Smart Manufacturing PHM. 7, no 12 (2016).

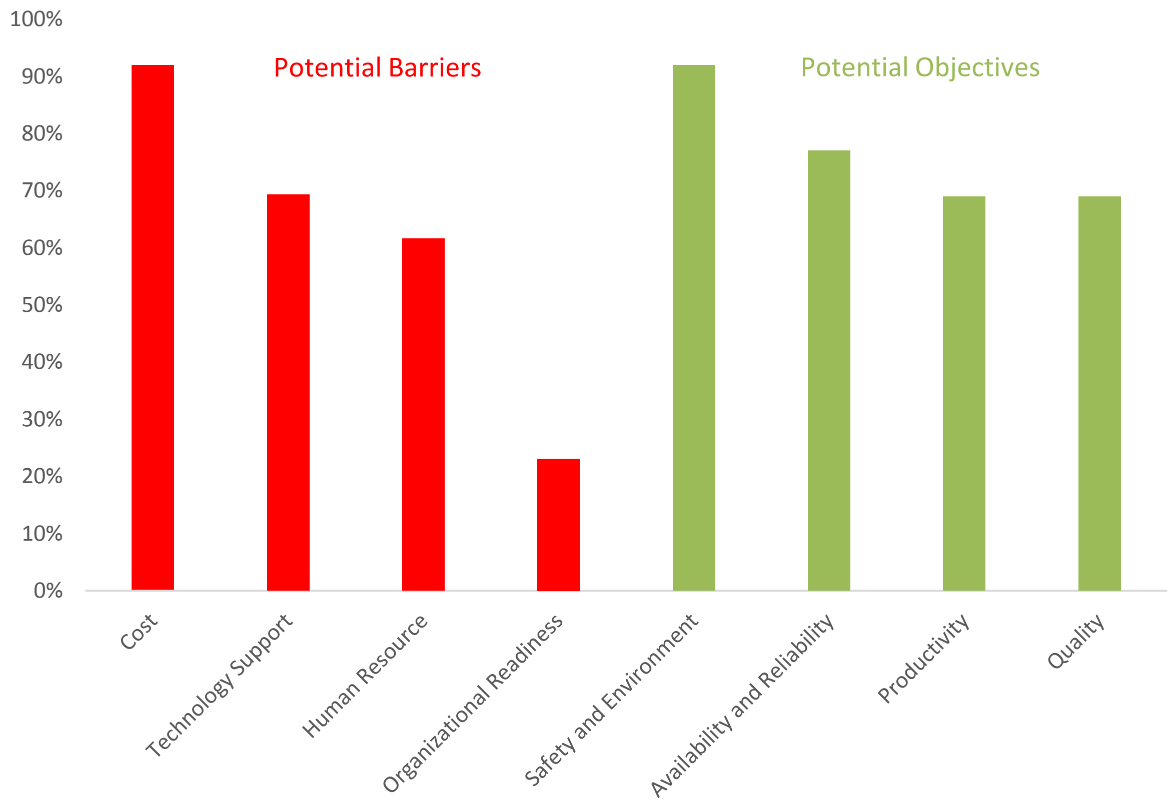

Figure 2.3: Objectives and Prevalent Barriers to the Adoption of Advanced Maintenance Techniques, Percent of Respondents

Sources: Jin, Xiaoning, Brian Weiss, David Siegel, and Jay Lee. "Present Status and Future Growth of Advanced Maintenance Technology and Strategy in US Manufacturing." International Journal of Prognostics and Health Management. Special Issue on Smart Manufacturing PHM. 7, no 12 (2016).
Jin, Xiaoning, David Siegel, Brian A. Weiss, Ellen Gamel, Wei Wang, and Ni Jun. "The Present Status and Future Growth of Maintenance in US Manufacturing: Results from a Pilot Survey." Manufacturing Review. 3 (2016): 1-10.

products, associated safety risks/incidents, reduced throughput, and excessive energy consumption. Many plants do not have reliable data on factors such as downtime and many more are unable to put an accurate cost on it.[44] Tabikh estimates, using survey data from Sweden, that 83 % do not have a model to evaluate and quantify the cost of downtime.[45] Additionally, maintenance is often treated as an overhead cost, making it difficult to associate efficiency improvements with this activity. The results of improved maintenance often get associated with other departments. These challenges make it difficult to document a justification for investments in advanced maintenance. Cost factors can include:

- Frequency and duration of breakdowns
- Overtime costs to make up for lost production

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[44] Mobley, An Introduction to Predictive Maintenance, 24-25.
[45] Tabikh, "Downtime Cost and Reduction."

- Delays in product delivery
- Repair costs
- Defective parts
- Safety
- Energy consumption
- Throughput
- Labor costs
- Inventory costs

In addition to these costs, there are the costs of purchasing, installing, and operating advanced maintenance equipment along with the costs of any associated training and labor.

Current Maintenance Practices: A study by Helu and Weiss examined the needs, priorities, and constraints of small-to-medium sized enterprises through a series of case studies.[46] The results suggest that small and medium firms might rely more heavily on reactive maintenance with limited amounts of predictive maintenance while larger firms seem to rely on preventive maintenance; however, these results are based on anecdotal evidence.[47] Barajas and Srinivasa suggest that the automobile industry has been engaged with advanced maintenance technologies for some time.[48] A survey of Swedish firms shows that the most prevalent maintenance strategy is preventive maintenance when asked about failure based maintenance (i.e., reactive maintenance), preventive maintenance, condition-based maintenance (i.e., maintenance based on monitoring), reliability-centered maintenance (i.e., asset specific maintenance to preserve system function), and total productive maintenance. Condition-based and failure-based maintenance was tied for the second most cited.[49] Swedish firms also revealed that 50 % of their maintenance time is spent on planned tasks, 37 % on unplanned tasks, and 13 % for planning. Approximately 70 % considered maintenance a cost rather than an investment or source of profit.

Companies, generally, compete either on cost or quality (quality is often referred to as differentiation or a portion of differentiation). A survey in Belgium provides insight into how competitive priorities (e.g., cost competitiveness) might influence maintenance strategies.[50] In addition to cost and quality, this survey had a third category labeled flexibility. Table 2-3 provides the number of respondents that indicated that they have a high, medium, or low level of each of the different maintenance types with the respondents being categorized by their competitive priority. For instance, in the top of the cost column (i.e., the third column) in the table, it indicates that four respondents are classified as cost competitors and have a low level of corrective maintenance. Moving down to the next row, it indicates that three respondents are cost competitors and have a medium level of corrective maintenance. The next row indicates that seven have a high level, resulting in a total of fourteen companies that are cost competitors,

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[46] Helu, "The Current State of Sensing," 1-9.
[47] Helu, "The Current State of Sensing," 1-9.
[48] Barajas, "Real-Time Diagnostics," 85-94.
[49] Alsyouf, Imad. "Maintenance Practices in Swedish Industries: Survey Results." International Journal of Production Economics. 121 (2009): 212-223.
[50] Pinjala, Srinivas Kumar, Liliane Pintelon, and Ann Vereecke. An Empirical Investigation on the Relationship between Business and Maintenance Strategies." International Journal of Production Economics. 104. (2006): 214-229.

Table 2-3: Maintenance Type by Competitive Priority (Numbers Indicate the Number of Respondents out of a Total of 46)

		Competitive Priority			
Maintenance Type	Level	Cost	Quality	Flexibility	TOTAL
Corrective Maintenance (i.e., reactive maintenance)	Low	4	5	0	9
	Medium	3	9	3	15
	High	7	7	8	22
Preventive Maintenance	Low	5	5	3	13
	Medium	5	5	8	18
	High	4	11	0	15
Predictive Maintenance	Low	5	5	3	13
	Medium	5	5	8	18
	High	4	11	0	15
TOTAL		14	21	11	46

Source: Pinjala, Srinivas Kumar, Liliane Pintelon, and Ann Vereecke. An Empirical Investigation on the Relationship between Business and Maintenance Strategies." International Journal of Production Economics. 104. (2006): 214-229.

which is indicated at the bottom of the cost column. The same respondents also indicate their level of preventive maintenance and predictive maintenance in the next six rows, which also each sum to fourteen. Companies that focus more on cost competition tend to favor corrective maintenance, as half of the respondents or seven of the fourteen respondents that prioritize cost competitiveness indicated they have a high level of corrective maintenance (i.e., reactive maintenance) and 73 % or eight of the eleven respondents that focus on flexibility indicated they had a high level of corrective maintenance. Meanwhile only a third of those that focus on quality have a high level (see Table 2-3). Approximately 52 % of companies that focus on quality indicated that they have a high level of predictive maintenance. Moreover, Table 2-3 shows that cost competitive companies along with those focusing on flexibility tend to favor reactive maintenance while those pursuing quality as a competitive priority favor preventive and predictive maintenance.

Jin et al (2017a and 2017b) found in a survey that companies are starting to consider predictive maintenance techniques with a majority of their respondents having active projects in manufacturing diagnostics and prognostics. The respondents also identified that they have had both successes and failures in diagnostics and prognostics. A little more than a quarter of the respondents indicated that they were mostly using reactive maintenance techniques.

The majority of research related to predictive maintenance focus on technological issues and, although there are some studies that incorporate economic data, these represent a minority of the literature.[51] Many of the economic assessments are individual case studies, personal insights, and other anecdotal observations. A limited number of them cite prevalent economic methods that

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[51] Grubic, Tonci, Ian Jennions, and Tim Baines. "The Interaction of PSS and PHM – A Mutual Benefit Case." Annual Conference of the Probnostics and Health Management Society. (2009). https://www.phmsociety.org/node/94

are used for investment analysis. Numerous papers present methods for examining maintenance costs, focusing on the technological aspects; however, many do not provide data or examples. This gap in the literature means that the potential benefits of widespread adoption of predictive maintenance are largely unknown or are based on anecdotal observations.

2.2. Relevant Data

There are a number of sources for aggregated data on manufacturing relevant to maintenance costs. These sources include the following:

- Annual Survey of Manufactures (Census Bureau 2018)
- Economic Census (Census Bureau 2018)
- Occupational Employment Statistics (Bureau of Labor Statistics 2018)
- Economic Input-Output Data (Bureau of Economic Analysis 2018)

These datasets are discussed in more detail below.

2.2.1. Annual Survey of Manufactures and Economic Census

The Annual Survey of Manufactures (ASM) is conducted every year except for years ending in 2 or 7 when the Economic Census is conducted. The ASM provides statistics on employment, payroll, supplemental labor costs, cost of materials consumed, operating expenses, value of shipments, value added, fuels and energy used, and inventories. It uses a sample survey of approximately 50 000 establishments with new samples selected at 5-year intervals. The ASM data allows the examination of multiple factors (value added, payroll, energy use, and more) of manufacturing at a detailed subsector level. The Economic Census, used for years ending in 2 or 7, is a survey of all employer establishments in the U.S. that has been taken as an integrated program at 5-year intervals since 1967. Both the ASM and the Economic Census use the North American Industry Classification System (NAICS); however, prior to NAICS the Standard Industrial Classification (SIC) system was used.[52,53] NAICS and SIC are classifications of industries, which are based primarily on the product produced (e.g., automobiles, steel, or toys). The categories include both intermediate and finished goods.

Together, the Annual Survey of Manufactures and the Economic Census provide annual data on manufacturing, including value added and capital. Value added is equal to the value of shipments less the cost of materials, supplies, containers, fuel, purchased electricity, and contract work. It is adjusted by the addition of value added by merchandising operations plus the net change in finished goods and work-in-process goods. Value added avoids the duplication caused from the use of products of some establishments as materials. It is important to note that the Bureau of Economic Analysis (BEA), which is a prominent source of data on value added, and the ASM calculate value added differently. The BEA calculates value added as “gross output (sales or receipts and other operating income, plus inventory change) less intermediate inputs

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[52] Census Bureau. “Annual Survey of Manufactures.” <https://www.census.gov/programs-surveys/asm.html />

[53] Census Bureau. “Economic Census.” <https://www.census.gov/EconomicCensus>

(consumption of goods and services purchased from other industries or imported)."[54] Moreover, the difference is that ASM's calculation of value added includes purchases from other industries such as mining and construction while BEA's does not include it. Although these two provide data on maintenance and repair, the estimates are for both buildings and machinery. The data that might be of more use is the data they provide to calculate the cost of goods sold and inventory data, which can be used to calculate material flow time.

2.2.2. County Business Patterns

The County Business Patterns series extracts data from the Business Register, a database of companies maintained by the US Census Bureau. The annual Company Organization Survey is used to provide establishment data for multi-establishment companies while several sources such as the Economic Census, Annual Survey of Manufactures, and Current Business Survey are used to assemble data on single-establishment companies. The County Business Pattern data is assembled annually. This data provides payroll and the number of establishments by employee by industry (see Figure 2.4). The industries of primary concern for this paper include the following NAICS codes, as defined by the US Census Bureau[55]:

- NAICS 333: Machinery Manufacturing – "Industries in the machinery manufacturing subsector create end products that apply mechanical force, for example, the application of gears and levers, to perform work."
- NAICS 334: Computer and Electronic Product Manufacturing – "Industries in the computer and electronic product manufacturing subsector group establishments that manufacture computers, computer peripherals, communications equipment, and similar electronic products, and establishments that manufacture components for such products."
- NAICS 335: Electrical Equipment, Appliance, and Component Manufacturing – "Industries in the electrical equipment, appliance, and component manufacturing subsector manufacture products that generate, distribute and use electrical power. Electric lighting equipment manufacturing establishments produce electric lamp bulbs, lighting fixtures, and parts. Household appliance manufacturing establishments make both small and major electrical appliances and parts. Electrical equipment manufacturing establishments make goods, such as electric motors, generators, transformers, and switchgear apparatus. Other electrical equipment and component manufacturing establishments make devices for storing electrical power (e.g., batteries), for transmitting electricity (e.g., insulated wire, and wiring devices (e.g., electrical outlets, fuse boxes, and light switches)."
- NAICS 336: Transportation Equipment Manufacturing – "Industries in the transportation equipment manufacturing subsector produce equipment for transporting people and goods. Transportation equipment is a type of machinery. An entire subsector is devoted to this activity because of the significance of its economic size in all three North American countries."

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[54] Horowitz, Karen J. and Mark A. Planting "Concepts and Methods of the U.S. Input-Output Accounts." (2009): Glossary-32. http://www.bea.gov/papers/pdf/IOmanual_092906.pdf

[55] Census Bureau. "North American Industry Classification System." https://www.census.gov/eos/www/naics

According to the most recently released data, which is for 2015, there are 54 022 establishments in NAICS codes 333-336.

2.2.3. Occupational Employment Statistics

The Occupational Employment Statistics program at the Bureau of Labor Statistics provides data on employment and wages for over 800 occupations categorized by the Standard Occupation Classification SOC) system and by NAICS code. This data has 52 categories of maintenance workers with one of them being machinery maintenance. Since the data is categorized by both occupation and industry, it is possible to estimate the amount of manufacturing maintenance labor by industry.

2.2.4. Economic Input-Output Data

Annual input-output data is available from the BEA for the years 1998 through 2016. Prior to 1998, the data is available for every fifth year starting in 1967. There is also data available for the years 1947, 1958, and 1963. More detailed data is available for years ending in two or seven. The input-output accounts provide data to analyze inter-industry relationships. BEA input-output data is provided in the form of make and use tables. Make tables show the production of

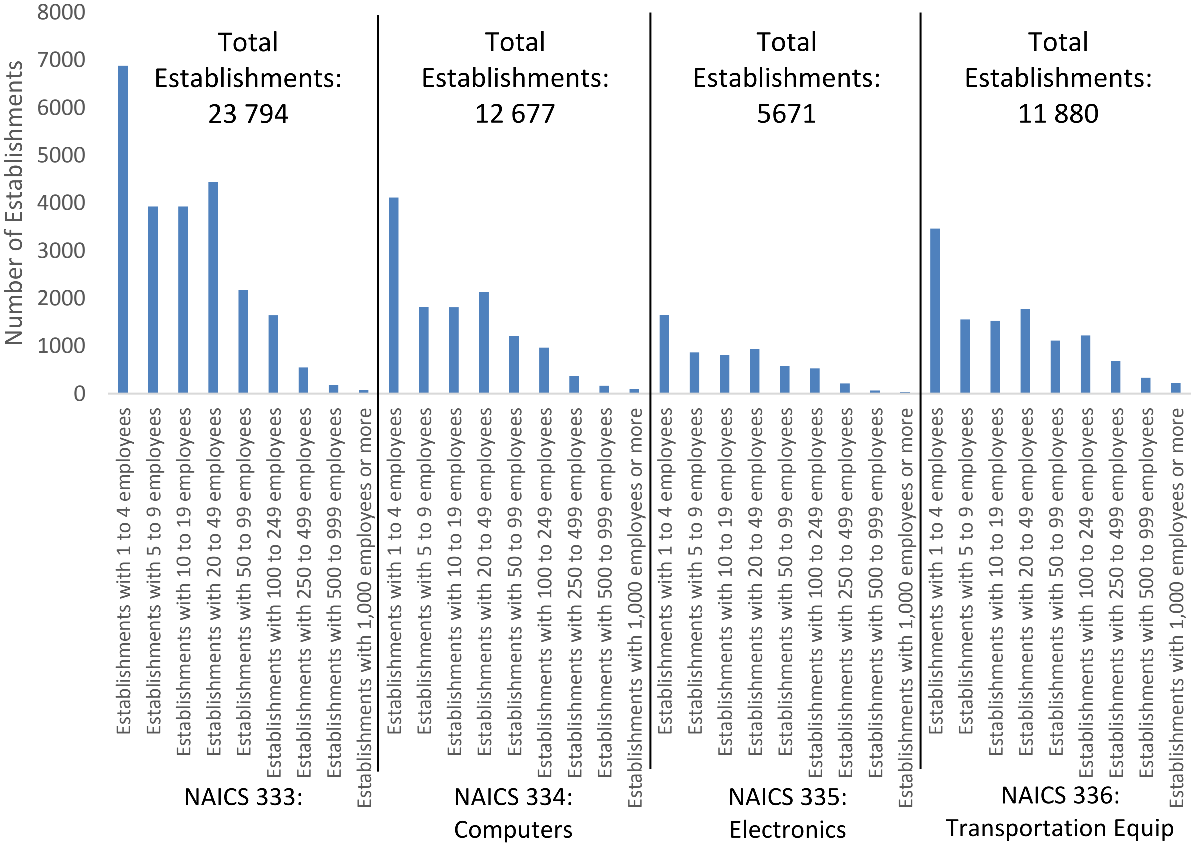

Figure 2.4: Number of Establishments by Employment, 2015

Source: Census Bureau. “Economic Census.” 2018. <https://www.census.gov/EconomicCensus>

commodities (products) by industry. Use tables show the components required for producing the output of each industry. There are two types of make and use tables: “standard” and “supplementary.” Standard tables closely follow NAICS and are consistent with other economic accounts and industry statistics, which classify data based on establishment. Note that an “establishment” is a single physical location where business is conducted. This should not be confused with an “enterprise” such as a company, corporation, or institution. Establishments are classified into industries based on the primary activity within the NAICS code definitions. Establishments often have multiple activities. For example, a hotel with a restaurant has income from lodging (a primary activity) and from food sales (a secondary activity). An establishment is classified based on its primary activity. Data for an industry reflects all the products made by the establishments within that industry; therefore, secondary products are included. Supplementary make-use tables reassign secondary products to the industry in which they are primary products.[56,57] The make-use tables are used for input-output analysis as developed by Leontief.[58,59]

The BEA benchmark input-output tables (detailed data), which are produced every five years, contains the purchases that manufacturing industries make from establishments categorized as NAICS code “811300: Commercial and industrial machinery and equipment repair and maintenance.” These purchases represent the value of outsourcing for manufacturing maintenance.

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[56] Over the years BEA has made improvements to its methods. This includes redefining secondary products. The data discussed in this section utilizes the data BEA refers to as “after redefinitions.”

[57] Horowitz, “Concepts and Methods,” 4.1-4.10.

[58] Horowitz, “Concepts and Methods,” 1.5.

[59] Miller, Ronald E. and Peter D. Blair. Input-Output Analysis: Foundations and Extensions. (New York, NY: Cambridge University Press, 2009): 16.

3. Potential Methods and Data Needs

Maintenance costs can be classified into a series of subcategories, which include labor, materials, and indirect costs. Indirect are defined in this report as including costs that result from maintenance or a lack thereof (e.g., downtime). Figure 3.1 details the different maintenance cost categories and highlights data needs in red. No data has been identified to separate maintenance costs into predictive, preventive, and reactive categories; thus, these are shown in red. As discussed previously, labor data is available on maintenance occupations from the Bureau of Labor Statistics. Additionally, input-output data contains information about maintenance purchases. The following sections discuss methods for estimating the costs and losses associated with maintenance, including the following:

- Direct maintenance and repair costs (Section 3.1)
    - Labor (Section 3.1)
    - Materials (Section 3.1)
- Indirect costs (Section 3.2 through 3.4)
    - Downtime (Section 3.2)
    - Lost sales due to quality/delays (Section 3.3)
    - Rework/defects (Section 3.4)
- Separating maintenance types (i.e., predictive, preventive, and reactive) (Section 3.5)
- Sample size needed for data collection (Section 3.6)

Direct maintenance and repair costs include the cost of labor and materials in Figure 3.1, along with cascading effects, which refers to subsequent damage caused by a breakdown of a machine (i.e., repair). Downtime includes the capital and labor costs that are the result of downtime related to maintenance. Rework/defects is the lost revenue or additional expenditures associated with defects that result from maintenance issues. Assessing the increased inventory is not pursued in this study. This study aims to gather data from maintenance personnel, who may have limited insight on the increase in inventories required due to variations in output. Separating costs and losses into the different methods of maintenance is discussed in its own section (i.e., Section 3.5) since each of the different cost/loss types will be treated in a similar fashion.

3.1. Direct Maintenance and Repair Costs

There are two methods to estimate direct maintenance costs. The first is to survey manufacturers and ask them to estimate these costs. The responses would then be scaled-up using industry data

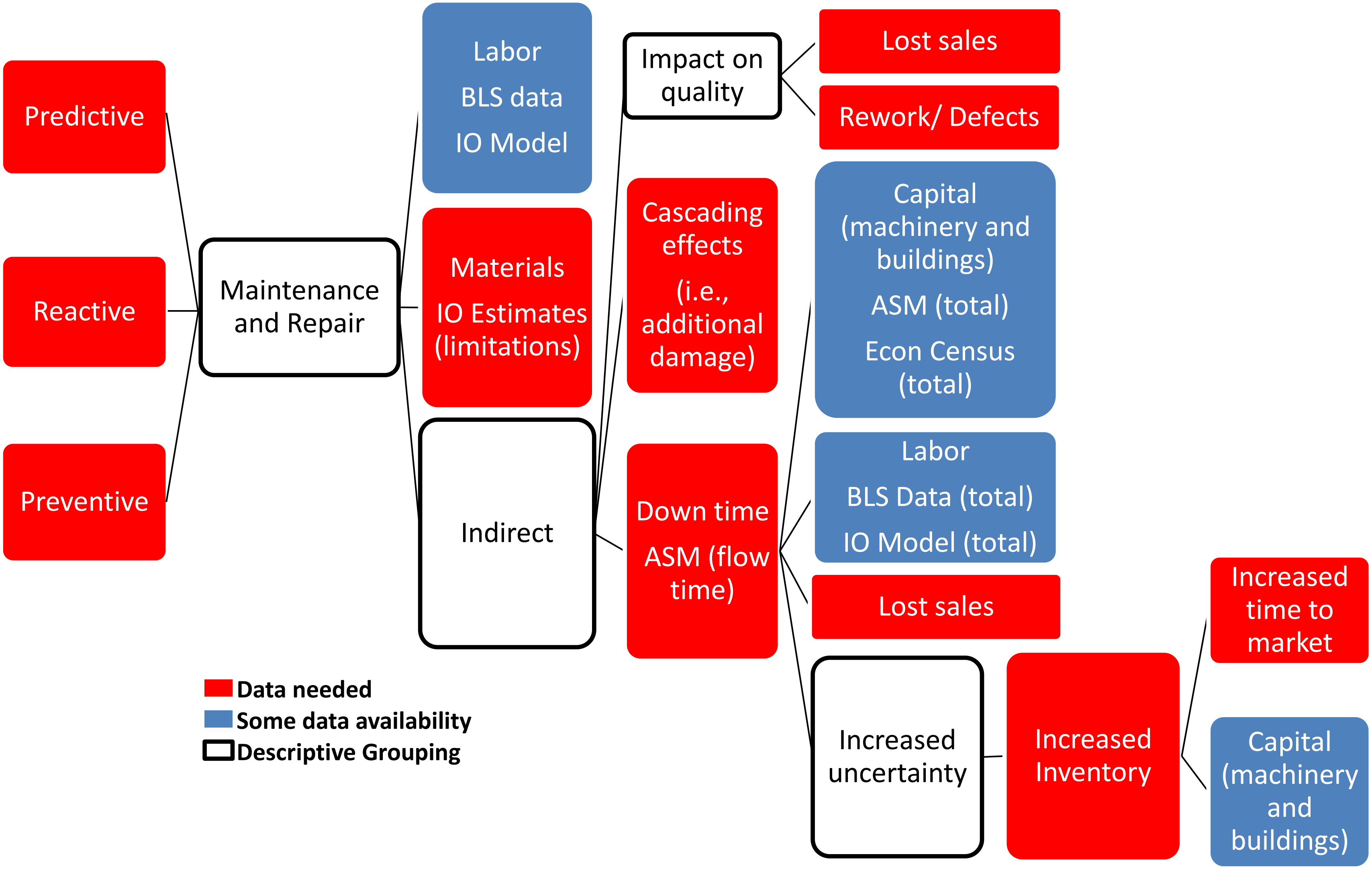

Figure 3.1: Data Map and Needs

on payroll. The scaling would match the company size and industry to corresponding national data:

Equation 1

$$DMC = \sum_{i=1}^{I} \sum_{s=1}^{S} \frac{\sum_{x=1}^{X} EM_{x,s,i}}{\sum_{x=1}^{X} PR_{x,s,i}} PR_{s,i}$$

where
DMC = Direct maintenance costs
$EM_{x,s,i}$ = Estimate of maintenance costs for establishment *x* with size *s* within industry *i*
$PR_{x,s,i}$ = Estimate of total payroll for establishment *x* within industry *i* with size *s*
$PR_{s,i}$ = Estimate of total payroll for industry *i* with size *s*

The challenge in doing so, is in acquiring enough responses to provide an accurate estimate, assuming that manufacturers even track this type of information. The number of establishments could replace payroll in the equation. Repair costs would need to be assessed in a similar fashion, replacing estimated maintenance costs ($EM_{x,s,i}$) in the above equation with estimated repair costs ($ER_{x,s,i}$).

An alternative to surveying costs is using input-output data. The BEA Benchmark input-output tables have data for over 350 industries (Bureau of Economic Analysis 2014), including “NAICS 8113: Commercial and Industrial Machinery and Equipment Repair and Maintenance.” This data includes Make tables, which show the production of commodities (products) by industry, and Use tables, which show the use of commodities required for producing the output of each industry. The data is categorized by altered codes from the North American Industry Classification System (NAICS). The tables show how much each industry (e.g., automobile manufacturing) purchases from other industries; thus, it shows how much “Commercial and Industrial Machinery and Equipment Repair and Maintenance” services were purchased by each industry. However, this does not reveal internal expenditures on maintenance and it also includes repairs. Internal expenditures for maintenance labor could be estimated using the Occupational Employment Statistics and estimating the additional costs using the data on “NAICS 8113: Commercial and Industrial Machinery and Equipment Repair and Maintenance.” Maintenance costs could be estimated using the following method:

Equation 2

$$DMC = PM\left(\frac{RM}{MO_{RM}} * MO_I + (PI * RM)\right)$$

where
DMC = Direct maintenance costs
RM = Total value added for NAICS 8113: Commercial and Industrial Machinery and Equipment Repair and Maintenance
MO_{RM} = Estimated compensation for maintenance occupations within NAICS 8113: Commercial and Industrial Machinery and Equipment Repair and Maintenance

MO_I = Estimated compensation for maintenance occupations within the industry of interest
PI = Proportion of value added from NAICS 8113 that is purchased by the industry of interest
PM = Proportion of maintenance and repair that is maintenance (i.e., maintenance activities that are not repairs)

3.2. Downtime Costs

There are three means for estimating downtime costs; however, each of them requires gathering data from manufacturers. The first involves a survey that asks a manufacturer to estimate the lost revenue due to downtime for maintenance. This data would then be scaled up using national industry data on payroll:

Equation 3

$$DWC = \sum_{i=1}^{I} \sum_{s=1}^{S} \frac{\sum_{x=1}^{X} ED_{x,s,i}}{\sum_{x=1}^{X} PR_{x,s,i}} PR_{s,i}$$

where
DWC = Downtime costs due to maintenance
$ED_{x,s,i}$ = Estimate of downtime costs for establishment *x* with size *s* within industry *i*
$PR_{x,s,i}$ = Estimate of total payroll for establishment *x* within industry *i* with size *s*
$PR_{s,i}$ = Estimate of total payroll for industry *i* with size *s*

The second method uses flow time. Manufacturing flow time can be thought of as water flowing into a bucket. Products flow through the assembly line and out of an establishment at a specific rate. Using data on the downtime due to maintenance that would be gathered using a survey, lost revenue could be estimated:

Equation 4

$$DWC = \frac{VA_i}{52.14 * Hr_{Plnt,i}} * DWN_i$$

where
$Hr_{Plnt,i}$ = Average plant hours for industry *i* per week in operation from the quarterly Survey of Plant Capacity Utilization
VA_i = Value added for industry i
DWN_i = Average number of hours of downtime for industry i gathered from survey data

The third method involves examining flow time. Downtime has an impact on the efficiency of capital use, which is often measured using flow time and inventory turns. The calculation for flow time can, again, be thought of as water flowing through a hose into a bucket. The cost of goods sold, $COGS$, is the total amount of water that runs into the bucket over a period of time and the inventory values are the amount of water in the hose at any given time. Since we know the total amount of water that flowed out of the hose (i.e., the amount in the bucket or $COGS$), we can estimate how many times the hose was filled and emptied over that period of time (inventory turns or TRN in the equation below) by dividing the amount in the bucket by the volume of the hose. If one takes the number of days in a year and divides it by the number of inventory turns TRN, the result is the flow time FT, which represents the time it takes to move from the beginning to the end of the hose. This method makes assumes first-in first-out (FIFO) where the oldest goods on hand are sold first.[60] Industry inventory time can be characterized into four categories (i.e., material goods, work-in-process down time, work-in-process, and finished goods).[61, 62] For this reason, a ratio is included in the calculation to account for each category. The proposed method for estimating flow time for materials and supplies inventories, work-in-process inventories, and finished goods inventories for an industry, represented by NAICS codes, is:

Equation 5

$$FT_{IND,Total} = \frac{\left(INV_{IND,i,BOY} + INV_{IND,i,EOY}\right)/2}{\left(INV_{IND,Total,BOY} + INV_{IND,Total,EOY}\right)/2} \times \frac{365}{TRN_{IND,Total}}$$

where
$FT_{IND,Total}$ = Total estimated flow time for industry IND
i = Inventory item where i is materials and supplies (MS), work-in-process (WIP), or finished goods (FG) inventories.
$INV_{IND,Total,BOY}$ = Total inventory (i.e., materials and supplies, work-in-process, and finished goods inventories) for industry IND at the beginning of the year
$INV_{IND,Total,EOY}$ = Total inventory (i.e., materials and supplies, work-in-process, and finished goods inventories) for industry IND at the end of the year
$TRN_{IND,Total}$ = Inventory turns for industry IND (defined below)

This equation calculates, for each industry, the flow time for materials and supplies inventories, work-in-process inventories, and finished goods inventories and, then sums them together. Calculating each of these stages is useful in identifying the source of the flow time (i.e., inventory time vs. work-in-process time). Downtime relates to work-in-process inventories; thus, it is necessary to calculate the flow time for this stage. The total industry flow time can be simplified to:

Equation 6

$$FT_{IND,Total} = \frac{365}{TRN_{IND,Total}}$$

The days that a dollar spends in each of the inventory categories is being calculated by taking the total number of days in a year and dividing it by the number of inventory turns TRN. This is then

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[60] Meigs, R.F. and W.B. Meigs. Accounting: The Basis for Business Decisions. (New York, NY: McGraw-Hill Inc., 1993): 409.
[61] Census Bureau. "Manufacturers' Shipments, Inventories, and Orders." 2017. <https://www.census.gov/manufacturing/m3/definitions/index.html>
[62] International Organization for Standardization. ISO 22400-2:2014(E).

multiplied by average inventory of type i divided by the total inventory. Finally, the summation of all types of inventory is calculated for industry IND.

Inventory turns, TRN_{Total}, is the number of times inventory is sold or used in a time period such as a year.[63,64,65] It is calculated as the cost of goods sold (COGS), which is the cost of the inventory that businesses sell to customers,[66] divided by the average inventory:

Equation 7

$$TRN_{Total} = \frac{COGS}{\left(\frac{INV_{Total,BOY} + INV_{Total,EOY}}{2}\right)}$$

where

$COGS = AP + FB + MAT + DEP + RP + OTH + (INV_{Total,BOY} - INV_{Total,EOY})$

AP = Annual payroll

FB = Fringe benefits

MAT = Total cost of materials

DEP = Depreciation

RP = Rental payments

OTH = Total other expenses

Inventory turns is usually stated in yearly terms and is used to study several fields, such as distributive trade, particularly with respect to wholesaling.[67] The data for calculating $COGS$ is from the Annual Survey of Manufacturing. In the previous two equations, inventories are calculated using the average of the beginning of year inventories and end of year inventories, which is standard practice.[68]

Flow time for work-in-process inventories (i.e., FT_{N} where in this case N is work-in-process) consists of two components: the time that a good is in work-in-process while the factory is open and the time that a good is in work-in-process while the factory is closed. Breaking out these two is useful for understanding where the flow time occurs. The time when the factory is closed can be estimated by multiplying the total flow time for work in process by the ratio of total hours that the plant is open:

Equation 8

$$FT_{WIPD} = \left(1 - \frac{Hr_{Plnt}}{168}\right) \times FT_{WIP}$$

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[63] Horngren, C.T., W.T. Harrison Jr., and L.S. Bamber. Accounting. 5th edition. (Upper Saddle River, NJ: Prentice Hall, 2002): 725.

[64] Stickney, Clyde P. and Paul R. Brown. Financial Reporting and Statement Analysis. (Mason, OH: Southwestern, 1999): 136-137.

[65] Hopp,W.J. and M.L. Spearman. Factory Physics. 3rd edition. (Long Grove, IL,Waveland Press, 2008): 230.

[66] Horngren, Accounting, 168.

[67] Hopp, Factory Physics, 230.

[68] Horngren, Accounting, 725, 186.

where:
FT_{WIPD} = Flow time for work-in-process downtime when the factory is closed
Hr_{Plnt} = Average plant hours per week in operation from the quarterly Survey of Plant Capacity Utilization
FT_{WIP} = Flow time for work-in-process

The value of 168 is the number of hours in a week. Breaking the flow time for work-in-process into time when the factory is open and closed aids in understanding the activities that are occurring during flow time.

A decrease in downtime would increase the number of inventory turns, reduce the work-in-process flow time, and improve the capital utilization. It could also have the indirect effect of reducing the amount of material inventory and/or finished goods inventory that is maintained. Data could be collected from establishments to calculate inventory turns and flow time. A regression analysis could then be used to estimate the impact that various forms of maintenance have on flow time while controlling for other factors (e.g., management style). Equation 4 could be applied to estimate the dollar impact.

3.3. Lost Sales due to Delays/Quality Issues

Estimating the lost sales due to delays or quality issues requires gathering this data through a survey. There is also the potential for large error in this estimate, as it is unlikely that there is official tracking of this information. The information would be scaled similar to previously discussed methods:

Equation 9

$$TLS = \sum_{i=1}^{I} \sum_{s=1}^{S} \frac{\sum_{x=1}^{X} LS_{x,s,i}}{\sum_{x=1}^{X} PR_{x,s,i}} PR_{s,i}$$

where
TLS = Total lost sales due to delays or quality issues
$LS_{x,s,i}$ = Estimate of lost sales for establishment *x* with size *s* within industry *i*
$PR_{x,s,i}$ = Estimate of total payroll for establishment *x* within industry *i* with size *s*
$PR_{s,i}$ = Estimate of total payroll for industry *i* with size *s*

3.4. Rework and Defects

In addition to lost sales, there are products that are scrapped or reworked because of defects. The cost of rework can be estimated by estimating the proportion of employee labor dedicated to rework, represented as:

$$RWK = \sum_{i=1}^{I} \sum_{s=1}^{S} \frac{\sum_{x=1}^{X} FTE_{RW,x,s,i}}{\sum_{x=1}^{X} FTE_{Tot,x,s,i}} PR_{s,i}$$

where

RWK = Cost of rework
$FTE_{RW,x,s,i}$ = Estimate of the full time equivalent employees dedicated to rework that is preventable through maintenance at establishment *x* with size *s* within industry *i*
$FTE_{Tot,s,i}$ = Estimate of total full time equivalent employees at establishment *x* with size *s* within industry *i*
$PR_{s,i}$ = Estimate of total payroll for industry *i* with size *s*

The lost revenue associated with defects can be approximated by estimating the ratio of output that is defective and can be represented as:

$$DEFLR = \sum_{i=1}^{I} \frac{OUT_i}{(1 - DEF_i)} - OUT_i$$

where
$DEFLR$ = Lost revenue associated with defects
DEF_i = Estimated average proportion of output in industry *i* that is discarded due to defects that are preventable through maintenance
OUT_i = Output for industry *i*

3.5. Breaking Down Predictive, Preventive, and Reactive Maintenance Costs

Separating maintenance into predictive, preventive, and reactive categories requires gathering the data through a survey. There is the potential for large error in this estimate, as it is unlikely that there is official tracking of this information. It is likely that this estimate will be based on the opinion or perspective of the person completing the survey. The following information would need to be gathered by establishment to estimate the potential savings from predictive maintenance:

- Scaling
  - Total payroll and number of employees in the plant
  - Industry NAICS code
- Direct costs of maintenance
  - Method 1: Collect direct cost data through survey and scale up
    - Maintenance and repair costs
    - Proportion of maintenance costs that are maintenance vs. repair
    - Proportion of direct costs for predictive, preventive, and reactive maintenance
    - Proportion of repair costs associated with reactive maintenance
  - Method 2: Use industry data and supplement with survey
    - Proportion of maintenance costs that are maintenance vs. repair
    - Proportion of direct costs for predictive, preventive, and reactive maintenance
    - Proportion of repair costs associated with reactive maintenance
- Downtime
  - Method 1: Collect downtime costs directly in a survey

        - Costs/Losses of downtime, including lost revenue, increased overtime, increased inventory, and lost sales from delivery delays or quality issues
    - Method 2: Use national flow time estimates and supplement with survey
        - Average factory operating hours per week
        - On average, the amount of downtime for a production line
        - Proportion of downtime due to predictive, preventive, and reactive (unplanned) maintenance
    - Method 3: Gather data on inventory turns with survey
        - Inventory turns per year or, alternatively, the following data to calculate it
            - Cost of goods sold (i.e., sum of annual payroll, fringe benefits, total cost of materials, depreciation, and total other manufacturing expenses)
            - Beginning and end of year inventories (or average inventory) for materials, work-in-process, and finished goods
        - Requires establishment level maintenance costs
            - Maintenance and repair costs
            - Proportion of maintenance costs that are maintenance vs. repair
            - Proportion of direct costs for predictive, preventive, and reactive maintenance
            - Proportion of repair costs associated with reactive maintenance
        - Competitive focus: cost competitiveness or differentiation (e.g., quality)
        - Primarily a push (i.e., make to stock) or pull (i.e., make to order) strategy of production
        - Primary management style
            - Autocratic: Decisions are made at the top with little input from staff
            - Consultative: Decisions are made at the top with input from staff
            - Democratic: Employees take part in decision making process
            - Laissez-faire: Management provides limited guidance
- Replacement costs, if any, due to damage that could be prevented using preventive or predictive maintenance
- Rework and defects
    - Full time equivalent employees needed for rework that could be prevented through maintenance
    - Output that was discarded due to defects that could be prevented through maintenance
- In the case where it is believed to be cost effective to switch from current practice to predictive maintenance, what is the estimated:
    - Total investment cost of switching to predictive maintenance as a percent of current maintenance cost
    - The potential percent increase in revenue, if any, due to increased quality and/or decreased delays from switching to predictive maintenance
    - Percent change in annual maintenance and repair costs from switching to predictive maintenance
    - Percent change in replacement costs, if any, due to switching to predictive maintenance

  - Percent decrease in total downtime due to switching to predictive maintenance

3.6. Required Sample Size for Data Collection

As mentioned previously, there are 54 022 establishments in NAICS 333-336. A required sample size is influenced by many items, including the margin of error and population size. An estimate of the sample size needed can be represented by:[69,70]

$$Sample\ Size = \frac{\frac{z^2 * p(1-p)}{e^2}}{1 + \left(\frac{z^2 * p(1-p)}{e^2 N}\right)}$$

where
N = Population size
e = Margin of error
z = z-score
p = proportion of the population

Using the estimate for maintenance in the Annual Survey of Manufactures and assuming a 10 % margin of error, a 90 % confidence interval, and a proportion of p equaling 0.5 (0.5 results in the worst-case scenario or largest sample size needed), a sample size of 68 is calculated. This method, however, is for estimating the proportion of a population that falls into a certain category (e.g., proportion of people that have red hair). This study is, generally, estimating the mean of a population, which can be represented as:[71]

$$Sample\ Size = \left(\frac{z\sigma}{e}\right)^2$$

where
σ = Standard deviation
e = Margin of error
z = z-score

The Annual Survey of Manufactures estimates the total value of manufacturing maintenance was $49.5 billion for 292 825 establishments with a sample size estimated at approximately 50 000, resulting in a standard deviation of $75 627, as calculated by:

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[69] Lepkowski, James. Sampling People, Networks and Records. 2018. Coursera course. https://www.coursera.org/learn/sampling-methods/home/welcome

[70] Barnett, Vic. Sample Survey: Principles and Methods. (New York, NY: Oxford University Press Inc., 2002): 58-63.

[71] NIST. Engineering Statistics Handbook. Sample Sizes. http://www.itl.nist.gov/div898/handbook/prc/section2/prc222.htm

$$\sigma = \frac{RSE}{100} * \frac{M\&R}{EST} * \sqrt{SPL}$$

where
RSE = Relative standard error from the Annual Survey of Manufactures
$M\&R$ = Repair and maintenance services of buildings and/or machinery from the Annual Survey of Manufactures
EST = Number of establishments in manufacturing from the County Business Patterns data
SPL = Approximate sample size of the Annual Survey of Manufactures

Assuming a 10 % margin of error and a 95 % confidence interval (i.e., $z = 1.96$), a sample size of 77 is calculated. Figure 3.2 graphs the various sample sizes required at different confidence intervals and margins of error with the standard deviation equaling $75 627. With a margin of error of 20 % and a confidence interval as low as 90 %, as few as 14 samples are needed.

Since the assessment of sample size relies on a number of assumptions, a probabilistic sensitivity analysis was conducted using Monte Carlo analysis. This technique is based on works by McKay, Conover, and Beckman (1979) and by Harris (1984) that involves a method of model sampling.[72,73] It was implemented using the Crystal Ball software product (Oracle 2013), an add-on for spreadsheets. Specification involves defining which variables are to be simulated, the

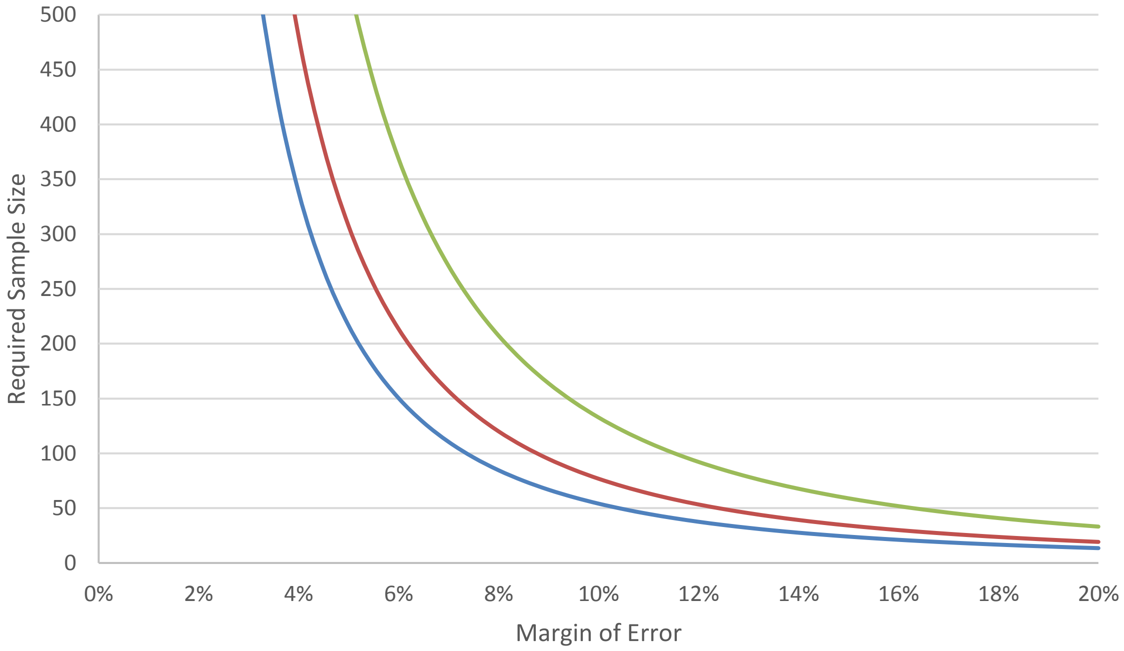

Figure 3.2: Required Sample Size by Margin of Error and Confidence Interval
Note: Standard deviation equals 75 627, as calculated from the Annual Survey of Manufactures

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[72] McKay, M. C., W. H. Conover, and R.J. Beckman. "A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code," Technometrics 21, (1979): 239-245.

[73] Harris, C. M. Issues in Sensitivity and Statistical Analysis of Large-Scale, Computer-Based Models, NBS GCR 84-466, Gaithersburg, MD: National Bureau of Standards (1984).

distribution of each of these variables, and the number of iterations performed. The software then randomly samples from the probabilities for each input variable of interest. The population, value of maintenance/repair, relative standard error, sample size from the Annual Survey of Manufacturers, and the samples size needed for this study were each varied using a triangular distribution with the parameters shown in Table 3-1. The z-score was varied between a 99 % confidence interval and a 90 % confidence interval. These variations allow for relatively large error in the assumptions for calculating the sample size and margin of error, as the standard deviation for maintenance cost ranges from a little less than 65 000 to more than 630 000.

A cumulative probability graph of the results is shown in Figure 3.3, which shows that for 80 % (i.e., a cumulative probability of 0.8) of the iterations the margin of error is below 0.52 (+/-52 % in estimating maintenance cost), as illustrated with doted lines in the figure. Figure 3.4 graphs the margin of error for those iterations in the Monte Carlo analysis that are at the 90 % confidence interval. As seen in the figure, the standard deviation has significant impact on the margin of error; thus, the accuracy of the assumptions has a substantial effect.

Table 3-1: Assumptions for Monte Carlo Analysis (Triangular distributions)

	Min	Most Likely	Max
Population (establishments)	248 901 (-15 %)	292 825	336 749 (+15 %)
Value of M&R	44.6 billion (-10 %)	49.5 billion	54.5 billion (+10 %)
Relative Standard Error	0.2	0.2	1.5
Sample Size (ASM)	40000	50000	55000
Sample Size (Needed)	20	40	150
z-score (uniform distribution)	1.65	-	2.58

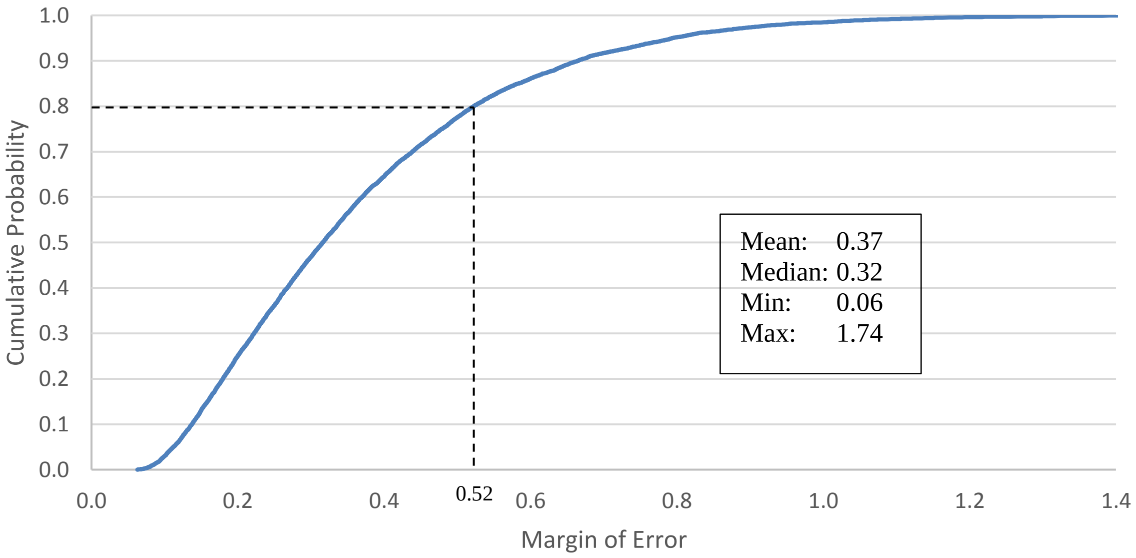

Figure 3.3: Cumulative Frequency Graph, Monte Carlo Analysis

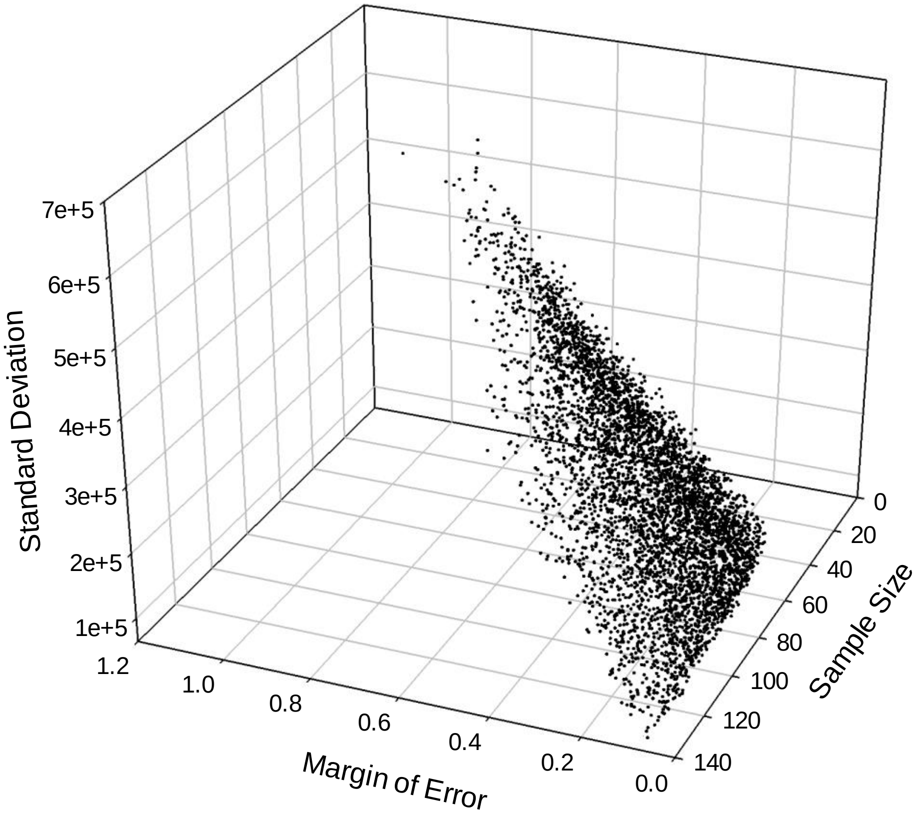

Figure 3.4: Margin of Error Graphed with Standard Deviation of Maintenance Cost and Sample Size from Monte Carlo Analysis (90 % Confidence Interval only)

4. Feasibility of Data Collection

Individual insight was sought out from staff at manufacturing firms to assess the feasibility of data collection. Conversations occurred with seven individuals with five being employed at manufacturing firms and two were employed by change agent organizations, which includes trade associations and research organizations. These discussions assessed whether the individual believed the following data items could be collected:

1. NAICS code
2. Payroll
3. Factory operating hours
4. Expenditure on maintenance and repair (M&R)
5. Separating maintenance from repair and estimating replacement
6. Separating M&R that are due to predictive, preventive, and reactive maintenance activities
7. Lost revenue and increased overtime due to maintenance issues
8. Total downtime and related costs/losses
9. Separating downtime into predictive, preventive, and reactive maintenance activities
10. Identifying instances where it would be cost effective to switch to advanced maintenance, including estimating increased revenue, reduction in costs, and reduction in downtime
11. Inventory turns per year
12. Competitive focus: cost competitive vs differentiation
13. Push vs pull strategy
14. Management style
15. Defect and rework rates

- The discussions indicate that it is reasonable to expect manufacturers to be willing to provide information on these items:
    - However, there was some uncertainty about the willingness to provide payroll and inventory turns.
    - In terms of ability to provide data, there were some reservations, as some items are not specifically tracked.
    - Generally, however, it was believed that an approximation could be provided in cases where data was unknown.
- All individuals indicated that they were willing and able to provide the NAICS code, factory operating hours, competitive focus, push/pull strategy, and management style.
- Individuals indicated that they would be willing and able to provide an estimate for maintenance and repair expenditures with one indicating they would have to approximate it.
- It was also indicated by some that separating out maintenance from repair and associating portions to predictive, preventive, and reactive maintenance might require approximating or “guestimating.”
- It was uncertain whether an estimate for lost revenue and increased overtime due to reactive maintenance could be provided and one indicated that they were unable to approximate it.

- Individuals indicated that they could provide an estimate of downtime and could approximate the amount of time that is associated with predictive, preventive, and reactive maintenance.
- Multiple individuals indicated that they could identify instances where it would be cost effective to switch to advanced maintenance techniques but estimating the costs and benefits of doing so was a little more uncertain with one indicating they were unable to make an estimate.
    - One individual explained that the costs of implementing advanced maintenance techniques are customized solutions; thus, estimating the cost would require tracking individual labor activities and materials.
- Each of the individuals indicated that they believed a blind survey would be better than a confidential one and they would be more likely to respond.
- They also indicated that being promised a copy of the report would make them more likely to respond, but it did not seem like a necessity.

5. Summary and Conclusions

This report investigates the data available from public sources and in the literature on the total cost of manufacturing maintenance, including data on separating those costs into planned and unplanned maintenance. It also investigates the feasibility of collecting data to measure maintenance costs and separate costs by firm size. This area of investigation includes identifying whether manufacturers can provide information to estimate and separate maintenance costs. This effort requires consulting literature on the data collected at establishments and consulting industry experts.

The data available in the literature and from statistical agencies could facilitate making estimates of US maintenance costs along with the potential benefits of moving toward advanced maintenance techniques; however, the estimate for benefits of advanced maintenance techniques would require strong assumptions that result in a high level of unmeasurable error. For instance, one would need to assume that the findings in studies of other industrialized countries apply to the US and across multiple US industries. It would also require the insight of a few experts accurately represents industry activity. This estimate would be low cost but have low accuracy, making it an estimated order of magnitude. A more reliable estimate requires data collection.

Manufacturers are, generally, willing to provide data; however, the data needed is often not specifically tracked or documented. Experienced maintenance managers and professionals, however, have indicated that they are able to provide an estimate for these cost items. A great deal of the uncertainty occurs in separating out maintenance and repair costs/losses into different categories.

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