NIST Advanced Manufacturing Series 100-34

# Economics of Manufacturing Machinery Maintenance

## A Survey and Analysis of U.S. Costs and Benefits

Douglas S. Thomas
Brian A. Weiss

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National Institute of
Standards and Technology
U.S. Department of Commerce

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## Abstract

This report examines costs of machinery maintenance along with losses due to inadequate maintenance strategies in discrete manufacturing (NAICS 321-339, excluding NAICS 324 and 325) using data collected from U.S. manufacturers. The report further examined the perceived and observed benefits of investing in and advancing maintenance strategies. Estimates for costs and losses are annual values for 2016. Machinery maintenance expenditures for NAICS 321-339 (excluding 324 and 325) were estimated to be $57.3 billion for 2016. Losses due to preventable maintenance issues amounted to $119.1 billion. The top 25 % of those establishments relying on reactive maintenance was associated with 3.3 times more downtime than those in the bottom 25 %. They were also associated with 16.0 times more defects, 2.8 more lost sales due to defects from maintenance, 2.4 times more lost sales due to delays from maintenance, and 4.9 times more inventory increases due to maintenance issues.

## Key words

Manufacturing; maintenance; machinery; economics; costs; monitoring; diagnostics; prognostics

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## Table of Contents

## List of Tables

## List of Figures

## Executive Summary

This report examines costs of machinery maintenance along with losses due to inadequate maintenance strategies in discrete manufacturing (NAICS 321-339, excluding NAICS 324 and 325) using data collected from U.S. manufacturers. The report further examined the perceived and observed benefits of investing in and advancing maintenance strategies. Estimates for costs and losses are annual values for 2016.

*Maintenance Costs:* 2016 Machinery maintenance expenditures for NAICS 321-339 (excluding 324 and 325) were estimated to be $57.3 billion. Additional expenditures due to faults and failures were estimated at $16.3 billion and costs for inventory to buffer against maintenance issues costed $0.9 billion. In total, these maintenance activities costed $74.5 billion.

*Preventable Losses:* The 2016 losses due to preventable maintenance issues amounted to $119.1 billion: $18.1 billion due to downtime, $0.8 billion due to defects, and $100.2 billion due to lost sales from delays and defects. Additionally, an estimated 16.03 injuries and 0.05 deaths per million employees were associated with these maintenance issues.

*Benefits of Advanced Maintenance Strategies:* The estimated 2016 perceived benefit of adopting some additional amount of predictive maintenance was $6.5 billion from downtime reduction and $67.3 billion in increased sales ($73.8 billion in total). Other perceived benefits such as reduced defects are also likely to occur but were not monetized.

The top 25 % of those establishments relying on reactive maintenance was associated with 3.3 times more downtime than those in the bottom 25 %. They were also associated with 16.0 times more defects, 2.8 more lost sales due to defects from maintenance, 2.4 times more lost sales due to delays from maintenance, and 4.9 times more inventory increases due to maintenance issues. On average, 45.7 % of machinery maintenance was reactive maintenance. Those who relied less on reactive maintenance, and more on preventive and/or predictive maintenance, were more likely to use a pull (i.e., make to order) stock strategy and tend to be differentiators as opposed to being a cost competitor. That is, they rely more on their reputation and produce products on demand. The implication being that reactive maintenance reduces quality and increases uncertainty in production time.

Among those establishments that primarily rely on preventive and predictive maintenance (i.e., less than 50 % reactive maintenance), the top 50 % in predictive maintenance was associated with 15 % less downtime, an 87 % lower defect rate, and 66 % less inventory increases due to unplanned maintenance. Those who relied more on predictive maintenance than preventive were more likely to have a pull (i.e., make to order) stock strategy and more likely to be a differentiator as opposed to being a cost competitor. Moreover, predictive maintenance is associated with higher quality products and shorter production times through reduced downtime. For those establishments that invested more heavily into preventive or predictive maintenance, on average they had 44 % less downtime, 54 % lower defect rate, 35 % fewer lost sales due to defects from maintenance, and 29 % less lost sales due to delays from maintenance issues.

## Acronyms

| | |
|---|---|
| **ASM** | Annual Survey of Manufactures |
| **BEA** | Bureau of Economic Analysis |
| **BOY** | Beginning of Year |
| **CBP** | County Business Patterns |
| **EC** | Economic Census |
| **EOY** | End of Year |
| **IO** | Input Output |
| **MEP** | Manufacturing Extension Partnership |
| **NAICS** | North American Industry Classification System |
| **NIST** | National Institute of Standards and Technology |
| **PdM** | Predictive Maintenance |
| **PM** | Preventive Maintenance |
| **R&D** | Research and Development |
| **RM** | Reactive Maintenance |
| **SMM** | Small to Medium-sized Manufacturer |
| **SMRP** | Society for Maintenance & Reliability Professionals |

# 1. Introduction

## 1.1. Background

Companies compete based on two primary factors: cost and differentiation. Cost competitors aim to produce and sell a product for a low price while differentiators focus on enhancing the quality and reputation of their brand and products. One factor that can affect product cost, quality, and production time is the maintenance of manufacturing machinery. Machinery maintenance typically leads to downtime, either planned or unplanned. Unplanned downtime often stems from breakdowns along with increasing defects when machinery operates outside of specification. This can result in production delays and customer dissatisfaction. The increase in unexpected delays often leads to increased inventory throughout the supply chain to deal with uncertainty, which incurs additional costs.

Generally, there are three primary approaches to manufacturing machinery maintenance. These strategies include the following (which are derived from a series of practical case studies[1, 2]):

- **Predictive maintenance (PdM)**, 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 (PM)**, which is related to scheduled maintenance and planned maintenance, is scheduled, timed, or based on a cycle
- **Reactive maintenance (RM)**, which is related to run-to-failure, corrective maintenance, failure-based maintenance, and breakdown maintenance, is maintenance done, typically, after equipment has failed to produce a product within desired quality or production targets, or after the equipment has stopped altogether.

RM, generally, requires the least amount of investment; however, it is associated with the most amount of downtime and defects. PdM requires a higher level of investment, but it likely results in the least amount of downtime (both planned and unplanned) and defects. PM is somewhere in the middle of these two. The potential effect on maintenance costs and benefits of moving between the different maintenance techniques is not well documented, especially at the aggregated national level. The estimates that have been made, which are mostly at the firm level, show the impacts of PdM are measured using a wide range of metrics and, within each metric, have a wide range of values.[3]

This report is a continuation of the work that developed NIST AMS 100-18, which examined the literature, available data, and data needs for estimating the costs and losses relevant to different manufacturing maintenance techniques.[4] The previous report

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[1] Jin, X., Siegel, D., Weiss, B. A., Gamel, E., Wang, W., Lee, J., & Ni, J. (2016). The present status and future growth of maintenance in US manufacturing: results from a pilot survey. Manuf Rev (Les Ulis), 3, 10. https://doi.org/10.1051/mfreview/2016005

[2] Jin, X., Weiss, B. A., Siegel, D., & Lee, J. (2016). Present Status and Future Growth of Advanced Maintenance Technology and Strategy in US Manufacturing. Int J Progn Health Manag, 7(Spec Iss on Smart Manufacturing PHM), 012. https://www.ncbi.nlm.nih.gov/pubmed/28058173

[3] Thomas, Douglas. (2018). The Costs and Benefits of Advanced Maintenance in Manufacturing. NIST Advanced Manufacturing Series 100-18. https://doi.org/10.6028/NIST.AMS.100-18

[4] Thomas, Douglas. (2018). The Costs and Benefits of Advanced Maintenance in Manufacturing. NIST Advanced Manufacturing Series 100-18. https://doi.org/10.6028/NIST.AMS.100-18

concluded that the majority of research related to predictive maintenance focuses on technological issues and, although there are some studies that incorporate economic data, these represent a minority of the literature. Many of the economic assessments are individual case studies, personal insights, and other anecdotal observations. A limited number of publications cite prevalent economic methods that 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 utilizing different maintenance methods are largely unknown or are based on anecdotal observations. This report extends the work of AMS 100-18 by analyzing data collected from discrete manufacturing establishments to estimate costs and losses.

## 1.2. Purpose, Scope, and Approach

The purpose of this report is to examine and measure the costs and losses associated with the three different approaches to machinery maintenance: reactive, preventive, and predictive maintenance. Much of this data was captured in a Machinery Maintenance Survey that was distributed to the manufacturing community.

This report utilizes the North American Industry Classification System (NAICS) for classifying industry activity. It focuses on examining discrete manufacturing, including:

- NAICS 321: Wood Product Manufacturing
- NAICS 322: Paper Manufacturing
- NAICS 323: Printing and Related Support Activities
- NAICS 326: Plastics and Rubber Products Manufacturing
- NAICS 327: Nonmetallic Mineral Product Manufacturing
- NAICS 331: Primary Metal Manufacturing
- NAICS 332: Fabricated Metal Product Manufacturing
- NAICS 333: Machinery Manufacturing
- NAICS 334: Computer and Electronic Product Manufacturing
- NAICS 335: Electrical Equipment, Appliance, and Component Manufacturing
- NAICS 336: Transportation Equipment Manufacturing
- NAICS 337: Furniture and Related Product Manufacturing
- NAICS 339: Miscellaneous Manufacturing

The manufacturing industries that are absent or not part of the examination include food manufacturing (NAICS 311), beverage and tobacco products (NAICS 312), textile mills (NAICS 313), textile products (NAICS 314), apparel and leather (NAICS 315 and 316), petroleum products (NAICS 325), and chemical products (NAICS 324). These were excluded as there were no responses to a survey questionnaire in these subsectors and they involved processes that differ from the other discrete manufacturing processes. The original focus of this work was on medium and high-tech manufacturing (i.e., NAICS 333-336); however, the Machinery Maintenance Survey was distributed through multiple means including notifications in mass media. As a result, the respondents to the Machinery Maintenance Survey varied outside of the targeted industries; therefore, the scope was widened to include more NAICS codes.

Examining industry activity often has either a solution-based focus or a problem/cost-based focus.[5] The difference can be elusive or unclear but is distinguishable and impacts the application of the data along with the revealed insights. As illustrated in Figure 1.1, a solution-based approach in manufacturing examines the reduced cost that might result from an improvement, investment, or technology. The left side of the figure represents component level data collection, which is more costly, and moving toward the right is more aggregated data collection, which is less costly but also less useful and accurate. Toward the top is more problem-based data collection while toward the bottom is solution-based data collection. To illustrate, consider examining the impact of adopting energy efficient lighting. An alternative to a solution-based approach is a problem/cost-based approach where costs are categorized by more natural classifications and avoids specifying a solution. For instance, examining the total expenditures on energy for lighting, there are

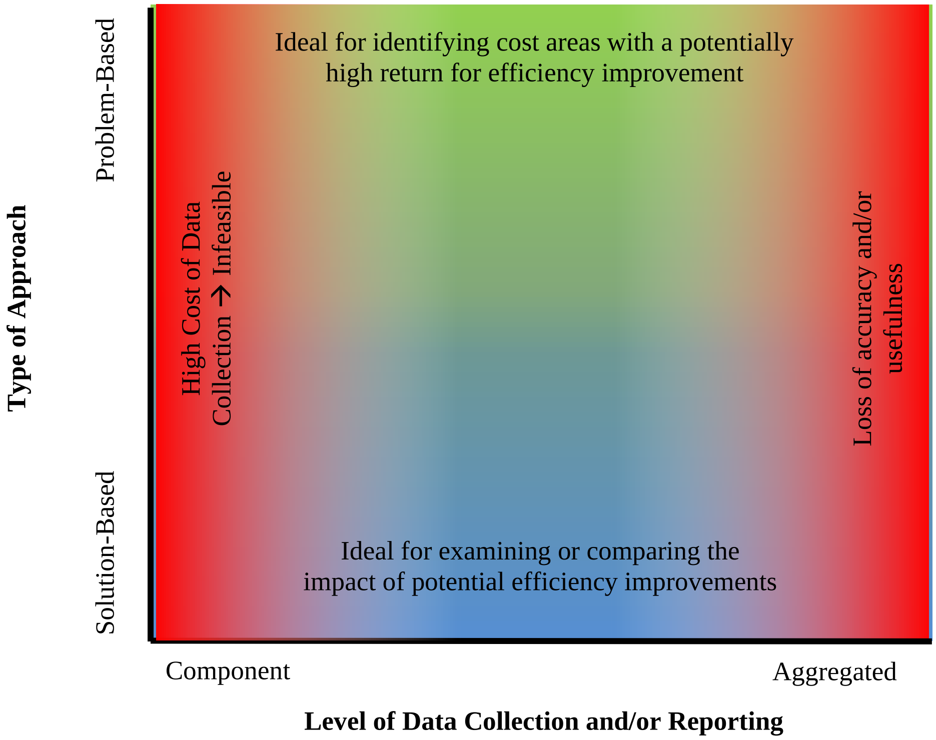

Figure 1.1: Categories of Cost Analysis

Source: Thomas, Douglas. 2019. The Model Based Enterprise: A Literature Review of Costs and Benefits for Discrete Manufacturing. Advanced Manufacturing Series 100-26. https://doi.org/10.6028/NIST.AMS.100-26

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[5] Thomas, Douglas. (2019). The Model Based Enterprise: A Literature Review of Costs and Benefits for Discrete Manufacturing. Advanced Manufacturing Series 100-26. https://doi.org/10.6028/NIST.AMS.100-26

many solutions to reducing lighting costs (e.g., energy efficient lighting, turning off some lights, or inserting skylights) and a solution-based approach could be used to examine each, but each of these solutions addresses a cost characterized in a problem-based approach. The effect on the data collection is how the costs are categorized. Neither approach is better, but rather, the approach taken affects the type of questions that can be answered from the results. This report has a problem/cost-based focus where it aims to examine the costs/losses that manufacturers face relevant to machinery maintenance. The benefit of such a focus is that it does not assume a solution; that is, it provides information that measures the magnitude of the problem to be solved (i.e., the costs/losses associated with maintenance or lack thereof). Thus, it presents a problem to be solved rather than a solution to be evaluated.

Another aspect of a cost analysis is the aggregation of costs. At least two challenges arise with high levels of aggregation. The first challenge is the accuracy of the analysis. If data for an analysis is gathered at a level that is too aggregated, there is the risk of a loss of accuracy, particularly in a solution-based approach, as this approach often cuts across natural cost categories tracked by a firm. To illustrate, consider a survey that asks someone to estimate the hours per year they spend driving their car compared to one that asks each component of their drive time (e.g., number of hours per day they spend driving to and from work). An aggregated question such as one on the total hours per year they spend driving is difficult to answer, as they must consider all at once the different places that they drive. Someone is much more likely to estimate with accuracy the amount of time they spend driving to work and other individual components of their total driving. The second challenge with high levels of aggregation is that it limits the insights of being able to identify solutions or efficiency improvements. The more aspects of the costs that are measured, the more possible solutions that may be identified and compared. Unfortunately, the more components there are, the higher the burden in data collection and analysis, which could make a study infeasible. Businesses and citizens are already weary of completing surveys and the higher the burden, the fewer the responses. This report will aim to measure detailed components of costs associated with maintenance. It utilizes the results of data collected from U.S. manufacturers through our Machinery Maintenance Survey discussed in detail within this report.

The preceding report, AMS 100-26 referenced above, identified categories of costs, losses, and maintenance, which include the following:

- Direct maintenance and repair costs
- Indirect costs
    - Downtime
    - Lost sales due to quality/delays
    - Defects
- Separating maintenance types (i.e., predictive, preventive, and reactive)

This report presents approaches to maintenance in Section 2 followed by a discussion on the Machinery Maintenance Survey in Section 3. Direct maintenance costs are discussed in Section 4. Section 5 discusses losses, including downtime, lost sales, and defects along with additional losses and injuries due to inadequate maintenance strategies. Section 6 discusses the perceived benefits that might be realized by increasing predictive maintenance while Section 7 highlights observed differences between firms that have adopted more preventive and predictive maintenance. Finally, Section 8 summarizes the findings.

## 2. Maintenance Strategies

Manufacturers deploy a range of maintenance strategies with the intent of optimizing their planned downtime and minimizing their unplanned downtime. Manufacturers, from large enterprises to small job shops, have all adopted and tailored a maintenance strategy, or combination thereof, to ensure the enterprise satisfies its customers through timely delivery of acceptable quality parts. Larger manufacturers typically have more established maintenance protocols that often include some more advanced maintenance capabilities based upon their own research and development (R&D) activities or emerging, commercially available solutions.[6] In contrast, small to medium-sized manufacturers (SMMs) are on average not as advanced in their maintenance approaches – compared to their larger counterparts, SMMs typically don't have the R&D personnel or additional capital to invest in emerging or advanced maintenance capabilities[7].

As noted in the Introduction, the three most common maintenance strategies are reactive maintenance, preventive maintenance, and predictive maintenance. Manufacturers use each of these strategies to varying effect to maintain their operational productivity, process/part quality, and equipment availability.

### 2.1. Reactive Maintenance

Reactive maintenance (RM) is the simplest and easiest of the maintenance strategies to define – do nothing until something breaks, fails, or stops operating within required specifications. Unfortunately, RM is often the most expensive maintenance strategy to employ long-term and can lead to unsafe scenarios, but has the lowest first-cost. At minimum, equipment failure leads to the repair or replacement of that specific item. The failure of a single piece of equipment can also lead to damage or failure(s) of other interconnected elements (e.g., failure of a timing belt in a car's engine often requires the repair or replacement of additional engine parts). More importantly, personal safety can be compromised in a failure (e.g., failure of the timing belt in a car can cause a deadly car accident). RM is seldom the preferred maintenance strategy to effectively maintain equipment or processes. Very few manufacturers know that something will break and not do anything to prevent it. RM is usually paired with some form of preventive and/or predictive maintenance (to be discussed in Section 2.2 and Section 2.3). The disadvantages of RM are well known. Perhaps the only advantage of RM is that it requires little to invest in this strategy (i.e., do nothing prior to any faults or failures). Manufacturers tend to avoid RM in nearly every instance possible realizing the costly and often unforeseen consequences that can arise.

One of the few, cost effective uses of RM is in the replacement of most light bulbs. When probing why RM works in most failed light bulb scenarios, there are a lot of reasons RM is the most preferred, cost-effective measure. The various reasons RM works in this situation include:

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[6] Jin, X., Siegel, D., Weiss, B. A., Gamel, E., Wang, W., Lee, J., & Ni, J. (2016). The present status and future growth of maintenance in US manufacturing: results from a pilot survey. Manuf Rev (Les Ulis), 3, 10. doi:10.1051/mfreview/2016005

[7] Helu, M., & Weiss, B. A. (2016). The current state of sensing, health management, and control for small-to-medium-szed manufacturers. Paper presented at the ASME 2016 Manufacturing Science and Engineering Conference, MSEC2016.

- Redundancy – when a light bulb fails, there is often a neighboring light bulb that still illuminates the area. The overall lighting may be dimmer than before the failure, yet the illumination is usually sufficient until a replacement is installed.
- Little collateral failures – when a light bulb fails, it seldom creates a domino effect causing other systems or elements to fail.
- Availability – most light bulbs are readily available either as a spare part within an organization's (or home's) inventory or as an item for purchase from a supplier (or local hardware store). Coupled with availability is that a light bulb is typically cost effective to keep in inventory.
- Minimal required tools – changing a lightbulb does not require any special tools. Sometimes, readily available tools are needed such as a screwdriver and/or a ladder.
- Minimal required skills – changing a lightbulb typically does not require any special or formal training

RM would be a viable option for other equipment, whether it be within an industrial facility or a home, if the equipment had similar failure and recovery characteristics noted above. Unfortunately, there are an extremely limited amount of processes and equipment whose failure would have such a minimal impact on a manufacturing organization. RM is the least preferred of the available maintenance strategies and is only undertaken as a last resort when faults or failures cannot be avoided.

## 2.2. Preventive Maintenance

Preventive Maintenance (PM) is a strategy focused on performing specific maintenance routines based upon a specified interval unit(s) - often time- or usage-based. A common example that has been prevalent is the guidance for an automobile owner to change the vehicle's oil every 3 months or 3000 miles (4828 kilometers) driven (whichever comes first). The units can be easily monitored as time in months or distance in miles (or kilometers). Similarly, there are numerous intervals that manufacturers monitor to guide their own PM activities. Manufacturers have a strong history of performing PM in their facilities to sufficiently uphold equipment and process uptime.[8] Some of the units that manufacturers track to determine maintenance routines include hours (e.g., how many hours has a process been operational since its last maintenance activity?), cycles (e.g., how many cuts has the machine made?), parts produced, and employee work shifts. PM units are often easy to measure, easy to track, and easy to articulate across all layers of the organization from the equipment operator, maintenance personnel, to the plant manager, and beyond. Additionally, PM is relatively easy to schedule, especially for legacy processes that have been relatively stable in their operations. The scheduling units for PM typically include units (e.g., parts, shifts, etc.) that are relatively inexpensive to track. Advanced sensing technology is seldom required to determine how many hours a piece of equipment has been running or how many parts have been produced by a process.

One disadvantage of PM is that it is possible to over-maintain equipment. Although the equipment may be less likely to experience an unexpected failure with more-than-

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[8] Jin, X., Weiss, B. A., Siegel, D., & Lee, J. (2016). Present Status and Future Growth of Advanced Maintenance Technology and Strategy in US Manufacturing. Int J Progn Health Manag, 7(Spec Iss on Smart Manufacturing PHM), 012. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/28058173

necessary PM, this excess can lead to wasted money in unnecessary labor hours and materials. PM is planned downtime which is still downtime. The more time a piece of equipment is down, the less opportunity there is for it to be operating to produce a product or perform a process to support the organization's revenue stream.

An organization typically designs the PM strategy to be a tradeoff between the potential for excess maintenance and the risk of not doing enough maintenance thereby increasing the presence of a fault and failure leading to RM. The potential for excess maintenance leading to excess cost is also balanced with the invested cost of a Predictive Maintenance strategy, discussed in detail in section 2.3.

## 2.3. Predictive Maintenance

Predictive Maintenance (PdM) is a strategy that dictates maintenance activities based upon measures of reliability and/or condition. Reliability-centered maintenance (RCM) and condition-based maintenance (CBM) are under the PdM strategy umbrella. Reliability and condition can be measured at the physical level of a piece of manufacturing equipment, workcell, assembly line, etc. and can also be measured at the functional level of a manufacturing process. Measurements are often obtained through sensor data and can be paired with historical data and models to ascertain existing reliability or conditions. Depending upon the availability of data and/or model richness, future reliability or conditions can be forecast. Regardless of the prediction of a future state, a manufacturers' awareness of current reliability and conditions offers them critical insight to plan maintenance activities.

A key benefit of PdM is that maintenance is timelier and less likely to be unnecessary and excessive as compared to PM. Since PdM maintenance is usually performed less frequently than PM maintenance, there is less equipment downtime allowing for more revenue-generating manufacturing operations. One downside to PdM is that it usually requires a larger upfront investment by the manufacturer as compared to PM. The manufacturer needs to determine exactly what and how they want to monitor. They need to determine what measurements will signal the need for maintenance activities. A financial investment is required to procure and integrate the appropriate hardware and software to capture and analyze the necessary data. Often a workforce investment is required to train personnel on what measures should be monitored, how data should be analyzed, and responses in the presence of specific triggers. Recognizing the advantages and disadvantages of PdM, most manufacturers seek to optimize between PM and PdM while minimizing RM. It is unlikely that manufacturers will maintain the same maintenance strategy paradigm throughout the life of their operation given changing manufacturing equipment and processes, the evolution of sensing and monitoring technology, the increased affordability of computing power and data storage, the expanded capability of software algorithms to monitor and predict future health states, and the possible reconfigurations of assembly lines to produce new or custom products. Manufacturers, particularly those that want to remain competitive on the global stage, should strategically look to advance their maintenance strategies to maximize equipment uptime and maintain necessary part quality and productive targets.

## 2.4. Maintenance Strategy Advancement

There are several motivations for a manufacturer to advance their maintenance strategy including the four motivations mentioned below.

- Increase safety – some faults and failures lead to unsafe working conditions, some of which could be deadly. Advancing a maintenance strategy can lower the probability of realizing a specific fault or failure and/or lower the consequence of the fault or failure in the event it occurs.
- Decrease downtime – all maintenance takes time. RM is unpredictable, can lead to events outside of an organization's control, and result in substantial downtime. Moving to a PM strategy allows an organization to better plan their maintenance efforts and be less likely to succumb to RM. Moving to PdM can also be a great way to further lower maintenance activities if it results in less downtime as compared to a PM strategy.
- Maintain quality – one common side effect of degraded equipment or process health is degraded part or process quality. Even though a process may be operational, degraded quality can indicate the increased potential for a fault or failure or depending upon the level of quality, the process (or equipment) could be considered in a failure state if it cannot produce parts at the required level of quality. Quality measurement can also be an indicator of equipment or process health.
- Maintain productivity – similar to degraded health leading to degraded quality, degraded health can also lead to degraded productivity. For example, if a healthy workcell can produce 35 parts an hour, a degraded workcell may no longer be able to produce at this rate. If the required productivity (to meet customer demand) is 32 parts an hour, a productivity decrease to 34 parts an hour may not result in an immediate maintenance response (if due to degraded health). A response is more likely to occur as the productivity continues downward especially if it falls below 32 parts an hour. Each manufacturer determines their own response to specific productivity changes.

Ultimately, a manufacturer wants to maintain or increase its competitiveness to remain profitable. This can include lowering costs through decreased maintenance activities or increasing revenue by maintaining necessary levels of quality or productivity. Each of the four elements noted above will influence the manufacturer regarding where they should focus their attention and investments. The more certainty a manufacturer has in quantifying a return on investment (especially if it's a relatively short period of time), the more likely they are to make an investment in that specific area – advancing maintenance strategies are no different. Currently, there is a wide range of financial investment in maintenance by the manufacturing community. The data collected in this survey attempts to better ascertain the state of manufacturing maintenance investment.

## 3. Survey and Sampling

Data was collected from manufacturing establishments through a survey instrument, the Machinery Maintenance Survey (see Appendix A), which targeted managers of machinery maintenance. The survey was distributed through multiple means: mail, email, newsletters, and in-person presentations. A total of 85 responses were returned; however, some of these were dropped due to issues with the responses. For instance, some respondents were not manufacturing establishments, and some did not complete key questions. Questions included in the survey are presented in Appendix A. The survey was reviewed by numerous practitioners to ensure that the questions were appropriate and reasonable. Below is a discussion regarding sample size, margin of error, and sample stratification.

### 3.1. Literature Gap and Data Needed

As discussed previously, this report is a continuation of the work that developed NIST AMS 100-18, which examined the literature, available data, and data needs for estimating the costs and losses relevant to different manufacturing maintenance techniques. That report identified that the current literature on maintenance costs and the benefits from investing in maintenance methods has focused on case studies. Much of the research was from other countries, which may or may not reveal insights into U.S. manufacturing. The report identified that data was needed to measure direct maintenance and repair costs, costs from unplanned downtime due to maintenance issues, lost sales due to delays from maintenance issues, lost sales due to quality degradation from maintenance issues, and the costs of defects. Data was also needed to measure the cost of increases in inventory that might result to address disruptions from maintenance issues. The Machinery Maintenance Survey presented in Appendix A was designed to collect the relevant data.

### 3.2. Sample Size and Margin of Error

A minimum sample size required for statistical analysis is influenced by several items, including the margin of error and population size. An estimate of the sample size needed can be represented by:[9,10]

Equation 1

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

where
$N$ = Population size
$e$ = Margin of error

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

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

$z$ = z-score
$p$ = proportion of the population

This method, however, is used 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:[11]

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

where
$\sigma$ = Standard deviation
$e$ = Margin of error
$z$ = z-score

An approximate sample size of 70 to 80 responses or more was targeted, as a previous NIST report estimated that a sample size of 77 would have a 10 % margin of error at a 95 % confidence interval.[12] However, as few as 14 respondents were estimated to result in a 20 % margin of error at a 90 % confidence interval. Figure 3.1 graphs the estimated sample sizes required at different confidence intervals and margins of error with a

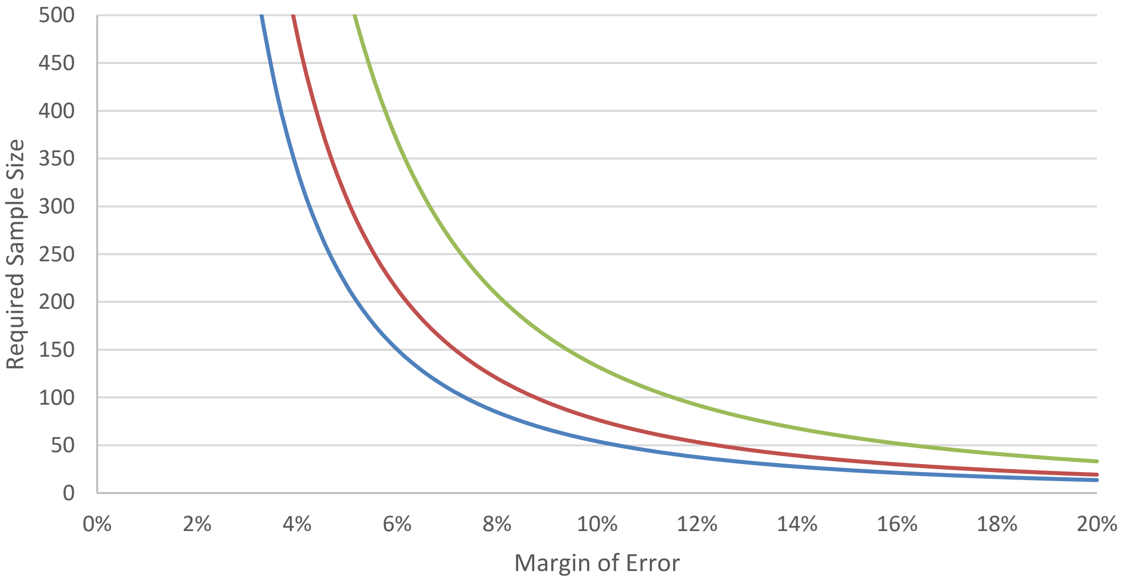

Figure 3.1: Required Sample Size by Margin of Error and Confidence Interval
Note: Standard deviation equals 75 627, as calculated from the Annual Survey of Manufactures
Source: Thomas, Douglas. (2018). The Costs and Benefits of Advanced Maintenance in Manufacturing. NIST Advanced Manufacturing Series 100 18. https://doi.org/10.6028/NIST.AMS.100-18

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[11] NIST. (2013). Engineering Statistics Handbook. Sample Sizes. http://www.itl.nist.gov/div898/handbook/prc/section2/prc222.htm
[12] Thomas, Douglas. (2018). The Costs and Benefits of Advanced Maintenance in Manufacturing. NIST Advanced Manufacturing Series 100 18. https://doi.org/10.6028/NIST.AMS.100-18

constant standard deviation estimated from the Annual Survey of Manufactures. This is only an estimate, as each set of responses in the Machinery Maintenance Survey has its own margin of error. The responses to the Machinery Maintenance Survey tended to have larger error compared to the estimates made using the Annual Survey of Manufactures. This is not entirely surprising, as the Annual Survey of Manufactures asks questions about items that are frequently tracked (e.g., payroll) while the Machinery Maintenance Survey asks about issues that, for many firms, are not formally tracked. A 90 % confidence interval was calculated for the estimates in this report by rearranging the equation for sample size to estimate the margin of error. This value was added/subtracted to the estimate to provide a 90 % confidence interval:[13]

Equation 2

$$Confidence\ Interval = Estimate \pm \frac{z\sigma}{\sqrt{Sample\ Size}}$$

For a 90 % confidence interval, $z$ is equal to 1.645.

### 3.3. Sample Stratification

The surveys that were mailed were stratified by establishment type to increase the probability that there were responses from different groups of establishments. These groupings were by region and industry. Establishments from NAICS 333, 334, 335, and 336 were selected randomly from three regions of the country for a total of 12 stratifications (see Table 3.1). The survey was anonymous; therefore, the responses do not indicate the region. Table 3.2 presents the responses by NAICS by establishment size after the filtering the data.

Table 3.1: Stratification for Mailing Surveys

| Region | NAICS | Description | Distribution |
|---|---|---|---|
| 1 | 333 | Machinery Manufacturing | 25% |
| 2 | 333 | Machinery Manufacturing | 12% |
| 3 | 333 | Machinery Manufacturing | 8% |
| 1 | 334 | Computer and Electronic Product Manufacturing | 10% |
| 2 | 334 | Computer and Electronic Product Manufacturing | 5% |
| 3 | 334 | Computer and Electronic Product Manufacturing | 8% |
| 1 | 335 | Electrical Equipment, Appliance, and Component Manufacturing | 5% |
| 2 | 335 | Electrical Equipment, Appliance, and Component Manufacturing | 3% |
| 3 | 335 | Electrical Equipment, Appliance, and Component Manufacturing | 3% |
| 1 | 336 | Transportation Equipment Manufacturing | 10% |
| 2 | 336 | Transportation Equipment Manufacturing | 7% |
| 3 | 336 | Transportation Equipment Manufacturing | 5% |

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[13] NIST. (2013). Engineering Statistics Handbook. Sample Sizes. http://www.itl.nist.gov/div898/handbook/prc/section2/prc222.htm

Table 3.2: Responses to Survey by Employment Size and Industry

| | 32 | 332 | 333 | 334 | 335 | 336 | 339 | TOTAL |
|---|---|---|---|---|---|---|---|---|
| a. 1 to 4 Employees | | 1 | | | | | | 1 |
| b. 5 to 9 Employees | 1 | 1 | 1 | 2 | | | | 5 |
| c. 10 to 19 Employees | | 1 | 3 | 3 | | | | 7 |
| d. 20 to 49 Employees | 3 | 5 | 3 | 4 | | 1 | 1 | 17 |
| e. 50 to 99 Employees | | 3 | 4 | 2 | 1 | 3 | 1 | 14 |
| f. 100 to 249 Employees | 2 | 8 | 1 | 1 | 2 | 2 | 1 | 17 |
| g. 250 to 499 Employees | 1 | 1 | | | 1 | 2 | 1 | 6 |
| h. 500 to 999 Employees | | 1 | | | | | | 1 |
| i. 1000 or more Employees | | | | 1 | | 1 | | 2 |
| Blank | | | 1 | | | | | 1 |
| TOTAL | 7 | 21 | 13 | 13 | 4 | 9 | 4 | 71 |

## 4. Maintenance Costs and Associated Inventory Costs

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 (e.g., repair). Section 4.1 discusses direct maintenance costs and Section 4.2 presents subsequent damage. Costs due to increased inventory due to uncertainty from maintenance issues is discussed in Section 4.3.

### 4.1. Direct Maintenance Costs

Two general methods are used to estimate direct maintenance costs (e.g., maintenance department expenditures). The first utilizes survey responses to the following topics:

- Establishment size (Question 1)
- Payroll (Question 2)
- Shipments (Question 4)
- NAICS codes (Question 5)
- Maintenance and repair (Question 6)

The responses are scaled-up using industry data on payroll or shipments. Additionally, post stratification by industry and employment size can be used, where portions of the data are each scaled. The scaling would match the company size and industry corresponding to national data:

Equation 3

$$DMC = \sum_{i=1}^{I} \sum_{s=1}^{S} \left( \frac{EM_{x,s,i}}{SM_{x,s,i}} SM_{TOT,s,i} \right)$$

where

$DMC$ = Direct maintenance costs

$EM_{x,s,i}$ = Estimate of maintenance costs for establishment *x* with strata size *s* within industry strata *i*

$SM_{x,s,i}$ = Scaling metric from establishment $x$, which is either total payroll or shipments (depending on the method used) for industry *i* with size *s*

$SM_{TOT,s,i}$ = Total payroll or shipments (depending on the method used) for industry *i* with size $s$, where $TOT$ indicates the total from either the Annual Survey of Manufactures or the Economic Census

Three different stratifications for calculating estimates are utilized in this approach. Stratification is used to address any over/under representation of any groups that could result in skewing estimates of costs. Manufacturers may experience different maintenance costs as a result of the types of products they are producing and the size of their establishment. If one group is over-/under-represented, it can skew the aggregated estimate. The first strata uses a combination of industry and establishment size:

- Industries: NAICS 321-333, 337 and Establishment size: 1 to 99 employees
- Industries: NAICS 334-336, 339 and Establishment size: 1 to 99 employees
- Industries: NAICS 321-333, 337 and Establishment size: 100 or more employees
- Industries: NAICS 334-336, 339 and Establishment size: 100 or more employees

In this strata, industry $i$ varies between two sets of industries: NAICS 321-333, 337 and NAICS 334-336, 339. The establishment size $s$ varies between "1 to 99 employees" and "100 or more employees." The second strata is by employment alone:

- 1 to 19 employees
- 20 to 99 employees
- 100 or more employees

The industry $i$ is constant (i.e., NAICS 321-339 excluding 324 and 325) while establishment size $s$ varies between the three groups. The last strata is by industry:

- NAICS 321-332, 337
- NAICS 333-334
- NAICS 335-336, 339

The establishment size is constant (i.e., all establishment sizes) while industry $i$ varies between the three groups. Moreover, there are three alternatives for varying establishment size $s$ and industry $i$.

The groupings attempt to combine similar types of manufacturing activities while also trying to keep a minimum number of establishments in each group. An alternative to using survey data 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.[14] The data is categorized by altered codes from NAICS (i.e., some codes are combined into unique groupings). 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 repairs.

To estimate internal expenditures, using input-output data, we can first estimate maintenance labor using the Occupational Employment Statistics and estimate additional costs using the data on "NAICS 8113: Commercial and Industrial Machinery and Equipment Repair and Maintenance." Maintenance costs could be estimated by taking the proportion of shipments to payroll in NAICS 8113, which creates a multiplier for maintenance overhead and costs, and multiplying it by the proportion of compensation for

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[14] For additional discussion on input-output tables, please see Horowitz, Karen J. and Mark A. Planting. (2009). Concepts and Method of the Input-Output Accounts. Bureau of Economic Analysis. https://www.bea.gov/sites/default/files/methodologies/IOmanual_092906.pdf

maintenance occupations in discrete manufacturing to total compensation for all employees. This value can then be multiplied by payroll for discrete manufacturing. Finally, the outsourced maintenance can be added. This method is represented as the following:

Equation 4

$$DMC = \left(\frac{SHIP_{8113}}{PR_{8113}}\right)\left(\frac{\sum_{IND=321}^{339}\sum_{OCC=1}^{3} COMP_{OCC,IND}}{\sum_{IND=321}^{339} COMP_{IND}}\right)\left(\sum_{IND=321}^{339} PR_{IND}\right) + OS$$

where

$SHIP_{8113}$ = Shipments or output from the BEA IO data for NAICS 8113 depending on the approach used

$PR_{8113}$ = Payroll from the BEA IO data for NAICS 8113

$PR_{IND}$ = Payroll from the BEA IO data, where $IND$ indexes the set of NAICS codes from 321 through 339, excluding 324 and 325

$COMP_{OCC,IND}$ = Compensation estimated in NIST's Manufacturing Cost Guide, where $OCC$ indexes the set of Standard Occupation Codes 491011, 492000, and 499000 and where $IND$ indexes the set of NAICS codes from 321 through 339, excluding 324 and 325

$COMP_{IND}$ = Compensation estimated in NIST's Manufacturing Cost Guide, where $IND$ indexes the set of NAICS codes from 321 through 339, excluding 324 and 325

$OS$ = Outsourced maintenance

There are numerous options regarding estimating the direct costs of maintenance using Equation 3. Three data sources could be used for $SM_{TOT,s,i}$:

- 2016 Payroll data from the County Business Patterns that is
  - Stratified by establishment size and/or industry NAICS or
  - Not stratified
- 2007 Shipment data from the Economic Census (as discussed later, this source is utilized due to data limitations) that is
  - Stratified by establishment size and/or industry NAICS or
  - Not stratified
- 2016 Shipment data from the Annual Survey of Manufactures
  - Stratified by industry NAICS or
  - Not stratified

To select an option, the following needs to be considered:

- Does using payroll as a proxy for shipments impact the estimate?
- Does maintenance vary significantly by establishment size?
- Does maintenance vary significantly by NAICS code?

The calculations from Equation 4 can be compared to that from Equation 3; however, the former may be less than the latter due to a couple of factors. The first is that there may be fundamental differences in the maintenance that is outsourced compared to that which is internal to an establishment. It is plausible that outsourced maintenance is more standardized, reducing costs and overhead. Internal maintenance might be more specialized or unique.

A series of direct maintenance cost estimates were made, as shown in Table 4.1. Each line in the table represents a different estimate varying the factors shown in the columns. The column labeled "Strata" indicates whether the estimate is stratified by the number of employees in an establishment (i.e., Emp) and/or by the industry NAICS code. The column labeled "Data for Scaling" indicates which dataset was used: County Business Patterns (CBP), Economic Census (EC), or the Annual Survey of Manufactures (ASM). It also indicates whether shipments or payroll was used. Stratified estimates also include the estimate for each stratum. The "Ratio" is the ratio of maintenance costs to payroll/shipments estimated from the survey respondents. The column labeled "Est. A" uses all the respondent data while "Est. B" excludes an outlier.

The estimates for NAICS 321-339 (excluding NAICS 324 and 325) range from $47.5 billion to $121.7 billion; however, as discussed later, using payroll as a proxy for shipments has a significant effect on the estimates. The range of estimates using shipments ranges from $51.9 billion to $79.5 billion. A primary driver in the difference is due to one outlier. As seen in Table 4.1, the average ratio using shipments ranges from 0.006 to 0.032; however, one response, the outlier, has a ratio that is nearly 10 times higher. This is unusually high and seemed to be a mistake when compared to other responses; however, it is also within an industry that produces precision parts. One commonly used threshold for identifying outliers is the lower/upper quartile minus/plus 1.5 times the interquartile.[15] The difference between the outlier and the threshold was more than 12 times the interquartile. Note that the method that avoids using the Machinery Maintenance Survey data (i.e., method using Equation 4) estimates maintenance costs at $47.5 billion, which is closer to the lower estimate using the survey.

Each resultant estimate in Table 4.1 has a different advantage and disadvantage in terms of controlling for various issues (e.g., sampling bias). There is no obvious approach to conclusively determine which method is the most accurate; however, the impact can be compared using different methods to identify which factors are likely to matter more. These comparisons provide anecdotal evidence for selecting the best methods for estimation.

Payroll does not necessarily correlate with the amount of production in an industry as production can be more/less labor intensive; therefore, shipments tends to be the preferred scaling metric. Unfortunately, industry level data on shipments that is stratified by establishment size and industry is from 2007, making it dated. Thus, there are tradeoffs between using shipments and payroll – shipments is a more robust scaler while payroll has more recent data. We can use recent data on shipments, but it will only be stratified by industry. Moreover, it must be determined what factors matter most.

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[15] National Institute of Standards and Technology. 2012. "What are outliers in the data?" https://www.itl.nist.gov/div898/handbook/prc/section1/prc16.htm

Table 4.1: Comparison of Methods for Calculating Direct Maintenance Costs

| Id | Strata | Size (employees) | #Obs. | NAICS Code Included* | Data for Scaling | Est A Ratio | Est B Ratio | Est A Standard Deviation | Est B Standard Deviation | Est A Mean $Billion | Est B Mean $Billion |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 -Emp/NAICS | 1 to 99 | 26 | NAICS 321-333, 337 | CBP: Payroll | 0.124 | 0.078 | 0.056 | 0.020 | 14.4 | 9.0 |
| 2 | 2 -Emp/NAICS | 1 to 99 | 18 | NAICS 334-336, 339 | CBP: Payroll | 0.099 | 0.099 | 0.023 | 0.023 | 3.7 | 3.7 |
| 3 | 3 -Emp/NAICS | 100 or More | 14 | NAICS 321-333, 337 | CBP: Payroll | 0.213 | 0.213 | 0.026 | 0.026 | 36.3 | 36.3 |
| 4 | 4 -Emp/NAICS | 100 or More | 12 | NAICS 334-336, 339 | CBP: Payroll | 0.045 | 0.045 | 0.003 | 0.003 | 8.1 | 8.1 |
| **5** | **Sum of Emp/NAICS Strata** | **Total** | **70** | **NAICS 321-339** | **CBP: Payroll** | **0.118** | **0.101** | **0.040** | **0.021** | **62.5** | **57.2** |
| 6 | 1 - Emp | 1 to 19 | 13 | NAICS 321-339 | CBP: Payroll | 0.112 | 0.112 | 0.024 | 0.024 | 4.5 | 4.5 |
| 7 | 2 - Emp | 20 to 99 | 31 | NAICS 321-339 | CBP: Payroll | 0.114 | 0.075 | 0.055 | 0.020 | 12.9 | 8.5 |
| 8 | 3 - Emp | 100 or More | 26 | NAICS 321-339 | CBP: Payroll | 0.134 | 0.134 | 0.022 | 0.022 | 47.0 | 47.0 |
| **9** | **Sum of EMP Strata** | **Total** | **70** | **NAICS 321-339** | **CBP: Payroll** | **0.118** | **0.101** | **0.040** | **0.021** | **64.3** | **60.0** |
| 10 | 1 - NAICS | Total | 28 | NAICS 321-332, 337 | CBP: Payroll | 0.178 | 0.136 | 0.057 | 0.021 | 79.6 | 61.2 |
| 11 | 2 - NAICS | Total | 26 | NAICS 333-334 | CBP: Payroll | 0.088 | 0.088 | 0.025 | 0.025 | 22.4 | 22.4 |
| 12 | 3 - NAICS | Total | 16 | NAICS 335-336, 339 | CBP: Payroll | 0.065 | 0.065 | 0.008 | 0.008 | 19.6 | 19.6 |
| 13 | **Sum of NAICS Strata** | **Total** | **70** | **NAICS 321-339** | **CBP: Payroll** | **0.118** | **0.101** | **0.040** | **0.021** | **121.7** | **103.2** |
| 14 | 1 -Emp/NAICS | 1 to 99 | 26 | NAICS 321-333, 337 | EC: Shipments | 0.031 | 0.020 | 0.056 | 0.020 | 18.4 | 12.0 |
| 15 | 2 -Emp/NAICS | 1 to 99 | 18 | NAICS 334-336, 339 | EC: Shipments | 0.017 | 0.017 | 0.023 | 0.023 | 2.9 | 2.9 |
| 16 | 3 -Emp/NAICS | 100 or More | 14 | NAICS 321-333, 337 | EC: Shipments | 0.027 | 0.027 | 0.026 | 0.026 | 35.9 | 35.9 |
| 17 | 4 -Emp/NAICS | 100 or More | 12 | NAICS 334-336, 339 | EC: Shipments | 0.006 | 0.006 | 0.003 | 0.003 | 8.3 | 8.3 |
| **18** | **Sum of Emp/NAICS Strata** | **Total** | **70** | **NAICS 321-339** | **EC: Shipments** | **0.022** | **0.018** | **0.040** | **0.021** | **65.6** | **59.1** |
| 19 | 1 - Emp | 1 to 19 | 13 | NAICS 321-339 | EC: Shipments | 0.023 | 0.023 | 0.024 | 0.024 | 3.2 | 3.2 |
| 20 | 2 - Emp | 20 to 99 | 31 | NAICS 321-339 | EC: Shipments | 0.027 | 0.017 | 0.055 | 0.020 | 17.2 | 10.8 |
| 21 | 3 - Emp | 100 or More | 26 | NAICS 321-339 | EC: Shipments | 0.017 | 0.017 | 0.022 | 0.022 | 46.4 | 46.4 |
| **22** | **Sum of EMP Strata** | **Total** | **70** | **NAICS 321-339** | **EC: Shipments** | **0.022** | **0.018** | **0.040** | **0.021** | **66.8** | **60.4** |
| 23 | 1 - NAICS | Total | 28 | NAICS 321-332, 337 | EC: Shipments | 0.032 | 0.021 | 0.057 | 0.021 | 49.4 | 32.0 |
| 24 | 2 - NAICS | Total | 26 | NAICS 333-334 | EC: Shipments | 0.021 | 0.021 | 0.025 | 0.025 | 17.5 | 17.5 |
| 25 | 3 - NAICS | Total | 16 | NAICS 335-336, 339 | EC: Shipments | 0.009 | 0.009 | 0.008 | 0.008 | 10.1 | 10.1 |
| **26** | **Sum of NAICS Strata** | **Total** | **70** | **NAICS 321-339** | **EC: Shipments** | **0.022** | **0.018** | **0.040** | **0.021** | **77.0** | **59.6** |
| 27 | 1 - NAICS | Total | 28 | NAICS 321-332, 337 | ASM: Shipments | 0.032 | 0.021 | 0.057 | 0.021 | 42.6 | 27.6 |
| 28 | 2 - NAICS | Total | 26 | NAICS 333-334 | ASM: Shipments | 0.021 | 0.021 | 0.025 | 0.025 | 13.5 | 13.5 |
| 29 | 3 - NAICS | Total | 16 | NAICS 335-336, 339 | ASM: Shipments | 0.009 | 0.009 | 0.008 | 0.008 | 10.8 | 10.8 |
| **30** | **Sum of NAICS Strata** | **Total** | **70** | **NAICS 321-339** | **ASM: Shipments** | **0.022** | **0.018** | **0.040** | **0.021** | **66.9** | **51.9** |
| 31 | n/a | Total | 70 | NAICS 321-339 | ASM: Shipments | 0.022 | 0.018 | 0.040 | 0.021 | 72.2 | 57.3 |
| 32 | n/a | Total | 70 | NAICS 321-339 | ASM: Payroll | 0.118 | 0.101 | 0.040 | 0.021 | 57.9 | 49.6 |
| 33 | n/a | Total | 70 | NAICS 321-339 | EC: Shipments | 0.022 | 0.018 | 0.040 | 0.021 | 79.5 | 63.0 |
| 36 | n/a | Total | n/a | Total | BEA IO + BLS Occ. | n/a | n/a | n/a | n/a | 47.5 | n/a |

* Excluding NAICS 324 (petroleum and coal products) and NAICS 325 (chemicals)

NOTE: Estimate B excludes an outlier

Table 4.2: Comparison of Methods for Estimating Maintenance Costs

| Reference | Comparison | ID | | Comparison | ID | Absolute Percent Change | Average of Abs. Percent Change |
|---|---|---|---|---|---|---|---|
| 1 | Payroll | 32 - Est. A | vs. | Shipments | 31 - Est. A | 24.7% | 20.1% |
| 2 | Payroll | 32 - Est. B | vs. | Shipments | 31 - Est. B | 15.6% | |
| 3 | 1 - Emp | 19 - Ratio | vs. | 2 - Emp | 20 - Ratio | 15.0% | 27.0% |
| 4 | 1 - Emp | 19 - Ratio | vs. | 3 - Emp | 21 - Ratio | 28.3% | |
| 5 | 2 - Emp | 20 - Ratio | vs. | 3 - Emp | 21 - Ratio | 37.6% | |
| 6 | 1 - NAICS | 23 - Ratio | vs. | 2 - NAICS | 24 - Ratio | 33.7% | 54.7% |
| 7 | 1 - NAICS | 23 - Ratio | vs. | 3 - NAICS | 25 - Ratio | 72.2% | |
| 8 | 2 - NAICS | 24 - Ratio | vs. | 3 - NAICS | 25 - Ratio | 58.1% | |
| 9 | ASM: Shipments | 31 - Est. A | vs. | EC: Shipments | 33 - Est. A | 10.0% | 12.6% |
| 10 | ASM: Shipments | 30 - Est. A | vs. | EC: Shipments | 26 - Est. A | 15.1% | |
| 11 | EC: Shipments | 33 - Est. A | vs. | EC: Shipments | 33 - Est. B | 20.7% | 20.7% |
| 12 | ASM: Shipments | 31 - Est. A | vs. | ASM: Shipments | 31 - Est B. | 20.7% | |

A selection of the estimates is compared in Table 4.2. To gain insight into whether using payroll as a proxy for shipments has a significant effect on the estimate, one can make several comparisons, which are labeled as reference 1 and 2 in the table. Reference 1 compares estimate A for ID 32 (i.e., 32 – Est. A) in Table 4.1 to estimate A for ID 31. Reference 2 compares estimate B for ID 31 and ID 32. These comparisons reveal insight into the impact of using payroll compared to shipments while holding the year, employment, and industry constant. Using payroll as a proxy changed the estimates by between 15.6 % and 24.7 %, a fairly large impact. Scaling using shipments tends to be more stable, regardless of stratification. For instance, all values using this data range between $51.9 billion and $79.5 billion, a range spanning $27.6 billion. Payroll, on the other hand, ranges between $49.6 billion and $121.7 billion, a $72.1 billion range. Moreover, it is preferable to use shipments, as payroll is not a perfect substitute.

Employment size and industry has an impact on the estimates, as seen in comparison reference 3 through 8, which examine the ratios from Table 4.1. As can be seen in the table, the ratios are not the same for different establishment sizes nor is it the same across industries. Therefore, stratification by industry and employment might have a significant impact on the estimates. To stratify using shipments means using the Economic Census data collected for 2007.

Comparing the use of Economic Census data adjusted to 2016 compared to using data from the Annual Survey of Manufactures (i.e., comparison reference 9 and 10) suggests there is a smaller impact (i.e., 12.6 %) from adjusting data than from excluding establishment size from the strata (i.e., 27 % change between strata from reference 3 through 5); however, estimates using the two methods are close. Moreover, using Economic Census data from 2007, excluding the outlier, is a reasonable method for scaling, which puts maintenance costs at \$63.7 billion with a 90 % confidence interval between \$33.9 billion and \$84.3 billion (not shown elsewhere).

One issue with stratifying the data, however, is that there are a small number of establishments (i.e., observations) per strata. Typically, between 10 and 30. Thus, an alternative is to use the Annual Survey of Manufactures estimate with no stratification, which has a similar estimate at \$57.3 billion (see ID 31 in Table 4.1), the confidence interval is slightly tighter, ranging from \$42.4 billion to \$72.2 billion. Because of this issue, when data is scaled, both the Economic Census data and Annual Survey of Manufacturers are used to produce estimates with the latter being considered the primary method.

## 4.2. Additional Costs due to Faults and Failure

In addition to direct maintenance costs (e.g., maintenance department costs), there are potentially unscheduled costs such as damage that might be caused by a breakdown. This category could be a loss rather than a cost; however, maintenance and repair, typically, includes replacement of various parts, components, and equipment. Therefore, for this report, it is included as a cost. To scale this data, Equation 3 is utilized where $EM_{x,s,i}$ is replaced with additional expenditures estimated from question 8 in the Machinery Maintenance Survey.

Table 4.3 provides an estimate of additional costs due to faults and failures. The values are scaled using shipments from the Economic Census and Annual Survey of Manufactures. Using shipments from the Economic Census stratified by size and industry, puts cost estimates at \$16.3 billion. The estimate using total shipments (i.e., ID 14 in Table 4.3) is \$16.3 billion with the 90 % confidence interval being between \$7.1 billion and \$25.5 billion (not shown elsewhere).

## 4.3. Inventory

Uncertainty in production time is often addressed by increasing inventory, which creates a buffer that prevents delays in deliveries. Inventory can result in significant costs, as it ties up the capital invested in producing the inventory and there are costs associated with warehousing. The inventory associated with maintenance is estimated by taking the average of the responses and multiplying by the inventory estimate from the Annual Survey of Manufactures:

Equation 5

$$INV_{TOT} = \sum_{i=1}^{I} \left( PI_i * \frac{INV_{ASM,BOY,i} + INV_{ASM,EOY,i}}{2} \right)$$

$INV_{TOT}$ = Total inventory maintained to deal with delays from unplanned maintenance

$PI_{x,i}$ = Average percent of finished goods inventory maintained to deal with delays from unplanned maintenance for establishments within industry strata $i$

$INV_{ASM,BOY,i}$= Finished goods inventory for the beginning of year (BOY) in the Annual Survey of Manufactures.

$INV_{ASM,EOY,i}$= Finished goods inventory for the end of year (DOY) in the Annual Survey of Manufactures.

The rule of thumb is that carrying costs are 20 % of the value of inventory.[16,17] As seen in Table 4.4, the estimated inventory due to maintenance issues is $4.1 billion, estimated

Table 4.3: Estimated Additional Costs due to Faults and Failures

| Id | Strata | Size (employees) | NAICS Code Included | Source | Ratio of Additional Losses to Shipments | Shipments ($billions) | Estimated Value of Additional Costs due to Maintenance Issues ($billions) |
|---|---|---|---|---|---|---|---|
| 1 | 1 -Emp/NAICS | 1 to 99 | NAICS 321-333, 337 | EC | 0.0056 | 538.4 | 3.4 |
| 2 | 2 -Emp/NAICS | 1 to 99 | NAICS 334-336, 339 | EC | 0.0032 | 154.7 | 0.6 |
| 3 | 3 -Emp/NAICS | 100 or More | NAICS 321-333, 337 | EC | 0.0080 | 1208.2 | 10.8 |
| 4 | 4 -Emp/NAICS | 100 or More | NAICS 334-336, 339 | EC | 0.0011 | 1265.1 | 1.5 |
| **5** | **Total** | **Total** | **NAICS 321-339** | **EC** | **0.0045** | **3166.3** | **16.3** |
| 6 | 1 - Emp | 1 to 19 | NAICS 321-339 | EC | 0.0046 | 121.7 | 0.6 |
| 7 | 2 - Emp | 20 to 99 | NAICS 321-339 | EC | 0.0048 | 571.4 | 3.1 |
| 8 | 3 - Emp | 100 or More | NAICS 321-339 | EC | 0.0044 | 2473.3 | 12.1 |
| **9** | **Total** | **Total** | **NAICS 321-339** | **EC** | **0.0045** | **3166.3** | **15.8** |
| 6 | 1 - NAICS | Total | NAICS 321-332, 337 | EC | 0.0072 | 1396.1 | 11.2 |
| 7 | 2 - NAICS | Total | NAICS 333-334 | EC | 0.0042 | 746.2 | 3.5 |
| 8 | 3 - NAICS | Total | NAICS 335-336, 339 | EC | 0.0014 | 1024.0 | 1.6 |
| **9** | **Total** | **Total** | **NAICS 321-339** | **EC** | 0.0045 | **3166.3** | **16.3** |
| 10 | 1 - NAICS | Total | NAICS 321-332, 337 | ASM | 0.0072 | 1342.4 | 10.7 |
| 11 | 2 - NAICS | Total | NAICS 333-334 | ASM | 0.0042 | 642.0 | 3.0 |
| 12 | 3 - NAICS | Total | NAICS 335-336, 339 | ASM | 0.0014 | 1228.7 | 2.0 |
| **13** | **Total** | **Total** | **NAICS 321-339** | **ASM** | **0.0045** | **3213.1** | **15.7** |
| 14 | n/a | Total | **NAICS 321-339** | ASM | 0.0045 | **3213.1** | **16.3** |

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[16] Tuovila, Alicia. 2019. "Inventory Carrying Cost." https://www.investopedia.com/terms/c/carryingcostofinventory.asp

[17] Wasp Barcode Technologies. 2020. "The Real Cost of Carrying Inventory." http://www.waspbarcode.com/buzz/real-cost-carrying-inventory

using industry strata, and $4.3 billion without strata. Therefore, the estimated costs, assuming the cost is 20 % of inventory, are between $0.8 billion and $0.9 billion.

Table 4.4: Inventory due to Maintenance Issues

| Id | Strata | Size (employees) | NAICS Code Included | Percent of Inventory due to Maintenance Issues | Total Inventories ($billion) | Inventory due to Maintenance Issues ($billion) |
|---|---|---|---|---|---|---|
| 1 | 1 -Emp/NAICS | 1 to 99 | NAICS 321-333, 337 | 3.8 | n/a | - |
| 2 | 2 -Emp/NAICS | 1 to 99 | NAICS 334-336, 339 | 2.3 | n/a | - |
| 3 | 3 -Emp/NAICS | 100 or More | NAICS 321-333, 337 | 2.6 | n/a | - |
| 4 | 4 -Emp/NAICS | 100 or More | NAICS 334-336, 339 | 5.4 | n/a | - |
| **5** | **Total** | **Total** | **NAICS 321-339** | **3.5** | **n/a** | **-** |
| 6 | 1 - Emp | 1 to 19 | NAICS 321-339 | 4.8 | n/a | - |
| 7 | 2 - Emp | 20 to 99 | NAICS 321-339 | 2.5 | n/a | - |
| 8 | 3 - Emp | 100 or More | NAICS 321-339 | 3.9 | n/a | - |
| **9** | **Total** | **Total** | **NAICS 321-339** | **3.5** | **n/a** | **-** |
| 10 | 1 - NAICS | Total | NAICS 321-332, 337 | 3.3 | 59.9 | 2.0 |
| 11 | 2 - NAICS | Total | NAICS 333-334 | 3.5 | 32.9 | 1.2 |
| 12 | 3 - NAICS | Total | NAICS 335-336, 339 | 3.1 | 31.7 | 1.0 |
| 13 | **Total** | **Total** | **NAICS 321-339** | **3.5** | **175.8** | **4.1** |
| **14** | **n/a** | **Total** | **NAICS 321-339** | **3.5** | **124.5** | **4.3** |

## 5. Losses due to Maintenance Issues

In addition to the costs of maintenance and repair, there are losses that result from inadequate maintenance and unexpected breakdowns that might have been prevented through more rigorous maintenance methods. This section estimates these losses, including unplanned downtime (Section 5.1), defects (Section 5.2), lost sales due to delays or defects (Section 5.3), and injuries (Section 5.4).

### 5.1. Unplanned Downtime

When machinery unexpectedly breaks down due to maintenance issues, operations can be stopped. This leaves labor and machinery unexpectedly idle. Question 9 of the Machinery Maintenance Survey inquires about the percent of planned production time that is unplanned downtime and the percent of that downtime that is due to maintenance activities. If there was less downtime, then lower levels of energy, labor, and capital would be, in general, needed to produce the same goods. To estimate the cost of unplanned downtime, the percent of planned production time that is unplanned downtime due to maintenance issues is multiplied by the cost of energy, labor, and capital. This can be represented as:

Equation 6

$$DTC = \sum_{i=1}^{I}\left[DWN_i * DM_i * \left(E_i + L_i + K_{i,M} + K_{i,B}\right)\right]$$

where

$DTC$ = Unplanned downtime costs due to maintenance issues

$DWN_i$ = Average percent downtime for industry strata $i$ from question 9 in the Machinery Maintenance Survey

$DM_i$ = Average percent of downtime that is due to maintenance for industry strata $i$ from question 9.a in the Machinery Maintenance Survey

$E_i$ = Sum of energy costs for industry strata $i$ from the Annual Survey of Manufactures

$L_i$ = Sum of labor costs for industry strata $i$ from the Annual Survey of Manufactures

$K_{i,M}$ = Sum of annual capital expenditures for machinery ($M$) for industry strata $i$ from the Annual Survey of Manufactures

$K_{i,B}$ = Sum of annual capital expenditures for buildings ($B$) for industry strata $i$ from the Annual Survey of Manufactures

Energy and capital data are not available by establishment size; therefore, estimates for size strata are not made. Table 5.1 presents the estimates for downtime costs due to maintenance issues. Labor costs range from $12.1 billion to $13.8 billion. Capital costs for machinery ranges from $2.5 billion to $2.6 billion and for buildings it is $1.0 billion. The cost of energy is between $1.1 billion and $1.3 billion. The total is $18.1 billion with the

Table 5.1: Downtime Costs due to Maintenance Issues

| Id | Strata | Size (employees) | NAICS Code Included | | Percent of Planned Production Time that is Downtime | Percent of Downtime due to Reactive Maintenance | Estimated Cost of Downtime due to Maintenance Issues - Labor ($billion) | Estimated Cost of Downtime - Capital Depreciation for Machinery ($billion) | Estimated Cost of Downtime - Capital Depreciation for Buildings ($billion) | Estimated Cost of Downtime - Energy ($billion) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 -Emp/NAICS | 1 to 99 | NAICS 321-333, 337 | EC | 7.9 | 39.9 | 3.7 | - | - | - |
| 2 | 2 -Emp/NAICS | 1 to 99 | NAICS 334-336, 339 | EC | 4.0 | 36.5 | 0.5 | - | - | - |
| 3 | 3 -Emp/NAICS | 100 or More | NAICS 321-333, 337 | EC | 12.8 | 15.8 | 3.9 | - | - | - |
| 4 | 4 -Emp/NAICS | 100 or More | NAICS 334-336, 339 | EC | 7.4 | 28.2 | 3.9 | - | - | - |
| **5** | **Total** | **Total** | **NAICS 321-339** | **EC** | **7.8** | **31.7** | **12.1** | **-** | **-** | **-** |
| 6 | 1 - Emp | 1 to 19 | NAICS 321-339 | EC | 8.5 | 19.8 | 0.5 | - | - | - |
| 7 | 2 - Emp | 20 to 99 | NAICS 321-339 | EC | 5.6 | 46.0 | 3.2 | - | - | - |
| 8 | 3 - Emp | 100 or More | NAICS 321-339 | EC | 10.5 | 21.7 | 8.7 | - | - | - |
| **9** | **Total** | **Total** | **NAICS 321-339** | **EC** | **7.8** | **31.7** | **12.4** | **-** | **-** | **-** |
| 10 | 1 - NAICS | Total | NAICS 321-332, 337 | EC | 9.8 | 32.9 | 8.0 | - | - | - |
| 11 | 2 - NAICS | Total | NAICS 333-334 | EC | 7.3 | 29.7 | 2.9 | - | - | - |
| 12 | 3 - NAICS | Total | NAICS 335-336, 339 | EC | 5.1 | 34.4 | 2.6 | - | - | - |
| 13 | **Total** | **Total** | **NAICS 321-339** | **EC** | **7.8** | **31.7** | **13.6** | **-** | **-** | **-** |
| 14 | 1 - NAICS | Total | NAICS 321-332, 337 | ASM | 9.8 | 32.9 | 8.0 | 1.7 | 0.6 | 1.0 |
| 15 | 2 - NAICS | Total | NAICS 333-334 | ASM | 7.3 | 29.7 | 2.9 | 0.4 | 0.2 | 0.1 |
| 16 | 3 - NAICS | Total | NAICS 335-336, 339 | ASM | 5.1 | 34.4 | 2.9 | 0.5 | 0.2 | 0.1 |
| 17 | **Total** | **Total** | **NAICS 321-339** | **ASM** | **7.8** | **31.7** | **13.8** | **2.6** | **1.0** | **1.3** |
| 18 | **n/a** | **Total** | **NAICS 321-339** | **ASM** | **7.8** | **31.7** | **13.5** | **2.5** | **1.0** | **1.1** |

90 % confidence interval for the total (i.e., ID 18 from Table 5.1) being between $9.4 billion and $29.5 billion (not shown elsewhere).

## 5.2. Defects

In addition to downtime costs, there are products that are scrapped or reworked because of defects. Question 10 in the Machinery Maintenance Survey asks about the rate of product defects and the percent that is associated with maintenance issues. To estimate the losses from defects, the percent of products that are defective due to maintenance issues is multiplied by the value of shipments:

Equation 7

$$COD = \sum_{i=1}^{I} DEF_i * DM_i * SHIP_i$$

where

$COD$ = Cost of defects

$DEF_i$ = Average percent of products that are defective for industry strata $i$ from question 10 in the Machinery Maintenance Survey

$DM_i$ = Average percent of defects for industry strata $i$ that is due to maintenance issues from question 10.a in the Machinery Maintenance Survey

$SHIP_i$ = The total value of shipments for industry strata $i$ from the Annual Survey of Manufactures or Economic Census

As seen in Table 5.2, the defect rate varies between 0.1 % and 2.7 % for the different strata. Only a small percent of the defects was attributed to maintenance issues, which

Table 5.2: Defects due to Reactive Maintenance

| Id | Strata | Size (employees) | NAICS Code Included | Source | Rate of Defects (percent) | Percent of Defects due to Reactive Maintenance | Shipments ($billions) | Estimated Value of Defects due to Reactive Maintenance ($million) |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 -Emp/NAICS | 1 to 99 | NAICS 321-333, 337 | EC | 1.3 | 2.5 | 538.4 | 200 |
| 2 | 2 -Emp/NAICS | 1 to 99 | NAICS 334-336, 339 | EC | 0.2 | 1.7 | 154.7 | 7 |
| 3 | 3 -Emp/NAICS | 100 or More | NAICS 321-333, 337 | EC | 2.7 | 0.2 | 1 208.2 | 71 |
| 4 | 4 -Emp/NAICS | 100 or More | NAICS 334-336, 339 | EC | 0.7 | 3.4 | 1 265.1 | 332 |
| **5** | **Total** | **Total** | **NAICS 321-339** | **EC** | **1.2** | **2.1** | **3 166.3** | **609** |
| 6 | 1 - Emp | 1 to 19 | NAICS 321-339 | EC | 0.1 | 0.1 | 121.7 | 0 |
| 7 | 2 - Emp | 20 to 99 | NAICS 321-339 | EC | 1.2 | 3.1 | 571.4 | 244 |
| 8 | 3 - Emp | 100 or More | NAICS 321-339 | EC | 1.7 | 1.9 | 2 473.3 | 899 |
| **9** | **Total** | **Total** | **NAICS 321-339** | **EC** | **1.2** | **2.1** | **3 166.3** | **1 143** |
| 10 | 1 - NAICS | Total | NAICS 321-332, 337 | EC | 1.5 | 1.3 | 1 396.1 | 291 |
| 11 | 2 - NAICS | Total | NAICS 333-334 | EC | 1.5 | 2.2 | 746.2 | 269 |
| 12 | 3 - NAICS | Total | NAICS 335-336, 339 | EC | 0.5 | 3.1 | 1 024.0 | 166 |
| **13** | **Total** | **Total** | **NAICS 321-339** | **EC** | **1.2** | **2.1** | **3 166.3** | **726** |
| 14 | 1 - NAICS | Total | NAICS 321-332, 337 | ASM | 1.5 | 1.3 | 1 342.4 | 250 |
| 15 | 2 - NAICS | Total | NAICS 333-334 | ASM | 1.5 | 2.2 | 642.0 | 207 |
| 16 | 3 - NAICS | Total | NAICS 335-336, 339 | ASM | 0.5 | 3.1 | 1 228.7 | 179 |
| **17** | **Total** | **Total** | **NAICS 321-339** | **ASM** | **1.2** | **2.1** | **3 213.1** | **636** |
| **18** | **n/a** | **Total** | **NAICS 321-339** | **ASM** | **1.2** | **2.1** | **3 213.1** | **810** |

ranged between 0.1 % and 3.4 % among the strata. The low percent associated with maintenance resulted in the cost of defects being one of the lower costs associated with maintenance. Using a method of stratifying by industry and establishment size, the cost of defects due to maintenance is estimated at $0.6 billion. Using unstratified data from the Annual Survey of Manufactures, the estimate is $0.8 billion with a 90 % confidence interval between $24 million to $2.7 billion (not shown elsewhere). The wide range is due to significant variation in both the reported defect rates and percent of defects due to maintenance.

### 5.3. Lost Sales due to Maintenance Issues

In some instances, defects and downtime can result in lost sales due to quality issues and delayed deliveries. The Machinery Maintenance Survey asked manufacturers about the lost sales due to these issues (see questions 9.b and 10.b). To estimate the value of lost sales, the percent of lost sales is multiplied by total shipments from the Annual Survey of Manufactures or the Economic Census:

Equation 8

$$TLS = \sum_{s=1}^{S} \sum_{i=1}^{I} \left[ SHIP_{s,i} * \left( LS_{DF,s,i} + LS_{DWN,s,i} \right) \right]$$

where

$TLS$ = Total lost sales due to delays or defects due to maintenance issues

$LS_{z,s,i}$ = Average of the percent of sales lost due to $z$ for establishments with strata size *s* within industry strata $i$ where $z$ is either defects ($DF$) or downtime ($DWN$)

$SHIP_{s,i}$ = Shipments from either the Economic Census or the Annual Survey of Manufactures within industry strata *i* with strata size *s*

As seen in Table 5.3, the cost of lost sales due to maintenance issues is estimated at $88.3 billion, using strata by size and industry. With no strata, the estimate is $100.2 billion with a 90 % confidence interval between $33.5 billion and $166.8 billion (not shown elsewhere). The wide range is not unexpected, as this is a difficult item to assess; that is, it is difficult to know what sales are lost. It is important to note that some of these sales are lost to other U.S. establishments; thus, one establishment's loss is another's gain. However, some losses can go to establishments outside of the U.S.

Table 5.3: Lost Sales due to Unplanned Downtime Caused by Maintenance Issues

| Id | Strata | Size (employees) | NAICS Code Included | Source | Average lost sales due to maintenance issues causing defects (percent) | Average lost sales due to maintenance issues causing delays (percent) | Estimated Value of Lost Sales due to Maintenance Issues ($billions) |
|---|---|---|---|---|---|---|---|
| 1 | 1 -Emp/NAICS | 1 to 99 | NAICS 321-333, 337 | EC | 1.8 | 3.6 | 31.9 |
| 2 | 2 -Emp/NAICS | 1 to 99 | NAICS 334-336, 339 | EC | 0.1 | 1.1 | 2.1 |
| 3 | 3 -Emp/NAICS | 100 or More | NAICS 321-333, 337 | EC | 0.2 | 1.5 | 23.3 |
| 4 | 4 -Emp/NAICS | 100 or More | NAICS 334-336, 339 | EC | 1.1 | 1.1 | 30.9 |
| **5** | **Total** | **Total** | **NAICS 321-339** | **EC** | **1.0** | **2.1** | **88.3** |
| 6 | 1 - Emp | 1 to 19 | NAICS 321-339 | EC | 1.0 | 2.3 | 4.4 |
| 7 | 2 - Emp | 20 to 99 | NAICS 321-339 | EC | 1.2 | 2.8 | 25.6 |
| 8 | 3 - Emp | 100 or More | NAICS 321-339 | EC | 0.7 | 1.3 | 53.8 |
| **9** | **Total** | **Total** | **NAICS 321-339** | **EC** | **1.0** | **2.1** | **83.9** |
| 10 | 1 - NAICS | Total | NAICS 321-332, 337 | EC | 1.1 | 3.1 | 64.5 |
| 11 | 2 - NAICS | Total | NAICS 333-334 | EC | 1.2 | 1.8 | 25.1 |
| 12 | 3 - NAICS | Total | NAICS 335-336, 339 | EC | 0.5 | 1.3 | 20.7 |
| **13** | **Total** | **Total** | **NAICS 321-339** | **EC** | **1.0** | **2.1** | **110.3** |
| 14 | 1 - NAICS | Total | NAICS 321-332, 337 | ASM | 1.1 | 3.1 | 55.6 |
| 15 | 2 - NAICS | Total | NAICS 333-334 | ASM | 1.2 | 1.8 | 19.3 |
| 16 | 3 - NAICS | Total | NAICS 335-336, 339 | ASM | 0.5 | 1.3 | 22.2 |
| **17** | **Total** | **Total** | **NAICS 321-339** | **ASM** | **1.0** | **2.1** | **97.1** |
| **18** | **n/a** | **Total** | **NAICS 321-339** | **ASM** | **1.0** | **2.1** | **100.2** |

## 5.4. Injuries

Machinery that breaks down can also be associated with injuries. Question 13 of the Machinery Maintenance Survey asks about the percent of injuries that are associated with reactive maintenance. To estimate the number of injuries and deaths, the average percent of injuries associated with maintenance issues was estimated for each industry strata and multiplied by the number of injuries in that strata recorded in the Bureau of Labor Statistics' Injuries, Illness, and Fatalities Program:[18]

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[18] Bureau of Labor Statistics. (2019). Injuries, Illness, and Fatalities Program. http://www.bls.gov/iif/

Equation 9

$$INJ_{MAIN} = \sum_{i=1}^{I} \left( PI_i * INJ_{BLS,i} \right)$$

where

$INJ_{MAIN}$ = Estimated number of injuries due to maintenance issues

$PI_i$ = Percent of injuries associated with maintenance issues from question 13 in the Manufacturing Maintenance Survey

$INJ_{BLS,i}$ = Number of injuries from industry strata $i$ from the Bureau of Labor Statistics' Injuries, Illness, and Fatalities Program

Deaths were estimated in a similar fashion where injuries are replaced with deaths from the Bureau of Labor Statistics' Injuries, Illness, and Fatalities Program. The industry data is not parsed by establishment size; therefore, estimates cannot be made using strata by establishment size. As seen in Table 5.4, the estimated number of injuries is 134.9 using

Table 5.4: Injuries and Deaths Associated with Maintenance Issues

| Id | Strata | Size (employees) | NAICS Code Included | Percent of Injuries due to Maintenance | Total Injuries | Total Deaths | Estimated Injuries due to Maintenance | Estimated Deaths due to Maintenance |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 -Emp/NAICS | 1 to 99 | NAICS 321-333, 337 | 0.0 | n/a | n/a | - | - |
| 2 | 2 -Emp/NAICS | 1 to 99 | NAICS 334-336, 339 | 0.0 | n/a | n/a | - | - |
| 3 | 3 -Emp/NAICS | 100 or More | NAICS 321-333, 337 | 0.2 | n/a | n/a | - | - |
| 4 | 4 -Emp/NAICS | 100 or More | NAICS 334-336, 339 | 0.7 | n/a | n/a | - | - |
| **5** | **Total** | **Total** | **NAICS 321-339** | **0.2** | **n/a** | **n/a** | **-** | **-** |
| 6 | 1 - Emp | 1 to 19 | NAICS 321-339 | 0.0 | n/a | n/a | - | - |
| 7 | 2 - Emp | 20 to 99 | NAICS 321-339 | 0.0 | n/a | n/a | - | - |
| 8 | 3 - Emp | 100 or More | NAICS 321-339 | 0.4 | n/a | n/a | - | - |
| **9** | **Total** | **Total** | **NAICS 321-339** | **0.2** | **n/a** | **n/a** | **-** | **-** |
| 10 | 1 - NAICS | Total | NAICS 321-332, 337 | 0.1 | 52 170 | 181 | 42.4 | 0.1 |
| 11 | 2 - NAICS | Total | NAICS 333-334 | 0.0 | 12 520 | 43 | 0.0 | 0.0 |
| 12 | 3 - NAICS | Total | NAICS 335-336, 339 | 0.4 | 22 100 | 43 | 92.5 | 0.2 |
| **13** | **Total** | **Total** | **NAICS 321-339** | **0.2** | **86 790** | **267** | **134.9** | **0.3** |
| **14** | **n/a** | **Total** | **NAICS 321-339** | **0.2** | **86 790** | **267** | **134.1** | **0.4** |

strata by industry and 134.1 with no strata with a 90 % confidence interval between 0 and 492.7 (not shown). The estimated number of deaths was 0.3 using strata by industry or roughly one death every three years. Using no strata, the number of deaths was 0.4 with a 90 % confidence interval between 0 and 1.5 (not shown).

## 6. Perceived Benefits of Advancing Maintenance Strategies

Managers of machinery maintenance might believe that their establishment would benefit from investing in their maintenance strategies. Question 12 of the Machinery Maintenance Survey asks about some of these benefits, including downtime, sales, and injuries. Benefits are estimated in Table 6.1. Cost savings from downtime reduction was calculated by multiplying the percent of establishments that indicated there would be a benefit from adopting predictive maintenance by the percent reduction in downtime multiplied by the percent of planned production time that was down time from question 9. This was multiplied by the sum of labor, capital, and energy expenditures from the Annual Survey of Manufactures:

Equation 10

$$Benefits_{Dwn} = \sum_{i=1}^{I} \left[ DWN_i * RD_i * \left( E_i + L_i + K_{i,M} + K_{i,B} \right) \right]$$

where

$Benefits_{Dwn}$ = Perceived benefits from reduced unplanned downtime resulting from adopting predictive maintenance

$DWN_i$ = Average percent downtime for industry strata $i$ from question 9 in the Machinery Maintenance Survey

$RD_i$ = Average percent reduction in downtime that is due to adopting predictive maintenance for industry strata $i$ from question 12 in the Machinery Maintenance Survey

$E_i$ = Sum of energy costs for industry strata $i$ from the Annual Survey of Manufactures

$L_i$ = Sum of labor costs for industry strata $i$ from the Annual Survey of Manufactures

$K_{i,M}$ = Sum of annual capital expenditures for machinery (M) industry strata $i$ from the Annual Survey of Manufactures

$K_{i,B}$ = Sum of annual capital expenditures for buildings (B) for industry strata $i$ from the Annual Survey of Manufactures

Increased sales due to the adoption of predictive maintenance was calculated by multiplying the percent increase in sales by shipments:

Equation 11

$$Benefits_{Sales} = \sum_{s=1}^{S} \sum_{i=1}^{I} \left[ SHIP_{s,i} * IS_{s,i} \right]$$

where

$Benefits_{Sales}$= Increased sales due to adopting predictive maintenance

$IS_{s,i}$ = Average increase in sales due to adopting predictive maintenance for establishments with strata size $s$ within industry strata $i$

Table 6.1: Perceived Benefits of Adopting Predictive Maintenance

| Id | Strata | Size (employees) | NAICS Code Included | | Percent that indicated a benefit | Percent change in downtime, if any | Cost Savings from Downtime Reduction ($billion) | Percent change in sales, if any | Increase in Sales ($billion) | Percent change in injuries, if any |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 -Emp/NAICS | 1 to 99 | NAICS 321-333, 337 | EC | 46.2 | -29.3 | | 5.3 | 13.2 | -0.3 |
| 2 | 2 -Emp/NAICS | 1 to 99 | NAICS 334-336, 339 | EC | 66.7 | -3.5 | | 1.2 | 1.3 | 0.0 |
| 3 | 3 -Emp/NAICS | 100 or More | NAICS 321-333, 337 | EC | 85.7 | -12.8 | | 1.7 | 17.9 | -1.0 |
| 4 | 4 -Emp/NAICS | 100 or More | NAICS 334-336, 339 | EC | 100.0 | -18.4 | | 2.2 | 27.7 | 0.0 |
| **5** | **Total** | **Total** | **NAICS 321-339** | **EC** | **67.2** | **-16.9** | | **3.1** | **60.1** | **-0.3** |
| 6 | 1 - Emp | 1 to 19 | NAICS 321-339 | EC | 33.3 | -6.3 | | 3.3 | 1.3 | -0.7 |
| 7 | 2 - Emp | 20 to 99 | NAICS 321-339 | EC | 62.1 | -23.0 | | 4.0 | 14.3 | 0.0 |
| 8 | 3 - Emp | 100 or More | NAICS 321-339 | EC | 92.0 | -14.7 | | 1.9 | 44.4 | -0.4 |
| **9** | **Total** | **Total** | **NAICS 321-339** | **EC** | **67.2** | **-16.9** | | **3.1** | **59.9** | **-0.3** |
| 6 | 1 - NAICS | Total | NAICS 321-332, 337 | EC | 60.7 | -16.4 | | 4.1 | 35.1 | -0.7 |
| 7 | 2 - NAICS | Total | NAICS 333-334 | EC | 66.7 | -16.7 | | 3.0 | 15.0 | -0.2 |
| 8 | 3 - NAICS | Total | NAICS 335-336, 339 | EC | 78.6 | -20.2 | | 1.8 | 14.6 | 0.0 |
| **9** | **Total** | **Total** | **NAICS 321-339** | **EC** | **67.2** | **-16.9** | | **3.1** | **64.6** | **-0.3** |
| 10 | 1 - NAICS | Total | NAICS 321-332, 337 | ASM | 60.7 | -16.4 | 3.5 | 4.1 | 33.7 | -0.7 |
| 11 | 2 - NAICS | Total | NAICS 333-334 | ASM | 66.7 | -16.7 | 1.4 | 3.0 | 12.9 | -0.2 |
| 12 | 3 - NAICS | Total | NAICS 335-336, 339 | ASM | 78.6 | -20.2 | 1.7 | 1.8 | 17.5 | 0.0 |
| **13** | **Total** | **Total** | **NAICS 321-339** | **ASM** | **67.2** | **-16.9** | **6.5** | **3.1** | **64.1** | **-0.3** |
| **14** | **n/a** | **Total** | **NAICS 321-339** | **ASM** | **67.2** | **-16.9** | **6.5** | **3.1** | **67.3** | **-0.3** |

$SHIP_{s,i}$ = Shipments from either the Economic Census or the Annual Survey of Manufactures within industry strata *i* with strata size *s*

The percent change in injuries is the average for each industry/size strata. The total benefits of decreased downtime and increased sales amount to $70.6 billion, estimated using industry strata. The total is $73.8 billion without stratifying and has a 90 % confidence interval between $39.5 billion and $109.4 billion (not shown elsewhere).

## 7. Observed Benefits of Preventive and Predictive Maintenance

On average, establishment maintenance practices were 17.3 % predictive maintenance, 31.8 % preventive maintenance, and 45.7 % reactive maintenance (see Table 7.1). However, there were significant variations between establishments. One question that arises is how the costs and losses compare for the different levels of predictive, preventive, and reactive maintenance. In this section, we compare establishments by the types of maintenance that they employ. It is important to note that although decreased costs/losses might be associated with advanced maintenance strategies, the decrease may not be completely caused by them. For instance, an establishment might take multiple measures to reduce defects or downtime.

Table 7.1: Distribution of Maintenance Types

| Id | Strata | Size (employees) | NAICS Code Included | Predictive | Preventive | Reactive | Other |
|---|---|---|---|---|---|---|---|
| 1 | 1 -Emp/NAICS | 1 to 99 | NAICS 321-333, 337 | 19.9 | 25.2 | 51.8 | 3.1 |
| 2 | 2 -Emp/NAICS | 1 to 99 | NAICS 334-336, 339 | 20.4 | 37.2 | 36.2 | 5.4 |
| 3 | 3 -Emp/NAICS | 100 or More | NAICS 321-333, 337 | 13.7 | 28.1 | 52.4 | 5.9 |
| 4 | 4 -Emp/NAICS | 100 or More | NAICS 334-336, 339 | 13.2 | 45.0 | 33.9 | 6.7 |
| **5** | **Total** | **Total** | **NAICS 321-339** | **17.3** | **31.8** | **45.7** | **4.7** |
| 6 | 1 - Emp | 1 to 19 | NAICS 321-339 | 20.2 | 31.0 | 43.8 | 5.1 |
| 7 | 2 - Emp | 20 to 99 | NAICS 321-339 | 20.1 | 29.7 | 46.2 | 3.4 |
| 8 | 3 - Emp | 100 or More | NAICS 321-339 | 13.5 | 35.9 | 43.8 | 6.2 |
| **9** | **Total** | **Total** | **NAICS 321-339** | **17.3** | **31.8** | **45.7** | **4.7** |
| 10 | 1 - NAICS | Total | NAICS 321-332, 337 | 17.9 | 27.1 | 49.9 | 5.1 |
| 11 | 2 - NAICS | Total | NAICS 333-334 | 20.0 | 31.3 | 44.6 | 4.9 |
| 12 | 3 - NAICS | Total | NAICS 335-336, 339 | 14.3 | 37.2 | 42.5 | 3.9 |
| 13 | **Total** | **Total** | **NAICS 321-339** | **17.3** | **31.8** | **45.7** | **4.7** |

### 7.1. High and Low Levels of Reactive Maintenance

Table 7.2 presents the average levels of various responses by the level of reactive maintenance that they have. The first group are those that heavily use reactive maintenance, representing the top 25 %. The next group are those that were in the middle (i.e., the middle 50 %) and the last group are those with the least amount, representing the bottom 25 %. As can be seen, those in the top 25 % had 3.28 times more downtime than those who used RM the least, 13.0 % downtime compared to 4.0 %. The planned production time that was downtime associated with maintenance was 7.17 times higher, 6.7 % compared to 0.9 %. The defect rate was 16.00 times higher for those in the top 25 % compared to those in the bottom 25 %, 3.3 % compared to 0.2 % defect rates. Similarly, lost sales were 1.9 % due

Table 7.2: High and Low Level of Reactive Maintenance Compared, Average of Responses

| Percent of Maintenance that is Reactive, Groupings | Percent of Maintenance that is Reactive | Ratio of Maintenance Costs to the Value of Shipments | Percent of Planned Production Time that is Downtime | Percent of Downtime that is due to Reactive Maintenance | Percent of Planned Production Time that is Downtime due to Maintenance Issues | Defect Rate | Percent of Sales Lost due to Defects Resulting from Maintenance Issues | Percent of Sales Lost due to Delays Resulting from Maintenance Issues | Ratio of Additional Costs Due to Irreparable Faults and Failures to Shipments | Percent Increase in Inventory due to Maintenance | Shipments ($million) | Percent that Primarily use a Pull or Make to Order Strategy as Opposed to a Push or Make to Stock Strategy | Percent that are Differentiators |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Highest 25 Percent | 81.5 | 0.019 | 13.0 | 51.6 | 6.7 | 3.3 | 1.9 | 2.6 | 0.0067 | 6.7 | 36.6 | 50.0 | 66.7 |
| Middle 50 Percent | 44.1 | 0.020 | 6.8 | 26.0 | 1.8 | 0.6 | 0.6 | 2.5 | 0.0044 | 2.5 | 6.1 | 77.4 | 74.2 |
| Lowest 25 Percent | 14.4 | 0.030 | 4.0 | 23.6 | 0.9 | 0.2 | 0.7 | 1.1 | 0.0030 | 1.4 | 121.7 | 89.5 | 73.7 |
| High 25 divided by Low 25 | 5.67 | 0.62 | 3.28 | 2.18 | 7.17 | 16.00 | 2.81 | 2.37 | 2.25 | 4.89 | 0.30 | 0.56 | 0.90 |
| Low 25 divided by High 25 | 0.18 | 1.61 | 0.30 | 0.46 | 0.14 | 0.06 | 0.36 | 0.42 | 0.44 | 0.20 | 3.33 | 1.79 | 1.11 |

to defects and 2.6 % for delays compared to 0.7 % and 1.1 %; that is, they were 2.81 and 2.37 times higher. The ratio of additional costs was 2.25 times higher and inventory increases were 4.89 times higher. Given the small sample in these different groupings, many of the differences are not statistically significant, making them anecdotal evidence; however, using the students t-test to "determine whether two samples are likely to have come from the same two underlying populations that have the same mean,"[19] the difference in downtime due to maintenance issues and inventory for the top and bottom 25 % were statistically significant at the 10 % level. In this instance it was assumed that there were unequal variances. Those who relied less on reactive maintenance were more likely to have a pull (i.e., make to order) stock strategy and were more likely to be a differentiator. These last two tendencies make sense, as customers are more likely to be affected by delays due to downtime in a make to order stock strategy. Similarly, defects have greater consequences for an establishment that competes by differentiating itself, as opposed to competing based on cost.

## 7.2. High and Low Levels of Predictive/Preventive Maintenance

The previous section examined reactive maintenance. This section examines those that utilizes predictive/preventive maintenance. Table 7.3 presents those with less than 50 %

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[19] Microsoft. 2019. T.Test Function. https://support.office.com/en-us/article/t-test-function-d4e08ec3-c545-485f-962e-276f7cbed055

reactive maintenance (i.e., those who primarily rely on predictive or preventive maintenance) to understand the impact of moving from preventive maintenance to predictive maintenance. Among this group, the upper 50 % using predictive maintenance had less downtime due to maintenance issues, a lower defect rate, and less inventory increases due to maintenance. Those who used less predictive maintenance and more preventive maintenance had 1.18 times as much downtime, 7.80 times more defects, and 2.98 times more increases in inventory due to maintenance issues.

Table 7.3: High and Low Level Predictive Maintenance Compared, Average of Responses (Establishments with <50 % Reactive Maintenance)

| Percent of Maintenance that is predictive, Groupings | Percent of Maintenance that is Predictive | Ratio of Maintenance Costs to the Value of Shipments | Percent of Planned Production Time that is Downtime | Percent of Downtime that is due to Reactive Maintenance | Percent of Planned Production Time that is Downtime due to Maintenance Issues | Defect Rate (percent) | Percent of Sales Lost due to Defects Resulting from Maintenance Issues | Percent of Sales Lost due to Delays Resulting from Maintenance Issues | Ratio of Additional Costs Due to Irreparable Faults and Failures to Shipments | Percent Increase in Inventory due to Maintenance | Shipments ($million) | Percent that Primarily use a Pull or Make to Order Strategy as Opposed to a Push or Make to Stock Strategy | Percent that are Differentiators |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lowest 50 Percent | 8.8 | 0.014 | 5.1 | 25.2 | 1.2 | 0.7 | 0.6 | 1.4 | 0.0033 | 2.8 | 69.7 | 87.5 | 81.3 |
| Highest 50 Percent | 43.9 | 0.043 | 4.4 | 20.8 | 0.6 | 0.1 | 0.8 | 1.2 | 0.0034 | 0.9 | 722.1 | 82.4 | 73.7 |
| Low divided by High | 0.20 | 0.32 | 1.18 | 1.21 | 2.13 | 7.80 | 0.74 | 1.21 | 0.96 | 2.98 | 0.10 | 1.06 | 1.10 |
| High divided by Low | 4.97 | 3.16 | 0.85 | 0.82 | 0.47 | 0.13 | 1.34 | 0.83 | 1.05 | 0.34 | 10.35 | 0.94 | 0.91 |

## 7.3. Levels of Investment in Maintenance

Table 7.4 parses the respondents out by question 15 in the Machinery Maintenance Survey, which is a multiple-choice question where respondents indicate the level of investment that their establishment makes in maintenance. Those with higher levels of investment used more predictive maintenance and tend to have less downtime, 9.6 % compared to 5.4 %. Defect rates also tend to be lower where those who indicated that they had few or minor investments had a defect rate of 1.6 % compared to 0.7 %. Similarly, those with more investment had less lost sales. Those with more maintenance investments tended to be more likely to use a pull (i.e., a make to order) stock strategy and was more likely to rely on differentiation as their competitive strategy, as opposed to being a cost competitor.

Table 7.4: Establishments Compared by Level of Investment in Maintenance, Average of Responses

| Percent of Maintenance that is predictive, Groupings | Percent of Maintenance that is Predictive | Ratio of Maintenance Costs to the Value of Shipments | Percent of Planned Production Time that is Downtime | Percent of Downtime that is due to Reactive Maintenance | Percent of Planned Production Time that is Downtime due to Maintenance Issues | Defect Rate (percent) | Percent of Sales Lost due to Defects Resulting from Maintenance Issues | Percent of Sales Lost due to Delays Resulting from Maintenance Issues | Ratio of Additional Costs Due to Irreparable Faults and Failures to Shipments | Percent Increase in Inventory due to Maintenance | Shipments ($million) | Percent that Primarily use a Pull or Make to Order Strategy as Opposed to a Push or Make to Stock Strategy | Percent that are Differentiators |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Few or Minor Investments (option A and B) | 12.1 | 0.018 | 9.6 | 33.0 | 3.1 | 1.6 | 1.1 | 2.5 | 0.0039 | 3.3 | 130.7 | 0.7 | 0.7 |
| Moderate or Major Investments (option C and D) | 25.0 | 0.030 | 5.4 | 31.1 | 1.3 | 0.7 | 0.7 | 1.8 | 0.0054 | 3.7 | 472.5 | 0.8 | 0.8 |
| Low divided by High | 0.49 | 0.62 | 1.78 | 1.06 | 2.32 | 2.16 | 1.53 | 1.41 | 0.71 | 0.89 | 0.28 | 0.79 | 0.80 |
| High divided by Low | 2.06 | 1.61 | 0.56 | 0.94 | 0.43 | 0.46 | 0.65 | 0.71 | 1.41 | 1.12 | 3.61 | 1.26 | 1.26 |

# 8. Summary

This report examined annual costs of maintenance along with losses due to inadequate maintenance strategies. It further examined the perceived and observed benefits of investing in and advancing maintenance strategies. Below is a discussion of the findings.

## 8.1. Costs and Losses

As shown in Table 8.1, maintenance expenditures for NAICS 321-339, excluding 324 and 325, were estimated to be $57.3 billion. Additional expenditures due to faults and failure were estimated at $16.3 billion and costs for inventory to buffer against maintenance issues costing $0.9 billion. In total, these maintenance activities costed an estimated $74.5 billion.

The losses due to preventable maintenance issues amounted to $18.1 billion due to downtime, $0.8 billion due to defects, and $100.2 billion due to lost sales from delays and defects with an estimated 134.1 injuries and 0.4 deaths on average being associated with maintenance issues. The total of the dollar losses amounts to $119.1 billion.

For context, these costs might be compared to other manufacturing costs; however, any comparison of this type will vary depending on how costs are categorized. Categorizing costs by NAICS code and measuring them in terms of value added using NIST's Manufacturing Cost Guide, both costs and losses related to maintenance each rank above

Table 8.1: Costs and Losses Associated with Maintenance

| | Estimate ($2016 Billion) | 90 % Confidence Interval | |
|---|---|---|---|
| Costs | 74.5 | 50.8 | 103.3 |
| Direct Maintenance Costs | 57.3 | 42.4 | 72.2 |
| Costs due to Faults and Failures | 16.3 | 7.1 | 25.5 |
| Inventory Costs | 0.9 | 1.3 | 5.6 |
| Losses | 119.1 | 43.9 | 197.3 |
| Unplanned Downtime | 18.1 | 10.4 | 27.8 |
| *Labor* | *13.5* | *7.1* | *22.1* |
| *Capital Depreciation Buildings* | *2.5* | *1.8* | *3.1* |
| *Capital Depreciation Machinery* | *1.0* | *0.7* | *1.2* |
| *Energy* | *1.1* | *0.8* | *1.4* |
| Defects | 0.8 | 0.0 | 2.7 |
| Lost Sales | 100.2 | 33.5 | 166.8 |
| *Due to Defects* | *31.2* | *3.6* | *58.7* |
| *Due to Delays* | *69.0* | *29.8* | *108.1* |
| Total Costs and Losses | 193.6 | 94.7 | 300.7 |

the 95th percentile for the industries examined in this report.[20] Moreover, maintenance costs rank relatively high. For additional context, the industries studied in this report spent $491 billion on payroll including maintenance staff, $82 billion on machinery/equipment, $33 billion on electricity, $15 billion on capital expenditures on buildings/structures, and $4 billion on computer hardware/other equipment, according to 2016 data from the Annual Survey of Manufactures.[21] According to the same data, the value added for these industries amounted to $1.5 trillion.

### 8.2. Perceived and Observed Benefits of Advanced Maintenance Techniques

The perceived benefit of potentially adopting some amount of predictive maintenance was $6.5 billion from downtime reduction and $67.3 billion in increased sales. Other benefits such as reduced defects may also occur but were not monetized.

As seen in Table 8.2, relying on reactive maintenance was associated with 3.3 times more downtime, 16.0 times more defects, 2.8 times more lost sales due to defects from maintenance, 2.4 times more lost sales due to delays from maintenance, and 4.89 times more inventory increases due to maintenance issues. On average, 45.7 % of machinery maintenance was reactive maintenance. Those who relied less on reactive maintenance were more likely to use a pull (i.e., make to order) stock strategy and more likely to be differentiators as opposed to being a cost competitor. That is, they rely more on their reputation and produced products on demand. The implication being that reactive maintenance reduces quality and increases uncertainty in production time. Among those establishments that primarily rely on preventive and predictive maintenance, predictive maintenance was associated with 15 % less downtime, 87 % lower defect rate, and 66 % less inventory increases due to maintenance issues. There were two counterintuitive results in this category. It is important to note that due to the limited number of respondents, some of the results are not statistically significant, including those that are counterintuitive. Moreover, the results in Table 8.2 should be seen as anecdotal. Those establishments that relied more on predictive maintenance were more likely to have a pull (i.e., make to order) stock strategy and more likely to be a differentiator as opposed to being a cost competitor, which associates predictive maintenance with higher quality products and shorter production times through reduced downtime.

For those establishments that invested more heavily into maintenance, on average they had 44 % less downtime, 54 % lower defect rate, 35 % fewer lost sales due to defects from maintenance, and 29 % less lost sales due to delays from maintenance issues. Those who invest more heavily in maintenance were more likely to have a pull (i.e., make to order) stock strategy and more likely to be a differentiator as opposed to being a cost competitor.

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[20] National Institute of Standards and Technology. 2019. Manufacturing Cost Guide. Beta Version 1.0. https://www.nist.gov/services-resources/software/manufacturing-cost-guide

[21] U.S. Census Bureau. (2020). Annual Survey of Manufactures. https://www.census.gov/programs-surveys/asm.html

Table 8.2: Observed Benefits of Advanced Maintenance Techniques

| | Reactive (top 25 %) vs. Other (Lowest 25 %) | Preventive vs. Predictive (top 50 %)* | Few/Minor Investments vs. Moderate/Major Investments in Maintenance |
|---|---|---|---|
| Ratio of Maintenance Costs to the Value of Shipments | Other is 1.61 times higher | Predictive is 3.16 times higher | Mod/Maj is 1.61 times higher |
| Percent of Planned Production Time that is Downtime | Reactive is 3.28 times higher | Preventive is 1.18 times higher | Few/Min is 1.78 times higher |
| Percent of Downtime that is due to Reactive Maintenance | Reactive is 2.18 times higher | Preventive is 1.21 times higher | Few/Min is 1.06 times higher |
| Percent of Planned Production Time that is Downtime due to Maintenance Issues | Reactive is 7.89 times higher | Preventive is 2.13 times higher | Few/Min is 2.32 times higher |
| Defect Rate (percent) | Reactive is 16.00 times higher | Preventive is 7.80 times higher | Few/Min is 2.16 times higher |
| Percent of Sales Lost due to Defects Resulting from Maintenance Issues | Reactive is 2.81 times higher | Predictive is 1.34 times higher | Few/Min is 1.53 times higher |
| Percent of Sales Lost due to Delays Resulting from Maintenance Issues | Reactive is 2.37 times higher | Preventive is 1.21 times higher | Few/Min is 1.41 times higher |
| Ratio of Additional Costs Due to Irreparable Faults and Failures to Shipments | Reactive is 2.25 times higher | Predictive is 1.05 times higher | Mod/Maj is 1.41 times higher |
| Percent Increase in Inventory due to Maintenance | Reactive is 4.89 times higher | Preventive is 2.98 times higher | Mod/Maj is 1.12 times higher |

* Among those establishments that primarily use either predictive or preventive maintenance

NOTE: Counterintuitive or unexpected results are shown in RED

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## Appendix A: Machinery Maintenance Survey

1. Approximately how many employees work at this establishment (select one)?
    a. 1 to 4 Employees
    b. 5 to 9 Employees
    c. 10 to 19 Employees
    d. 20 to 49 Employees
    e. 50 to 99 Employees
    f. 100 to 249 Employees
    g. 250 to 499 Employees
    h. 500 to 999 Employees
    i. 1000 or more Employees
2. What is the estimated total annual payroll for this establishment?
3. What type of products are produced at this establishment?
4. What is the estimated total annual value of products shipped for this establishment?
5. What is the primary NAICS code for this establishment?
6. What is the estimated annual expenditures on manufacturing machinery maintenance and repair at this establishment (e.g., maintenance department budget)?
7. What percent of machinery maintenance and repair costs do you estimate is predictive (i.e., condition-based maintenance using data such as temperature, noise, and/or vibration), preventive (i.e., scheduled, timed, or based on a cycle), and reactive maintenance (i.e., run to failure)?

    Predictive Maintenance %

    Preventive Maintenance %

    Reactive Maintenance %

    Other Maintenance Costs (e.g., training) %

    Total maintenance and repair 100 %

8. In addition to the costs discussed above, what do you estimate were additional expenditures per year, if any, used for replacing machinery that was damaged due to irreparable faults or failures?
9. What percent of the planned production time do you estimate is downtime?

    Is this information tracked formally? ☐ Yes ☐ No
    If so, are you familiar with the estimates? ☐ Yes ☐ No

   a. What percent of the downtime (i.e., planned production time that is downtime) is due to reactive maintenance (i.e., unplanned maintenance and repair)?

   b. What percent, if any, of sales do you estimate were lost due to delays from downtime caused by maintenance issues?

      Is this information tracked formally? ☐ Yes ☐ No
      If so, are you familiar with the estimates? ☐ Yes ☐ No

10. What do you estimate is the rate of product defects for this establishment?

   a. What percent of defects do you estimate are a result of reactive maintenance?

      Is this information tracked formally? ☐ Yes ☐ No
      If so, are you familiar with the estimates? ☐ Yes ☐ No

   b. What percent of sales, if any, do you estimate were lost due to defects caused by maintenance issues?

11. Do you believe that your establishment would benefit from converting some portion of reactive and preventive maintenance to predictive maintenance?
   a. Yes
   b. No
12. If yes, what benefits and costs do you believe could come about by converting some portion of reactive and preventive maintenance to predictive maintenance?

   ☐ % change in maintenance and repair costs, if any

   ☐ % change in downtime, if any

   ☐ % change in sales, if any

   ☐ % change in injuries, if any

   Other benefits, costs, or comments

13. What percent of injuries, if any, are associated with reactive maintenance at this establishment?
14. What is the lead time for a product at this establishment (i.e., the time it takes a new set of inputs to move all the way through the operation)?
15. Please select the most accurate statement for this establishment:

   a. Very few investments are made to reduce future maintenance related costs and losses.
   b. Minor investments, such as in planning software, are made to reduce future maintenance related costs and losses.
   c. Moderate investments, such as in monitoring equipment for some machinery, are made to reduce future maintenance related costs and losses.
   d. Significant or major investments, such as analysis software and monitoring equipment for most machines, are made to reduce future maintenance related costs and losses.

16. How many hours per week is this establishment operating on average this year?
17. What percent increase in finished goods inventory, if any, do you estimate is maintained to deal with delays from unplanned maintenance issues?
18. What is the primary competitive focus of this establishment and its products (select one)?
    a. Cost competitiveness: we compete primarily based on having a low cost for the customer
    b. Differentiation: we compete primarily based on differentiating ourselves from others through quality, reputation, service, brand name, or other similar characteristics
19. Does this establishment primarily use a push (i.e., make to stock) or pull (i.e., make to order) strategy (select one)?
    a. Push or make to stock strategy
    b. Pull or make to order strategy
20. What best describes the management style used at this establishment (select one):
    a. Autocratic: Decisions are made at the top with limited input from staff
    b. Consultative: Decisions are made at the top with input from staff
    c. Democratic: Employees take part in the decision-making process
    d. Delegative: Employees make a great deal of the decisions with limited guidance from management