Improving the management of manufacturing assets across large-scale networks of suppliers in the plastic industry

by

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Submitted to the Department of Mechanical Engineering and the MIT Sloan School of Management in partial fulfillment to the requirements for the degrees of

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Abstract

Beckman Coulter, one of Danaher's operating companies, provides diagnostic equipment and consumables to the health industry. A variety of plastic manufacturing methods are used to make instrument parts and consumables worldwide via third-party manufacturers who operate assets owned by the original brand. Worldwide, more than 200 of these manufacturers operate more than 2000 tools owned by Beckman Coulter. The lack of a centralized visibility of the real-time condition of these tools promotes a faulty maintenance plan that causes unexpected failures, reduces its productivity, and stimulates a "fire-fighting" environment within the engineering team.

The motivation for this research is to contribute to protect the company's revenue stream by improving the efficiency of the manufacturing assets, which will ultimately improve the on-time deliveries and reduce procurement and operational costs. The thesis proposes that those objectives can be achieved through an efficient and effective system to track the current condition of manufacturing assets (primarily tooling) designed for the complex network of part manufacturers. The system provides reliable and dynamic information about the progress of the tools' life-cycle, record maintenance and failure events, monitors the OEE, and collects relevant data to enable a predictive model for future failures.

The research starts investigating root causes for low effectiveness, through the analysis of the current state, and evaluates alternatives to track assets' condition and life-cycle across the complex and large supplier network. The selected alternative is to use the parts receipts, currently available through the company's ERP, as a proxy for the tools' shot-count. This indicator is used as the cornerstone for the Manufacturing Assets Management System, which acts as a single-reference point database and interface to visualize the assets' life-cycle, interdependencies with other elements in the network, condition, and effectiveness. It is also a depository for maintenance and failure data which could enable predictive maintenance. It is designed to scale up and to be useful for any internal and external manufacturing assets. Lastly, the thesis analyzes the ideal conditions and characteristics that the system would require to achieve Industry 4.0 standards, exploring and proposing the most effective technologies that are viable to be implemented in a large, commoditized, supplier-based, manufacturing network, to enable more advanced predictive analytics designed to improve OEE.

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Introduction

Recent changes and trends in the supply chain complexity of global businesses respond to more demanding, specialized and sophisticated consumer of the business' goods or services, be it for a final consumer or for another business. The speed and responsiveness of a supply cycle is a major player in the commercial success, and these are characteristics that seemingly contradict to the additional need to constantly reduce costs to remain competitive in the industry. These conditions are common ground for almost all industries, and even more for businesses that are far from holding competitive advantages of a highly-differentiated product or a natural monopoly.

Plastic manufacturers are no exception. The commoditization of plastic manufacturing processes make the industry players to be very concerned about high effectiveness and throughput, looking for attractive service levels and on-time deliveries. At the same time, manufacturing costs are directly correlated to an efficient maintenance plan that improves the return over the invested capital and dilutes fixed costs such as overhead and depreciation.

In this context, the efficiency of the capital expenses in a company becomes a competitive advantage against competitors. Recent progress in data acquisition and processing technologies have made sophisticated systems for capex efficiency evaluation and improvement a more available resource for companies. According to a Deloitte study on Industry 4.0 alignment, 31% out of 1,600 C-Level Executives [1] believe that "Smart and autonomous technologies" will have the greatest impact on their organization over the next five years. At the same time, only 15% of the polled executives believe that their organization is highly prepared to address this challenge.

1. Project Motivation

A smart asset management system that collects information and analyzes it without significant human intervention would probably be the ideal-state. However, obtaining the required buy-in for such an investment and change in operational practices, within the strategic and other executive decision makers in their organization, is usually hard. In most cases, this is due to a lack of strategic alignment internally and a focus on the short term. The main goal of this project, therefore, is to create a low-cost, non-intrusive, first-stage approach to a manufacturing asset management system that would not only improve the performance of the assets and the company's investments, but that would also prove that an asset-focused strategy drives immediate tangible value. The system should provide leading indicators to protect the company's revenue stream and reduce operational costs, which will ultimately gain buy-in from the top of the organization, facilitating larger commitment for a more sophisticated system.

2. Problem Statement

Beckman Coulter Diagnostics is a global provider of solutions to the medical industry, in particular to laboratories, supplying them with innovative diagnostic instruments that are complemented with information systems and a diverse menu of tests. Customers in the diagnostics market see value from the instruments' original manufacturers in their capacity to provide a timely delivery of the existing and newly available test reagents in the market, and in enabling their tests to be performed successfully. Before Danaher Corporation acquired Beckman Coulter in 2011 [2], the company decided to outsource their plastic manufacturing processes to rely on specialized plastic suppliers, while, at the same time, maintaining ownership of their manufacturing assets and proprietary mold designs. This action allowed Beckman to run more competitive manufacturing operations and freed capital for other strategic investments.

Beckman Coulter currently uses more than 200 contract manufacturers around the globe to supply them with more than 3000 different plastic manufactured parts, both consumables and non-consumables. However, as mentioned before, the majority of the suppliers use Beckman's manufacturing assets in their processes. These assets are mostly molds, but also presses, assembling robots, and others. Since Beckman is not in constant contact with these assets, they lose almost all the visibility of their real-time condition and effectiveness. This negatively affects operational excellence. The Overall Equipment Effectiveness (OEE)[1] observed in some selected assets for the study shows to be at 74% on average, which is below the industry standard at 85%. Improvements in this area could address savings of $3.4M over an $85M annual spend. It will also contribute to secure

[1] Overall Equipment Efficiency (OEE) is an industry-wide indicator first used by Seiichi Nakajima in 1982 [3], and it is calculated by multiplying the availability of the assets (uptime over total scheduled time), times the quality rate (percentage of good products), times the performance (ratio of the real performance over its designed capacity). The concept will be explained in more detail in the corresponding section of the Literature Review chapter

the main business revenue stream of $2.5B in consumables' sales, preventing them from being out-of-stocks and ensuring on-time deliveries to clients.

After analyzing the main contributors to the gap, the author decided to focus mostly on injection molding processes, since they contribute to almost 80% of that gap. They also have a very similar process within them that would make a solution easier to replicate and expand.

Real-time tracking of the condition, maintenance events, and mileage of these tools requires a centralized monitoring system that is able to work independently of the suppliers. The system intends to reduce the risk of running out-of-stock of manufactured items, improving on-time delivery. At the same time, it should also allow to improve the overall effectiveness of the manufacturing equipment, and have the reliability of the process in control, which is translated into a lower variability of the periodic effectiveness. Consequently, this enables a reduction of the safety stock quantities required to maintain service level goals, especially of the stock held by the suppliers.

3. Beckman Coulter's supplier-based manufacturing network

This project is mostly focused on the manufacturing side of Beckman Coulter's operations, more specifically in the plastic parts manufacture. The characteristics of the plastic manufacturing operations at Beckman Coulter are the result of their focus on core capabilities and their outsourcing of the processes that could be performed better by specialized suppliers. At the same time, they decided to maintain ownership over the assets that directly relate to the design of their commercialized instruments and consumable parts.

Beckman's revenue come mainly from two sides: first from the instruments' sales and then, in a recurring basis, from the consumables used to run the tests in the instruments. Both revenue streams require plastic parts to be manufactured and delivered on-time and cost-efficiently. Beckman currently has more than 3,000 plastic parts manufactured by more than 200 different suppliers, representing a total spend of $85M per year.

4. Thesis Overview

This thesis proposes that an adequate manufacturing asset management system is crucial to optimize the overall performance of the assets and to ultimately generate additional value to a company with a large and outsourced manufacturing structure. It also suggests a feasible and affordable asset management alternative for such a structure to assess real-time condition and to collect relevant data to enable predictive analytics that will improve the assets' effectiveness.

Chapter II provides background into the different tools and settings covered in this thesis. It first provides an overview of contract manufacturing services and the complexities inherent to the organizations that heavily rely on them for their operations. Following, the chapter reviews asset management practices, objectives, and current trends. After that, the concept of Overall Equipment Effectiveness is introduced, given its importance as an indicator for an asset's performance. Lastly, the most relevant framework and tools for predictive maintenance programs are reviewed.

Chapter III provides detail regarding the current state of the Synchron® cartridge manufacturing operation and performance, quantifies the problem, investigates the root-causes, and proposes alternative solutions to improve the asset's performance. The chapter also analyzes how these solutions could be applicable to other assets, besides the one used for the study.

Chapter IV develops the design and implementation plan for an asset management system, explaining the details of the underlying working principles, describing the available features for the users, and explains the current limitations.

Chapter V presents an explanation of what would be an ideal state of a manufacturing asset management system, under Industry 4.0 standards and potentials. The chapter also covers an analysis and proposal of the specific tools and resources that could be used to achieve the Industry 4.0 ideal state, towards turning Beckman's manufacturing network into a smart factory.

Finally, the thesis covers recommendations for future research work, and provides the conclusions of this exploration.

Chapter II

Literature Review

This section will review the framework used in this research to approach the manufacturing asset management needs. Manufacturing and maintenance principles have previously included a wide range of indicators and tools proposed to facilitate asset management. This previous work will be assessed in its capacity to optimize the performance and investments in the plastic manufacturing network at Beckman Coulter. The chapter will also identify and define the limitations of the existing frameworks to achieve this aforementioned objective. This is also meant to enable further discussion of the contributions of the system developed by the author to the existing challenges, initially at Beckman Coulter, and furthermore expanding the scope to other similar cases. It will also provide a necessary review of relevant elements of the processes and assets that are part of this system, such as injection molds and presses, from the perspective of performance improvement.

1. Complexities in Contract Manufacturing

Contract manufacturing (CM) is widely used by brands and companies in different industries, both on times of expansion and shrinking economies [3]. In general terms, this strategic decision is made by the organization to achieve one or more of the benefits described below [4]:

- Increase focus on core activities: companies will allocate their resources in focusing on the core competencies and value-adding activities. Handing off the production to a specialized manufacturer leverages on the know-how of the contract manufacturer.
- Reducing costs by using external economies of scale: a single company's operations and demand might not be enough to fully optimize the use of facilities required for the specified needs. The contract manufacturer pools demand from their different clients and distributes fixed costs across all the products. Therefore, the final cost could be lower than the one obtained by manufacturing in-house, even after the CM's expected margins. At the same time, if the manufacturing specs are well designed, the manufacturing service is easily interchangeable, which allows a situation where manufacturers lower their margins to compete.

- Capital costs and investment reduction: even if it is related to reducing fixed costs, an additional benefit comes from reducing their investment in manufacturing facilities and equipment. This allows to increase capacity without additional funding.
- Leverage on outsourced specialized know-how: companies are in no need to develop specialized processes' skills that the CM already has. This involves personal qualifications, relationships with suppliers, and methods of efficiency. These capabilities should also push forward the quality-vs-cost frontier.
- Securing long-term flow of business: a well-designed contract should put in place the right incentives to create value in both sides and reduce non-incumbent risks. These contracts are usually signed for several years, which allows the CMs to decide over long-term positions.

However, as Van den Bossche et al. argue, the execution of this strategy usually exposes several sources for inefficiencies. Their study shows that "they become more dependent on these third parties to achieve strong supply chain performance, improve their cost position, and drive innovation. So, the selection, contracting, and, especially, the ongoing management of the supplier relationship is becoming increasingly important" [3]. Furthermore, after analyzing the performance of a CM network in the different organizations that are part of the study, it becomes clear that there is significantly more effort put in the up-front aspects of the decision, than in the execution and control of the on-going structure. Potential sources of inefficiencies typical come from:

- Control over production program and processes: companies lose control over the decisions that drive production prioritizations, resource allocations, and other aspects that affect the delivery of the finished goods. This is especially true when the company's production volume represents a small portion of the CM's total production. Incentives can be put in place to award good performance with the existing or additional business, and mitigate this risk.
- Inefficient relationships with the CMs: usually, the organizational structure is not designed to match and collaborate effectively with the CM's structure. Both organizations act and react in different ways with respect to changes in demand, sourcing issues, and innovation efforts. Additionally, as the number of CMs that work with a company increases, the capacity to have a structure that is designed to work effectively with all of them is lessened.
- Quality concerns: the CMs are usually subjected to different quality standards that are dependent on the product and industry of the range of their clients. Adapting to all these different sets of standards is usually challenging as it is tied to an intrinsic manufacturing mindset and culture.
- Intellectual property loss: companies are required to provide and divulge formulas, designs and technologies that are necessary to implement the processes.

- Hidden and indirect costs: outsourcing brings along new challenges and constrictions that are eventually translated into additional costs, usually overlooked. Language barriers, cultural differences, and longer lead times are some examples of these. Reduced visibility over the conditions that affect the performance of the processes create a "fire-fighting" environment that eventually generates additional resources to be allocated to resolve these situations, with no value added. This could make the management of contract manufacturers more difficult, expensive and time-consuming [5].
- Total costs: Lastly and ironically, some companies can experience an increment in the total cost of a product when it is outsourced, especially when more than one of the aforementioned risks are substantially present. The selection of the CM must be executed hand-in-hand with contractual control mechanisms to avoid or solve for such a situation.

2. Manufacturing asset management systems

Asset management systems (AMS) were developed in the oil & gas sector driven by incidents and challenges in the industry that required systematic changes in the way that the companies' infrastructure was being measured for performance. Complete business models were reassessed and large companies recognized that their strategic advantages and economies of scale were being hindered by overlooked operational efficiency and the agility that smaller organizations hold effortlessly. These large, asset-intensive organizations started to focus on creating multi-disciplined teams to enhance the utilization, maintenance plans, condition tracking and information systems to be asset-centered and to exploit its maximum value [6]. Asset Management is now a term used to describe the management of industrial infrastructure in an integrated, whole-life, risk-based way [7]. According to Peter Welander, in an article called "What is asset management?" [8], the concept of asset management is, at its core, used to answer the question of how to eliminate, reduce, or at least manage risk of equipment failure and the associated costs and losses of production.

Improving the performance of the capital expenditure in a firm is one of the top priorities for management as it is a major driver to deliver value to the shareholders. Capital expenditure, or capex, involved in a manufacturing infrastructure is a significant component of the costs in the form of depreciation and maintenance. Additionally, reducing investment in assets or, alternatively, producing more out of the existing capex, improves a firm's leverage on debt, which creates more financial flexibility, reducing the average cost of capital and the financial distress risk. From an asset optimization perspective, understanding and improving the relationship between the input (capex and investments) and the output (throughput) is the purpose and responsibility of an asset management system [6]. The market pressure to reduce costs forces the companies to run their manufacturing assets at the maximum possible capacity. Asset management systems, therefore, are very valuable to improve the availability of the infrastructure and allow a higher return over the invested capital. They should allow an organization to visualize the performance of the assets and their current state at different levels, according to the criticality of the asset in terms of risk.

These systems should be aligned with the strategy of the company and adapted to the nature of the assets. Capital acquisition plans and the general maintenance policy of the company should be driven from the information that an asset management system provides. Maintenance, renewal, retrofitting, and service decisions are based on the condition and performance of assets. Having a clear knowledge of these aspects will limit the company's exposure to business risks and possible loss of service potential caused by premature failure of assets. The inefficiencies in the use of these assets also generate hidden costs that come from an inadequate allocation of resources. For example, the production engineers spend more time fixing failures instead of performing value-adding tasks. Therefore, the system should be designed considering what information is going to be valuable to make these decisions.

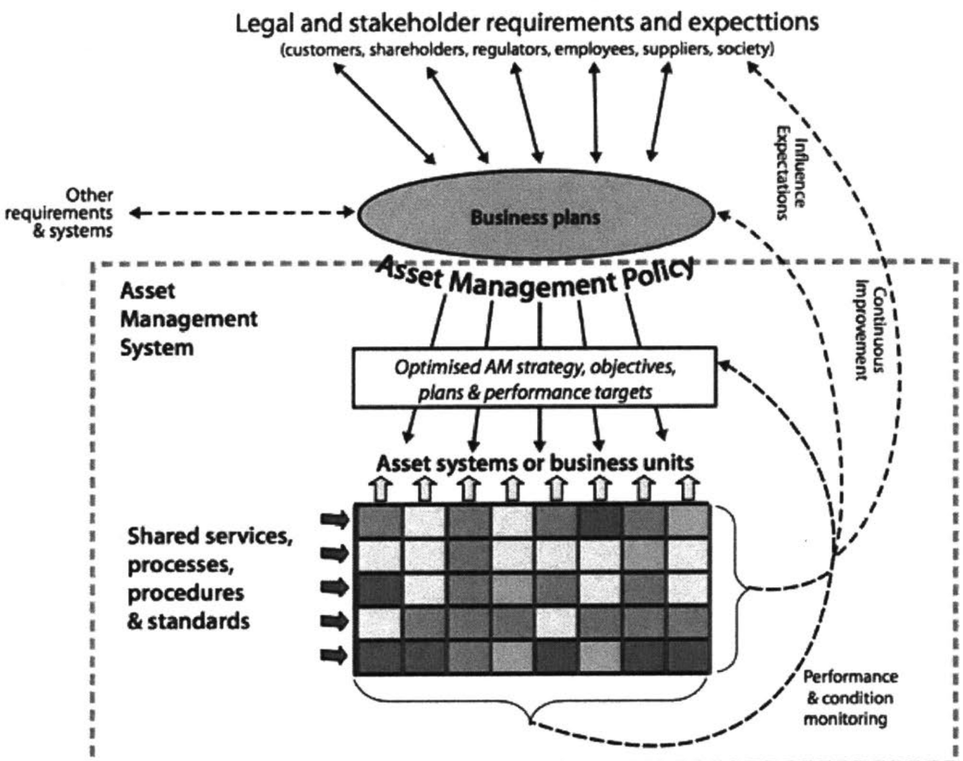


Figure II-1. Asset Management System boundaries. Adapted from John Woodhouse, Asset Management: Joining up the jigsaw puzzle [6]

According to a National Research Council study, asset management systems require [9]:

- Accurate data on assets' characteristics and condition
- Performance measures to evaluate the effects of different types of actions (such as maintenance versus renewal) and to evaluate the timing of investments
- Models for predicting the condition and performance based on the collected data

Most of the literature on this topic propose an initial evaluation of the criticality of the individual assets, which is followed by a maintenance plan. The proactiveness of this plan depends on the assessed risk of the individual equipment. A typical analysis is based on a "Criticality Assessment Rating Tool", which takes in consideration different variables that are combined into an overall risk indicator:

System Name (+characteristics)	HSE Impact	Quality Impact	Profit Impact	Customer Impact	Strategic Plan Impact	Reliability	Replacement Cost	Utilization	**Criticality Rating**
Factor Weight									
Score									

Table II-1. Criticality Assessment Rating Tool. Adapted from David Mierau, "Defining Holistic Asset Criticality to Manage Risk" [10]

Based on the overall risk of the individual assets, they will receive a different treatment from a maintenance plan perspective. The least proactive type is "run-to-failure", which is applied to the assets with the lower overall risk. For some equipment, this is appropriate. There are noncritical devices, with a low criticality rating, that are not to be replaced preventively, before they fail. A classic example is a light bulb, which has a low criticality because its failure does not, for instance, represent a safety risk, nor has an impact on the quality of the product, and has a low replacement cost. On the other hand, some assets are highly critical to the overall performance of a work cell, or even the whole plant. The refrigerant compressor of a cold storage facility, for example, would be rated highly on its potential impact to safety and the environment, would have a significant effect on the ability to maintain the quality of the storage services, and have a high replacement cost, to mention a few factors. For such a case, the use of additional technology, such as sensors to assess the asset's condition, would be not only valuable but probably mandatory. Subsequently, an effective asset management system will follow the prioritization provided by the risk assessment and pursue two objectives: minimize interruptions and reduce unnecessary and premature maintenance costs.

a. Economic Loss and the Cost of Dependency

A shutdown causes loss in production which derives to an economic loss. The exact calculation of this cost depends on the type of process, type of equipment, layouts, demand factors, and other operational conditions. Fundamentally, they are all related to the cost of waste in the dependent productive resources. They can be quantified as the cost of relying upon the asset in terms of output, capacity surplus, and demand. Systems dependency can be formulated as the system's output minus the system's capacity surplus, as a ratio to the demand. At the same time, the capacity surplus is the design capacity of the system minus the demand. Importantly, the design capacity of a series system is the capacity of the smallest design capacity of the individual capacities in the process (bottleneck). In a parallel system, the design capacity is the sum of the individual capacities in the process [11].

Therefore:

Dependency (%) = (Output - (Design Capacity - Demand))/Output

The total economic loss due to a shutdown is the production loss during that period, at its relative value of dependency.

Economic Loss = (Lost time) x (Cost of production loss at 100% dependency) x (Dependency (%))

The real economic loss calculation should serve as the point of reference for investments on assets. When a new investment is evaluated, the difference between the current economic losses for the asset's inefficiencies and the future ones should be considered as the savings that the investment is generating.

b. Life-Cycle Analysis and Life-Cycle Costs

A life-cycle analysis is done to measure performance both at the system and at the equipment life-cycle stages, as well as across the total engineered installation life cycle, from design to possible salvage. The issues critical to life-cycle engineering analysis include system performance analysis and performance regimes, system life-cycle data modelling and analysis, performance trade-off measurement, and problems of life-cycle engineering analysis in the context of complex integrated systems. The life-cycle costs (LCC) are the total costs related to an asset, from its planning to its disposal. It is highly dependent on the design, the operational procedures, disposal method, and the maintenance practices. The sum of all these costs far exceeds procurement costs, even if they are the most used cost criteria when evaluating an asset, due to the easy access to acquisition costs information. The cost of sustaining equipment can be from 2 to 20 times the equipment acquisition cost over its useful lifespan [11].

Stapelberg [11] differentiates acquisition from sustaining costs with a list similar to the following:

Acquisition Costs

- Capital investment and financial management for the construction, fabrication or installation

- Research & development, engineering design, and pilot tests
- Permits, leases and legal fees, indemnity and statutory costs
- Development of technical documents and specifications
- Ramp-up and warranty, modifications and improvements
- Support facilities and utilities and support equipment

Sustaining Costs

- Facility usage and energy consumption
- Management, consultation and supervision
- Operations and consumption materials
- Servicing and maintenance consumables
- Equipment replacement and renewal
- Scheduled and unscheduled maintenance
- Logistic support and spares supply
- Labor, materials and overhead
- Environmental green and clean
- Remediation and recovery
- Disposal, wrecking and salvage

Asset management systems should be designed to include these two concepts in order to correctly drive the decisions over the life of an asset, including repairing, replacement, retrofitting, or disposal. There are several ways to evaluate the performance of an asset, in terms of its effectiveness to deliver value. However, as mentioned before, they are typically constructed only over the acquisition costs, without considering the total life-cycle costs. For example, a widely-used performance indicator is the Return on Invested Capital (ROIC), which measures the additional obtained value from an asset, compared to the investment on the asset, therefore:

ROIC = (Gain from Investment - Cost of Investment) /(Cost of Investment)

A life-cycle cost approach should consider all the acquisition and sustaining cost, in present value, as the cost of investment. The total Gain from Investment would also be related to all the additional value generated by the asset, in present value. This gain should include all the reductions in the economic losses explained above, and is directly related to the asset's effectiveness, which will be detailed in the next chapter.

3. Overall Equipment Effectiveness (OEE)

Galar et al. [7] discuss how the use of Key Performance Indicators (KPIs) is required for each asset class to relate their performance to the service level to customers. These performance measures are usually related to reliability, availability, capacity, and meeting customer demands and needs. Measuring and reporting the values of these indicators constantly will improve the decision-making for the assets because it enables a system that reveals the dependencies between the desired outcomes and the necessary input of resources, to adjust the plan accordingly.

The Overall Equipment Effectiveness (OEE) is a widely-used indicator, originally coined by Seiichi Nakajima [12], considered to be a cornerstone in maintenance operations, equipment engineering, and asset management, and it is usually the starting point for a root cause analysis to identify and reduce the major causes for poor asset performance. It is "a measure of equipment or asset performance based on actual availability, performance efficiency and quality of product or output when the asset is scheduled to operate" [13], typically expressed as a percentage.

The calculation of the OEE is based on the following formula:

OEE (%) = Availability (%) × Performance Efficiency (%) × Quality Rate (%)

Where:

- *Availability (%) = Uptime (hrs) / [Total Available Time (hrs) – Idle Time (hrs)]*
- *Uptime (hrs) = Total Available Time (hrs) – [Idle Time (hrs) + Total Downtime (hrs)]*
- *Total Downtime (hrs) = Scheduled Downtime (hrs) + Unscheduled Downtime (hrs)*
- *Performance (%) = Actual Production Rate (units/hr) / Best Production Rate (units/hr)*
- *Quality rate (%) = [Total Units Produced – Defective Units Produced] / Total Units Produced*

There are several considerations in the implementation of this indicator, which are likely out of the scope of this research. However, two important concepts require further attention. The first one is related to the planned and scheduled maintenance time. If this activity is performed during idle time (e.g., when there is no demand for the asset), that maintenance time should not be considered downtime. Note that this could create some discrepancies or misleading values of OEE at different periods of time when idle time is reduced (or increased) only because of changes in demand. This affects the available time to perform maintenance tasks while the asset is idle, and therefor results in apparently improved or diminished OEE values that are driven by external factors (i.e. demand). The second important concept to consider is the "Six Big Losses" classification (see Table II-2), introduced by Nakajima himself [14]. The six losses are a sub-classification of the three components of the OEE, used to identify the original cause of the loss in performance:

OEE components	Availability	Performance	Quality
"Six big losses"	Breakdowns	Minor stoppages	Production Rejects
	Set-up and adjustments	Reduced speed	Rejects on start up

Table II-2. Six big losses [14]

The OEE is recommended to be used as a "relative, internal improvement measure for a specific asset or single-stream process" [12]. This is important in evaluating the usefulness of an asset management system by observing improvements in the OEE.

At the same time, the OEE should be observed in combination with efficiency indicators, such as the maintenance costs required to achieve the desired goals since the OEE itself does not include them. Iannone and Nenni compare these two concepts in the manufacturing context in a very elegant way: "The difference between efficiency and effectiveness is that effectiveness is the actual output over the reference output and efficiency is the actual input over the reference input. The Equipment Efficiency refers thus to the ability to perform well at the lowest overall cost. Equipment Efficiency is then unlinked from output and company goals. Hence the concept of Equipment Effectiveness relates to the ability of producing repeatedly what is the intended producing, that is to say to produce value for the company" [15].

4. Predictive maintenance

Predictive maintenance (PdM) usage and accessibility has grown significantly over the latest years as faster data processing, cheaper data collection, smarter algorithms, and more reliable sensors have appeared in the market. Certain sectors with high capital costs and demanding markets have adopted this type of maintenance for their more critical processes [16]. A PdM foresees failure events in an operating system with the goal of reducing the overall maintenance efforts, or to take them to a defined target. Reducing maintenance efforts, in general, is the usual goal, as these efforts are not only the direct costs of servicing or repairing an asset, but also all the associated economic losses or costs of dependencies mentioned before. In other words, PdM not only aims for failure prevention but also for efficient operation, hence improved safety, product quality, reliability, availability and reduction in energy cost [17]. A PdM does this by a constant evaluation of the current state of the system or the asset, and analyzing the historical data available. A PdM system will attempt to detect early signs of failure through different types of indicators (Condition-based) and apply statistical algorithms (Statistical-based) to obtain conclusions that will trigger maintenance procedures. PdM data provide both diagnostics and prognostics information, telling what is wrong, where the problem is, why it is happening, whether it indicates a failure or just a fault and when failure is going to happen, if any [18]. This information makes the maintenance work to be more proactive, and therefore more efficient and effective, improving the reliability, availability and maintainability of the assets. Additionally, PdM information provides prognostic conclusions that can help to estimate the unobservable condition of a system given certain observable variables, for example, estimating wear of a hidden component.

Jardine et al. [18] describes the three main steps of a PdM system: data acquisition, data processing and maintenance decision-making.

a. Acquisition of the data

Data is categorized into two main types: the event data and condition monitoring data. Event data include the information that describe events or actions done to the asset (e.g. breakdown, minor repair, preventive maintenance, oil change, etc.). Condition monitoring data is related to the health and state of the asset in a versatile manner (e.g. vibration, acoustics, oil analysis, temperature, moisture). Current collection has been made cost-effective through sensors of different uses and adaptable to difficult environments, and communicated via wireless network into storage and handling platforms like computerized maintenance management systems (CMMS). This type of systems also allows manual input of qualitative condition assessment of the asset and event information.

b. Processing the data

This stage starts with the cleaning, eliminating errors and useless information. After this, the data is analyzed through a variety of models, depending on the type of data collected. Data can be in the form of value type (e.g. all data that is collected discretely, such as temperature, pressure), waveforms (e.g. vibrations), or image data (e.g. thermographs, x-rays) and they are all processed with different techniques to extract information from it. Waveforms and image data need additional processes to obtain feature values which, overly simplified, finds discrete values that represent the continuous nature of the signals.

After these processes are performed, they can all be treated as value type data and used to identify patterns and trends through regression analysis and time series models. Data reduction methods for data sets with a large number of variables for each data point are also used in PdMs, such as Principal Component Analysis (PCA) and Factor Analysis. This topic is out of the scope of this thesis but, if further reference is needed, Fodor [19] explains in detail the different techniques to reduce the number of variables. They are broadly focused in finding common factors and correlations between the variables, in order to maintain only the ones that explain most of the variance, with minimal loss of information.

c. Maintenance decision making

The next step is to enable the condition monitoring through: setting appropriate limits, identifying when next to monitor the machinery, and predicting when to change or repair the machine after a problem has been identified [20]. Once a specific observed variable from the condition monitoring data is seen to surpass a set point in the control limits (based on Statistical Process Control parameters), the subject enters in the P-F region. A P-F region is the period of time since a failure is detectable (i.e. observed variable out of control limits) and an actual failure. The objective is to understand the failure behavior to develop the strategy once we are able to anticipate the failure. A P-F curve shows the points where failures occurred but were not detectable (P), the failures that were detectable (P_1 to P_n), generally known as potential failure, and the point where system fails, is called the functional failure (F) point. The time taken from potential failure to decay into functional failure is P-F interval. When an appropriate hazard model is developed for a subject (e.g. a type of failure for a manufacturing asset), the P-F interval is set to be the period when the asset is monitored to prevent the failures. All the analyses and maintenance to be performed are limited to this interval. The order of this interval depends on a given system's characteristics [16].

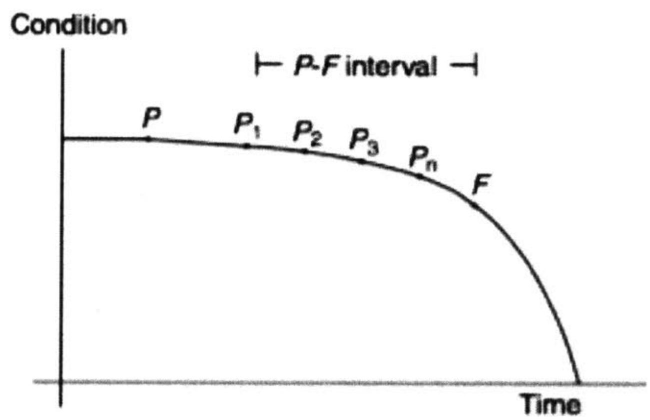


Figure II-2. Equipment failure shown in P-F Curve [16]

After the alarm limit (P_1) is reached, the machine is in the failure zone and it is assumed that there is an issue, and the time to a functional failure (F) is shortening.

Goode et al. [20] explains how estimating the length of the P-F interval (in units of time) is hard and usually not approximated by a constant value. A suitable distribution for it is the Weibull distribution. Derived from it, and starting from P_1, the Total Time to Failure (TTF) is represented by:

$$TTF = \gamma_{PF} + \eta_{PF} \times (-\ln(1 - F(t)))^{1/\beta_{PF}}$$

Where:

$F(t) = Cumulative\ probability\ function\ until\ failure$

$t = Time\ elapsed\ since\ P_1$

$\beta_{PF} = shape\ parameter\ of\ the\ PF\ interval\ (obtained\ from\ Weibull\ fit)$

$\gamma_{PF} = location\ parameter\ of\ the\ PF\ interval\ (obtained\ from\ Weibull\ fit)$

$\eta_{PF} = characteristic\ life\ parameter\ of\ the\ PF\ interval\ (obtained\ from\ Weibull\ fit)$

Goode et al. [20] includes the condition-monitoring information to improve this model:

$$TTF = \left(\gamma_{PF} + \eta_{PF} \times (-\ln(1 - F(t)))^{1/\beta_{PF}}\right) \times \left(1 - \frac{\ln\left((X(t)-LL)/(AL-LL)\right)}{\ln\left((UL-LL)/(AL-LL)\right)}\right)$$

Where:

$X(t) = Condition\ monitoring\ measurement\ in\ time\ t$

$LL = Lower\ limit\ of\ control\ for\ variable\ X$

$UL = Upper\ limit\ of\ control\ for\ variable\ X$

$AL = Alarm\ level\ for\ variable\ X\ (entry\ point\ to\ the\ PF\ curve)$

Then, F(t) can be replaced by a desired risk level that the user is willing to take, appropriate for the specific asset (depending of criticality of the asset, mentioned in Chapter II.2.).

5. Conclusion from literature review

Plastic manufacturers compete in a low-cost, high-volume environment that is constantly pushing processes to be more efficient, and investments to perform better. Even in these strenuous and demanding circumstances, high service levels are a must for manufacturers that want to maintain their customer-base.

The work in this thesis is intended to contribute in improving asset management systems' design and implementation for a CM-based manufacturing network. In particular, networks where the manufacturing assets are owned by the OEM but are operated by the contract manufacturers. The author believes that this specific situation holds some nuances, in the form of access to information, opposed incentives, and barriers for execution, that require a specialized approach. At the same time, however, the author believes that the existence of this situation is not unique to the company in this study, and therefore the applicability of the proposed solutions is relevant for new asset management applications. The specifics and particularities of this state will be explained in more detail in the Current State Analysis (Chapter III).

Chapter III

Current State Analysis

The case study of this thesis is a particular contract manufacturing situation where the assets are owned by the company but the manufacturing processes are outsourced to the CMs, who are specialized plastic manufacturers. This strategic decision was made to mitigate some of the risks and downsides of a CM structure. For example, under this new version of the manufacturing organization, the control over the production program is increased, although not eliminated, as the assets are exclusively used for the asset owner. Intellectual property is also more protected since the design of the molds is done in-house. This, in combination with a contract that allows pricing modifications based on process improvements, enables effective value engineering plans to reduce costs. Under this scheme, the company can also leverage on their contract manufacturers' expertise and capabilities to constantly search for process and even product innovation [3].

However, the CM-based structure makes the control over the assets' and capex performance a more challenging task but at the same time a crucial one. First of all, because there is no direct visibility over the assets on a regular basis, the constantly changing conditions of the assets are not easily traceable. It requires significant collaboration from the CM to maintain updated information on maintenance events, failures, downtimes, and mileage. Second, the incentives of the process-owner (CM) differ from the incentives of the asset-owner (the company). Since the CM is not responsible for repairing failures in the asset, their incentive to run it until failure are higher. Finally, the uneven production management philosophies and cultures from the different suppliers make the implementation of any asset management system across all the suppliers a tougher execution challenge. Ranging from different information technologies and software, to different levels of commitment with an information-based manufacturing floor operation, trying to apply a one-fits-all solution to collect accurate information is unfeasible, at least in the short-run.

A clear business case needs to be put in place and communicated to the CMs, showing and proving the advantages of an Asset Management System. We believe that the best way to do this is through a relevant pilot that covers a significant volume of the manufacturing network, but that at the same time is not dependent on actions from the supplier. The manufacturing process of the Synchron® Reagent Cartridge was the selected process to understand how inefficiencies in the use of an asset could affect the performance and, furthermore, the business metrics.

1. Description of the Synchron® Reagent Cartridge manufacturing line

This process involves three main work cells (see Figure III-1), the first two are injection molding presses acting in tandem to manufacture the bottom and the top part of the cartridge, respectively. The third station is a sealer that uses hot-plate welding to join the two parts together.

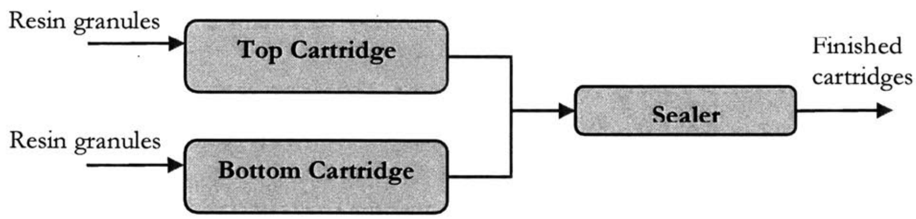


Figure III-1. High-level diagram of Synchron® Reageant Cartridges (created by the author)

The two injection molding presses receive the resin pellets through the hopper into a reciprocating screw that melts the resin and pushes it through a nozzle and a gate into the eight-cavities mold. In this case, the process is done with hot runners, which means that the melted resin is constantly heated in the runners, before the gate, into the cavities (see Figure III-2). This is done to avoid having cold runners that need to be scrapped with every shot and to reduce the total cycle time. After the cavities are filled, the resin is cooled-off and the press opens the mold, releasing the batch of eight pieces. Finally, a small robotic arm sucks out the pieces from the cavities and deposits them into a conveyor that runs towards the sealer, in parallel with the pieces from the other press. The cycle time, which is the same for the two presses, is 24 seconds, which is equivalent to a designed capacity of 1,200 parts/hr.

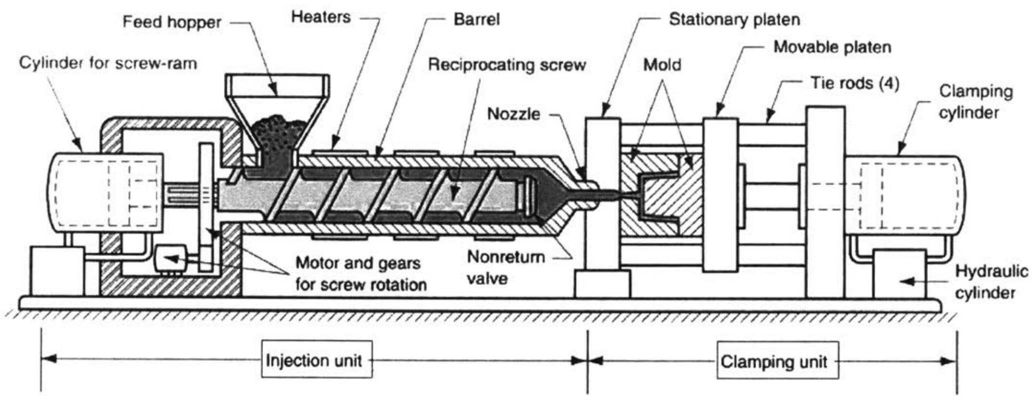


Figure III-2. Injection Molding schematics. (Source: Azure Machines [21])

The sealer is an automatized work cell that incorporates four processes using a robotic arm: (1) fitting: the robotic arm secures the bottom and top parts and fits them together; (2) welding: the robotic arm rotates 90 degrees to the welding station, where the two parts are pressed against a hot-plate to weld the two pieces together; (3) testing: the robotic arm rotates another quarter of a full turn into the testing station where the recently welded cartridge is tested for leaks through a sensor that detects the variations of ionized air caused by high voltage around the joint, and (4) the arm makes a final 90-degrees rotation, where the batch is deposited into a conveyor for final packaging.

This particular process was selected to be the object of study due to different reasons. Firstly, the process is owned by a CM or supplier with a good and collaborative relationship with the company, open to innovation and to implement trials for testing alternatives that could advance their processes towards a more efficient operation. Secondly, it is made up of a variety of integrated processes that are familiar to parts produced by other suppliers, which should drive to inclusive conclusions. The final product from this line is a part number that consists of two different injected parts that go through an additional assembly process, all integrated through automation. Finally, it had sufficient data to properly calculate the OEE and the sources of low performance.

2. Problem-Solving Process to improve assets performance in the Synchron® line

The problem-solving process (PSP) is a standardized framework designed to be successful in solving an issue or closing a gap. It is widely used in lean manufacturing and is an essential framework in the Danaher Business System (DBS). The first part of the process is to clearly define the problem, differentiating it from the symptoms and causes. A problem should be viewed as the discrepancy, or gap, between a desired state and the actual state, and should be clearly tied to a quantifiable measurement (a performance indicator, for instance). This gap needs to be specific and quantified in order to analyze its main contributors and to therefore identify the root causes, which is usually the following step of the process. This is usually done asking the question "why is this happening?" several times (the framework recommends to do so five times). This step will identify a number of root causes that are arranged according to the size of their own contribution to the overall gap, which allows to use the 80/20 rule (Pareto principle) to focus on the root causes that have the largest impact. After this, alternative solutions are proposed to tackle the most impactful root causes, and an implementation and sustaining plan is proposed and executed [22].

a. Defining the gap. The OEE of the Synchron® line

Production data was obtained from the two injection molding machines in the Synchron® line. This data, provided by the production team within the CM's operational organization, contains information about the downtime and uptime of the machine -including a brief note about the cause-, the total quantity produced at each uptime interval, and the number of defective parts produced per interval. Filtering out the idle time (due to scheduled non-production hours), the OEE is calculated on a monthly basis to observe variations in time and the gap in relation to an accepted industry standard of 85% [23].

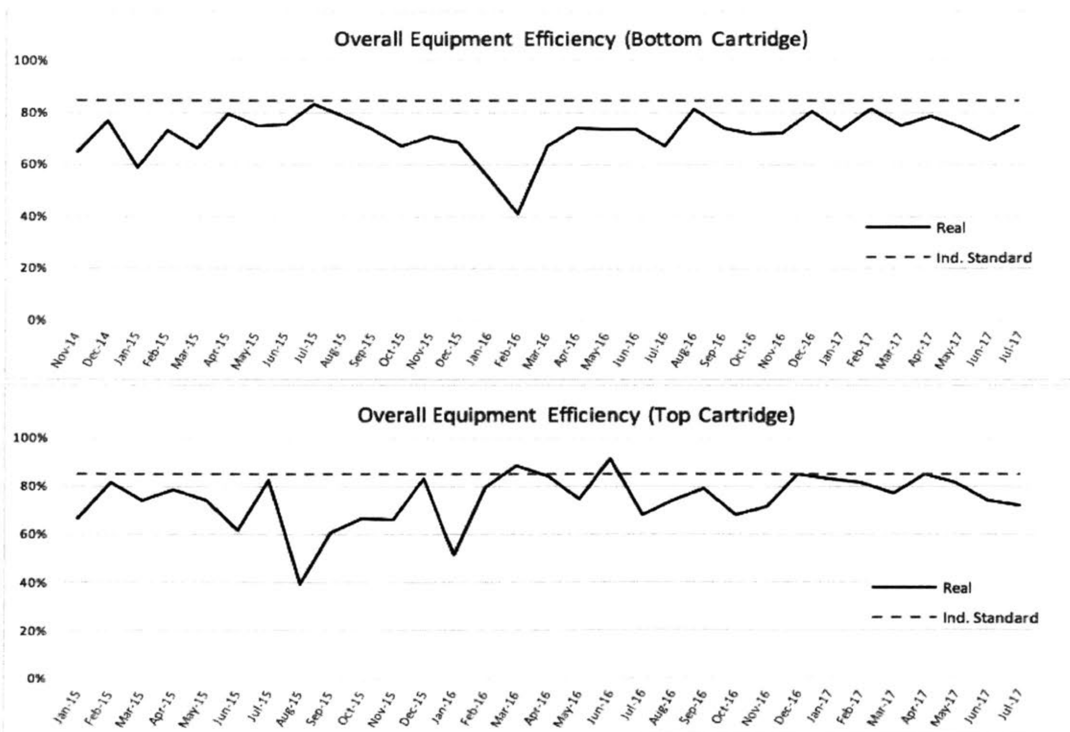


Figure III-3. OEE of injection molding machines in the Synchron® line (created by the author with CMs production data)

The overlapping observed period extends from January of 2015 to July of 2017. During this time, we observe that the average OEE is 72% and 74% for the bottom and top part of the cartridge, respectively. As we see, this is a 13% and 11% gap to the industry standard, which has a significance impact in the total manufacturing costs. In these particular cases, the current gap is creating additional costs to the CM, which are mostly in the form of fixed costs that are distributed over fewer units produced. In the case of the Synchron® Cartridge parts, the underperformance of the assets is affecting the total manufacturing costs as explained in Table III-1[2]. Considering only a change in the allocation of the fixed costs, the unitary cost of the cartridges is holding an over-cost of 2.6%, which is calculated by multiplying the sum of the equipment depreciation (10%), the general and administrative costs (4%), and the manufacturing overhead fixed costs (8%), by the average OEE gap (12%). This considers a few assumptions worth noticing. First, we assume the change in the OEE does not make an effect in the raw material cost, since the real amount used per piece would remain the same. However, if there was a significant change in the quality rate –which will be shown as trivial in section b below of the current chapter- an additional cost reduction would occur. The second important assumption is that any additional capacity obtained from an OEE improvement would be utilized to fulfill additional orders. This is a fair assumption considering that the Synchron® Cartridges, like most of the consumable part numbers, are considered critical and produced to stock. It is important to mention that this cost reduction would be associated to the CM's cost structure, and not to the company's. Nevertheless, the company could still benefit indirectly from this improvement either as an incentive for the CM to collaborate with the implementation of a system that contributes to OEE improvements, or through an open-books price contract revision.

		Variable or Fixed	% of Total Unitary Cost	Affected by asset performance?
Direct Costs			63%	
	Raw material	Variable	48%	No
	Direct Labor	Variable	8%	No
	Energy	Variable	7%	No
Indirect Costs			27%	
	Equipment depreciation	Fixed	10%	Yes
	General & Administrative	Fixed	4%	Yes
	Mfg. overhead	Fixed	8%	Yes
	Sales	Variable	5%	No

[2] Because of confidentiality issues, the absolute figures are not shown and the percentage figures have been slightly modified

CM's net margin	10%	No

Table III-1. Unitary cost allocation by type for Synchron® cartridge. Asset performance affects unitary fixed costs (Modified by the author from supplier contract)

The low OEE is additionally causing a reduction in the Return Over Invested Capital (ROIC) metric. Particularly at Danaher, and therefore at Beckman Coulter, this is an important core-value driver because it affects the company's debt ratio, which at the same time increases the cost of financing. If the same asset were to increase the OEE from 74% to 85%, it would be able to produce more units in the same period of time, and therefore will increase the Net Operating Profit After Taxes (NOPAT), leading to a better ROIC. The exact ROIC improvement would be hard to quantify because the incremental sales would not respond directly and proportionally to a production boost, since they depend on market conditions for the cartridges. However, if we assume a conservative 10% sales capture of the additional production, current ROIC would improve by 1.5% (see Table III-2[3]).

Mold Capital Expenditure	$290,000	
	Current	**Goal**
OEE	74%	85%
Units Produced	170000	195270
Additional units sold (10% of production improvement)		2527
Operating Profits	$204,000	$207,032
NOPAT (at 35% tax burden)	$132,600	$134,571
ROIC	2.19	2.15
ROIC Improvement		**1.5%**

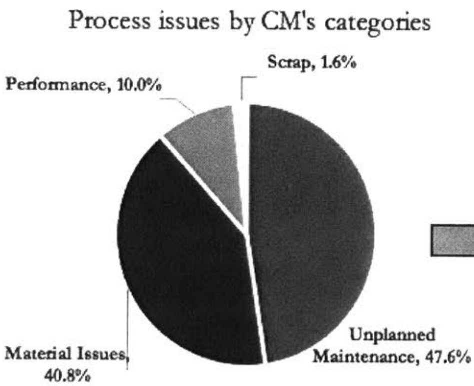
Table III-2. Potential ROIC values at OEE goal (Compiled by the author. Absolute figures modified)

A process with a low OEE will also have a high risk of running out of stock. A higher and more constant OEE allows a more efficient scheduling of maintenance and production plans. The standard deviations of this indicator in these processes are at 8.2 pts and 10.9 pts respectively, which translates into variability of the manufacturing lead-times, which at the same time increases the safety stock levels.

[3] Because of confidentiality issues, the absolute figures have been modified

b. Root-Cause analysis

Following the Problem-Solving Process, the OEE gap is investigated deeper to find what type of issue is causing it. The natural way to categorize the issues is using the aforementioned Six Big Losses. The data collection system at the CM level is not specifically designed to classify the issues within the same categories as the original conception of the Six Big Losses, however we can re-interpret the CM categories based on their own definition.



OEE contributors	Six big losses	%
Availability	Breakdowns	47.6%
	Set-up and adjustments	40.8%
Performance	Minor stoppages Reduced speed	10.0%
Quality	Production Rejects Rejects on start up	1.6%

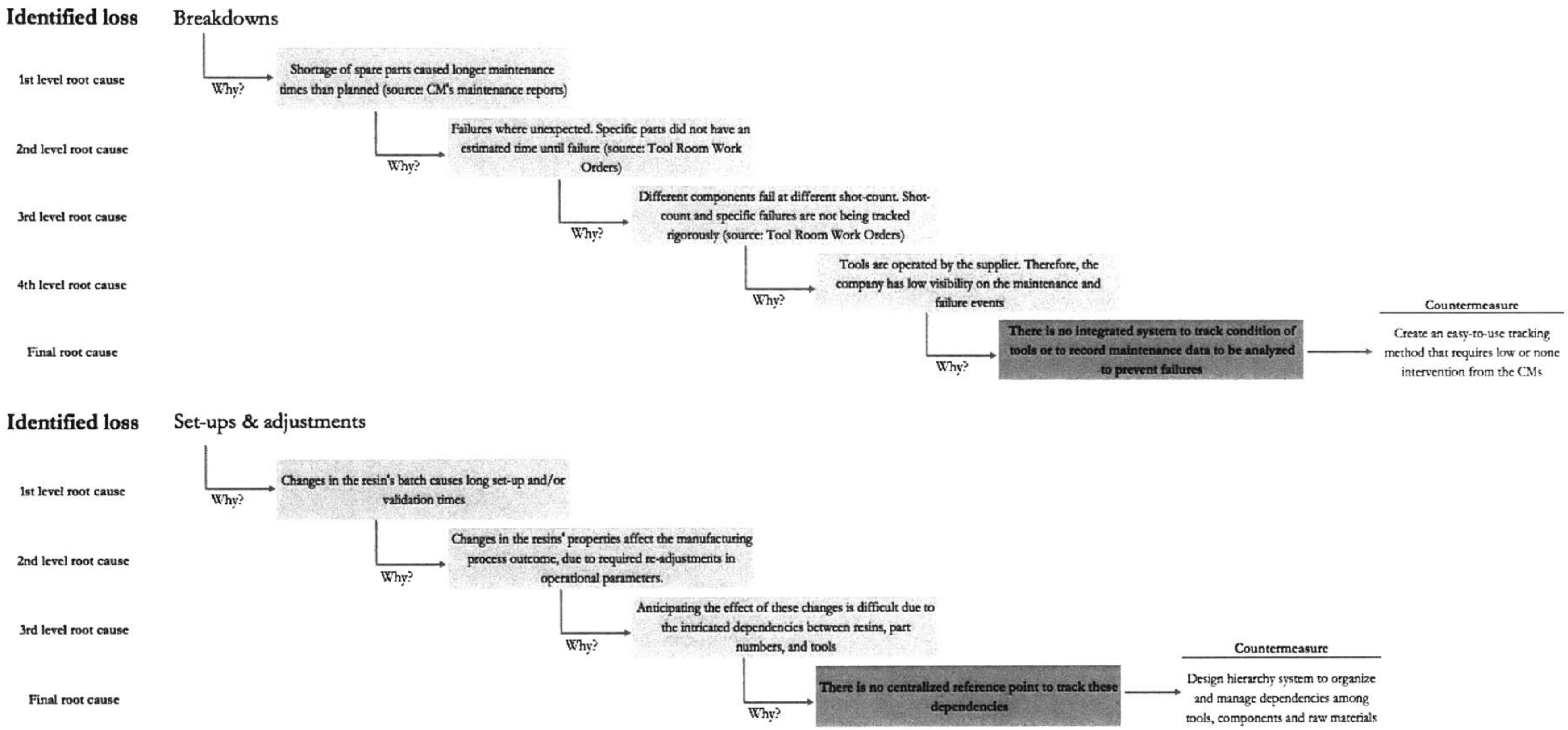
Figure III-4. CM's categories conversion to "Six Big Losses" (Elaborated by the author)

The material issues and the unplanned maintenance correspond to the largest portion of the losses and they are both related to the availability. Respectively, they can be attributed to "Set-up and adjustments" and to "Breakdowns". Material issues, as explained by the manufacturing floor personnel and the maintenance supervisor, are the problems that are related to slight changes in the materials composition that require some adjustments to the temperature and pressure control. This procedure takes some important time from the total availability. It is worth noticing that given the fact that the presses are utilized solely for the Synchron® Cartridge molds, there is virtually no time lost on setting up the mold itself, which is usually a significant portion of the availability losses [23], especially in plastic manufacturing. In our particular case, mold set-ups only occur before and after a maintenance event, which is time that is included in the breakdown time. These other types of losses are related to the unplanned maintenance events. As observed in many cases, breakdowns are usually extended beyond the actual maintenance tasks themselves due to unavailability of spare parts. Even during planned maintenance (PMs) events, the operator usually spots wear that calls for a replacement and the spare parts' shortage causes dilation of the maintenance event. The additional time used for a PM beyond its planned time is also counted towards the breakdown time.

The performance losses are related to an overall slower manufacturing pace. Either if the decelerated pace is caused by minor stoppages or just a speed reduction from the designed capacity is hard to tell from the CM's production report. Therefore, this loss is aggregated as "Performance" losses. This category only accounts for 10% of the losses in the Synchron® Cartridge molding process.

The scrap rate is a combination of the number of defective parts produced during the ramping and the defective parts produced during normal operation. Again, differentiating them in the manufacturing report is difficult and they only account for 1.6% of the total losses.

Figure III-5. Root cause analysis for major OEE-related losses



A Pareto analysis suggests that we focus on the main contributors to the gap. In this case, this is Breakdowns (47.6%), and Set-ups and adjustments (40.8%).

Addressing these losses requires taking a deep-dive into the underlying causes. As mentioned before, the classic PSP approach is to ask "why is this happening?" several times until reaching a "lever" or an actionable item that lays within the scope of the process owner. Ultimately, and philosophically if one may, there are no root causes as they can all keep moving backwards and away from the organization's responsibilities. However, the question to answer is how can the problem be solved economically and effectively to prevent recurrence [23]. Following this logic, a root cause analysis of the two main contributors to the OEE losses is shown in Figure III-5, landing in two root causes:

- The lack of an integrated system to track condition of tools or to record maintenance data to be analyzed to prevent failures
- The lack of a centralized reference point to track dependencies between assets, parts produced and raw materials

c. Countermeasures and alternative solutions

The root causes aforementioned are actionable by the company through the following proposed countermeasures:

Life-cycle tracking

The starting point of this method is to have a way to accurately track the condition of a tool. The tools' shot-count is used as an indicator for the current tool condition, and to index failure and maintenance events. This is an indicator of the "mileage" of the tool [24]. We can look at it as equivalent to how the odometer of a car is an indicator of the age of the car, and almost all maintenance and failure events relate to that indicator. In plastic manufacturing, a shot-count is the occurrence of one full cycle of an injection molding machine. This corresponds to completing the injection trough the nozzle and gates into the cavities –with the mold closed-, cooling the parts, opening the mold, ejecting the parts, and closing the mold again to prepare for the next shot. However, this could be re-applied to other type of machineries of interest such as the Sealer, in which case a shot-count –which again, is the occurrence of one full cycle- corresponds to the completion of the picking, hot-sealing, testing, and releasing stages. After defining this indicator as the cornerstone of the tracking method, the system around it needs to be designed following some guidelines that will help to tackle the implied root cause in this countermeasure: (1) increase visibility of the conditions of the tools that are owned by Beckman Coulter but operated by the CMs, (2) enable a depository of relevant information related to maintenance and failure events that will improve the predictability of future failures, and (3) monitor indicators about the effectiveness and efficiency of the asset, and (4) it should work independent from the CM participation in the designed system.

Galar et. al. [7] propose a few alternatives for effective data collection for life-cycle tracking. The most applicable for this system are:

- Bar codes and scanners: placed on the tools and the components. They are scanned to pull the asset's info from a computer maintenance system to allow the operator to record usage and maintenance information.
- RFID systems and sensors: combining the use of radio tags, radio readers and sensors permits a more automated data collection process, with less human intervention. The tags hold a microchip that stores data and radio readers collect and modify the information in the tags. The sensors installed on the machinery monitor motion, acceleration, pressure, or temperature, and are connected to a computer maintenance system.

Besides these, an alternative that is not usually considered by other authors is using existing production or logistic reports as a proxy for the usage of the assets. We considered this additional option given the fragmented nature of the manufacturing network. Specifically, the company could use the internal receipts from the warehouses as a proxy for the production rate of the assets and calculate the assets' shot-count. Since all the manufactured plastic parts pass through the internal warehouse, this is an all-inclusive measurement.

The three alternatives were evaluated by four different criteria: implementation cost, organizational fit, timeliness, and data accuracy. Table III-3 summarizes the results from this analysis.

System	Cost per asset tracked	Organizational Fit	Timeliness	Data Accuracy
RFID	$500 – $1,500	Low	High	High
Bar codes	$100 - $200	Medium	Medium	Low
Internal Receipts	Negligible	High	High	Medium

Table III-3. Analysis for alternative solutions for life-cycle tracking (compiled by the author)

In terms of cost, the RFIDs stand as the most expensive option, with total costs ranging from $500 to $1,500 per each tracked asset, including installation [25]. RFID costs have significantly reduced lately but there is a significant infrastructure to be installed besides the actual tag, such as readers. Bar codes are older technology, only requiring labels, handheld readers ($100 -$200) and connection to the centralized system. Lastly, using the internal receipts from warehouses do not represent an additional cost for the company since they are available in their ERP systems.

The organizational fit is related to the nature and size of the manufacturing network. The company uses more than 200 different CMs, with different degrees of modernization, and dispersed around the globe. RFIDs and bar codes are, therefore, challenging to be implemented across all the network both because they do not share a standard technology within them, and because their reluctance to modify their current methods. Internal receipts are, on the contrary, agnostic to participation of the CMs.

Timeliness is associated to the frequency at which the information could be realistically collected and reported. RFIDs do this automatically, and the internal receipts information could be retrieved on demand, and in few minutes for hundreds of assets. Bar codes require constant scanning, which implies difficulties to be done very frequently. Additionally, they would require the operators to spend time manually inputting production quantities and times.

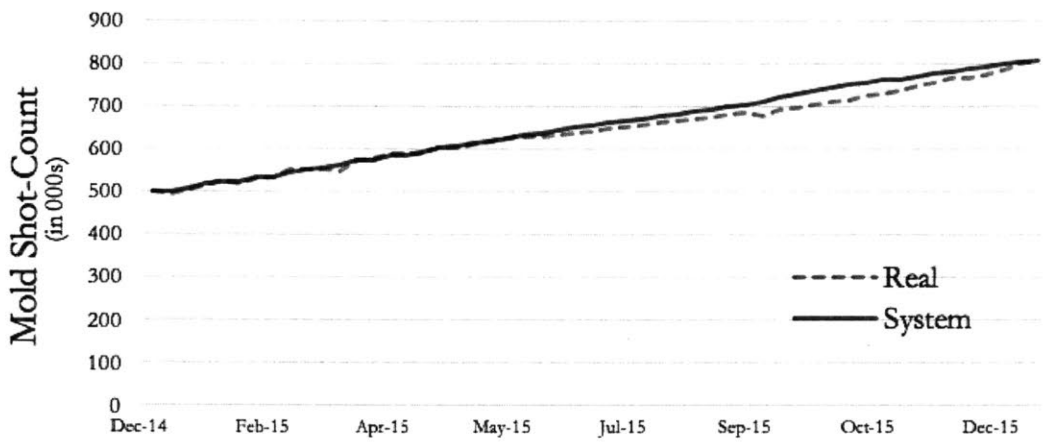


Figure III-6. Internal receipts tracking accuracy (elaborated by the author)

The data accuracy is how close the system is to represent the real information, in terms of shot-count and production times. RFIDs would use sensors to calculate and record the cycle counts, hence have a high accuracy. Bar codes would require manual input from the manufacturing operators, therefor accuracy is expected to be low. The internal receipts were tested for accuracy using information available from the few assets that had a dataset of their real usage. As an example, Figure III-6 shows the differences between the real shot-count and the calculation based on the internal receipts of the Synchron® cartridges. The calculated R-squared for the relationship is 0.961.

Based on this analysis, the selected alternative was to use the internal receipts for tracking the life-cycle progression of the assets. This research identified, however, three different types of discrepancies that this method could generate: (1) the effect of changing finished parts inventories at the CM level, (2) inability to differentiate receipts that are manufactured by two or more interchangeable assets, and (3) the effect of unexpected and inconstant scrap rates. The limitations of this method are, in the author's judgement, surpassed by its advantages and will be discussed in more detail in Chapter IV3. , jointly with alternatives to mitigate them.

Visualization of dependencies

The second countermeasure is to establish a relationship map that shows the dependencies between the part numbers produced, the raw materials, the molds, presses and other machinery. Ideally, this would set the framework for a system to easily identify, anticipate and mitigate the impact of different contingencies, such as changes in the properties of raw materials, shortage of a component's spare part, or an upstream process' breakdown. It requires to be supported by a software platform where the users, manufacturing and procurement teams, enter the information from the relevant assets and their processes, and set the relationships that exist between them.

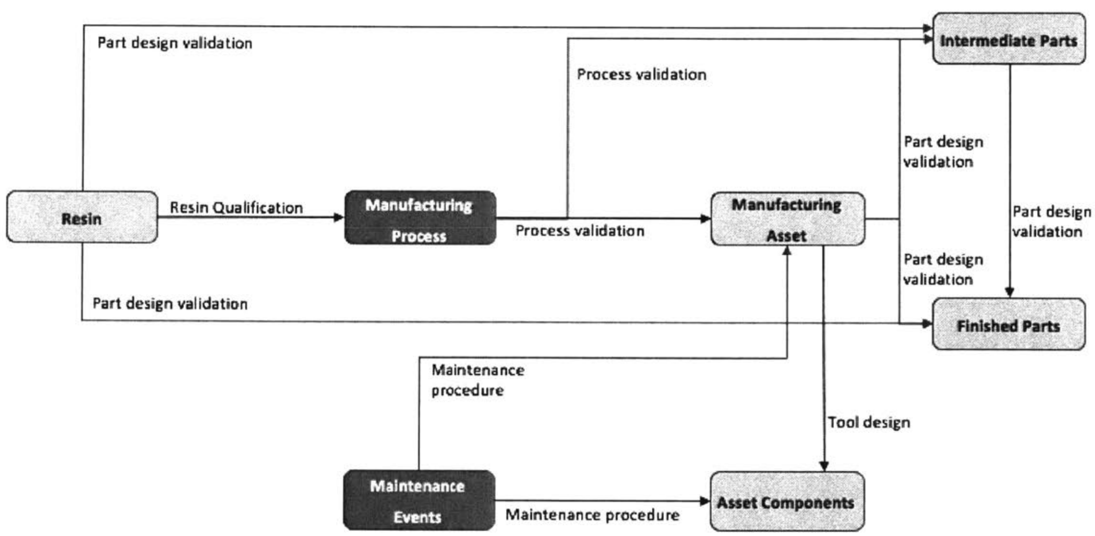


Figure III-7. Observed dependencies in the manufacturing system (elaborated by the author)

In Figure III-7, the arrows identify the internal document that defines the nature and scope of the dependencies existing among the manufacturing system. This dictates the design of the database architecture that will be used to populate the information about every individual element in the network. Coming back to our Synchron® cartridge example, all the resins that have been qualified to make the part number are internally linked to the processes, the intermediate, and the finished parts that use this resin. Similarly, the processes are linked to the parts that they govern, and the assets that are used in the process.

This type of database, based on objects and relationships, is conveniently deployable in MS Access® which, at the same time, is ubiquitous among the typical AMS' user profile. MS Access® allows to observe upstream and downstream relationships, both from a database design perspective, to an individual track for each asset's dependents and predecessors.

From the perspective of an asset management system that satisfies the characteristics described in Chapter II2. , these two countermeasures could serve as the basis for such a system. Modern asset management systems include complex predictive models and sophisticated economic evaluations, but this starting point holds significant advantages. Firstly, its simplicity and potential impact encourages its adoption. It is a relatively easy-sale to get approval from management as a pilot to evidence its functionalities and usefulness. Second, it acts as an incubator for new features that could be required as the users grasp the asset management mindset. One important feature is the implementation of predictive analytics, which require granularity and rigorous data collection either through manual input or using process sensors.

Chapter IV

Pilot Design and Implementation

The Asset Management System translates the internal receipts information into the mileage of the assets, using shot-counts as the main indicator for mileage. All life-cycle events are indexed to the asset's shot-count, serving as a type of time-reference point. Additionally, this system is built on a dependency-based database.

1. Basic structure of the proposed system

The first technical challenge for the pilot design was to identify the right way to relate the receipts information to the appropriate manufacturing assets. A typical receipts report, obtained from the company's ERP, has the following information:

Org	Item	Item_Desc	Receipt_Num	Receipt_Date	Qty_Received	Supplier	Supplier_Site	PO_Num	Blanket_Num

Table IV-1. Information available from Internal Receipts report (adapted by the author)

Most of the fields are self-explanatory. However, some of them require further explanation: "Org" is the internal organization receiving the delivered batch, which is mostly a different company location. "Item" is the Part Number received in the batch. Note that this Part Number is not necessarily the same part number that is used for the manufactured part, since the received parts are usually assemblies of more than one part, or packages of multiple items with a different final part number. The rest relate either to characteristics of the CM (e.g. name, location), information about the specific delivered batch (e.g. date, quantity) or other internal references to procurement documents (e.g. number of PO, number of blanket or contract).

After this initial information is imported to the system, the system identifies unique combinations of the fields "Item" (which is the Part Number as-Purchased, or PNP), "Supplier" and "Supplier_Site". Then these triads are clustered in all the different unique combinations found, and the "Item" from the triad is matched to a "Part Number as-Manufactured", or PNM, which is defined as the part that comes out from a fundamental manufacturing process. A fundamental manufacturing process is, at least in the pilot stage, an injected part[4]. This relationship can be single-to-single (one PNP matched to one PNM) or single-to-multiple (one PNP matched to several PNMs, which is the case of assembled parts). The opposite is not feasible (one PNM to several PNPs) because no PNM is part of different PNPs. Since most suppliers have only single manufacturing lines producing each part at a specific location, in the vast majority of steady-state situations (i.e. no change in scrap rate nor in the finish goods inventory levels at the CM), the quantity accumulated in each triad is directly and fully correlated to the quantities produced by the manufacturing assets[5]. Therefore, the system is able to identify the assets that manufactured each PNM, and accounts for the cumulative count of parts in that triad as the parts that were manufactured by this asset. This is, after a few correction factors, equivalent to the asset's shot-count. In Figure IV-1 we can visualize the relationships described in this paragraph.

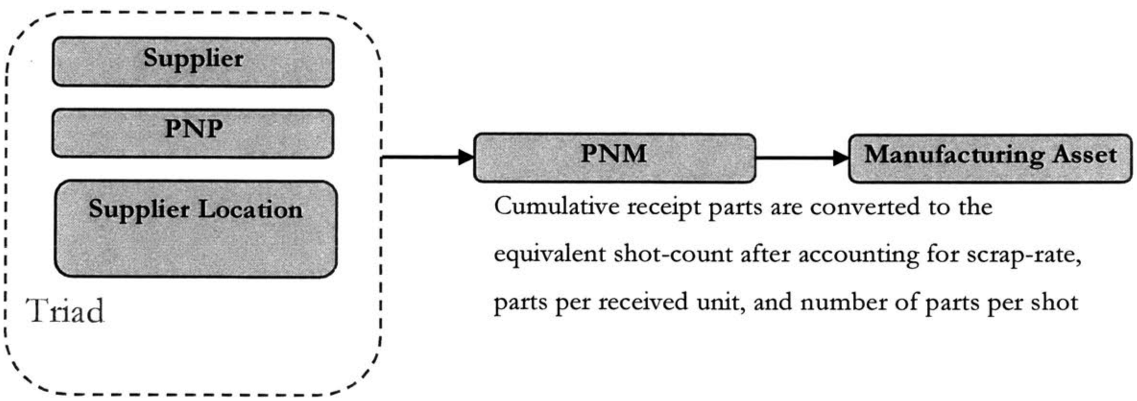


Figure IV-1. Information flow to establish relationship between receipts and shot-count (elaborated by the author)

To finally convert the number of parts received to actual shot-counts, we need to take in consideration some characteristics that are inherent to the asset itself. These characteristics are entered by the user into the system only once, when they enter the asset or assets that they want to track. The most relevant ones are:

- Units/EACH: Is the ratio between the number of PNMs (that are produced by the asset in question) that go in every unit of PNP. I.e.: A certain PNP could be received in packages of 100 parts, which are counted as one unit in the receipts report. In this case, the Units/EACH ratio would be 100.

[4] In a scaled system, the fundamental manufacturing process could be any process that creates a new part number from raw materials

[5] The only case when this would not be true is when the same part number is manufactured by more than one asset that do the exact same task, at the same supplier, and at the same supplier location (in this case, a triad that is actually accounting for the production of more than one asset). This case will be analyzed later when we describe the limitations of the system.

- Scrap-Rate: Is the average percentage of scrapped parts in all the downstream process from the asset in question, until the warehouse that reports the receipts.
- Number of cavities: Is the number of PNMs that are made in every shot.
- Designed capacity: Is the number of parts that, by design and in ideal conditions, an asset is able to process in one hour.
- Base-point date: Is a reference point in time at which we know for certain what was the shot-count of a specific asset. This is useful to make up for bad or lack of receipts information during a period in the past. Typically, the user will set up a base-point date and shot-count after that period to start counting from that point.
- Base-point shot-count: Is the shot-count that is tied to the base-point date.

The exact way in which the current Shot-Count of an asset is calculated is, therefore:

$$Current\ ShotCount_{Asset} = \frac{Cum.Receipts_{Triad} \times Units/Each_{Asset}}{(1 - ScrapRate_{Asset}) \times Num.Cavities_{Asset}}$$

An additional consideration in the calculation of the "Current Shot-Count" is that when an asset has a "Base-Point Shot-Count" set at a different value than zero, the "Current Shot-Count" starts counting from that point and only accounts for the cumulated receipts entries that have happened after the corresponding "Base-Point Date". This is because, as explained before, the user can have information about the asset's history that starts on a specific date and does not have information –or has bad information- prior to that date.

This calculation provides a timeline for the assets' life cycle, in the form of a time series, to which different events and indicators are indexed. Figure IV-2 is an example of the main outcome obtained from the base structure of the proposed system.

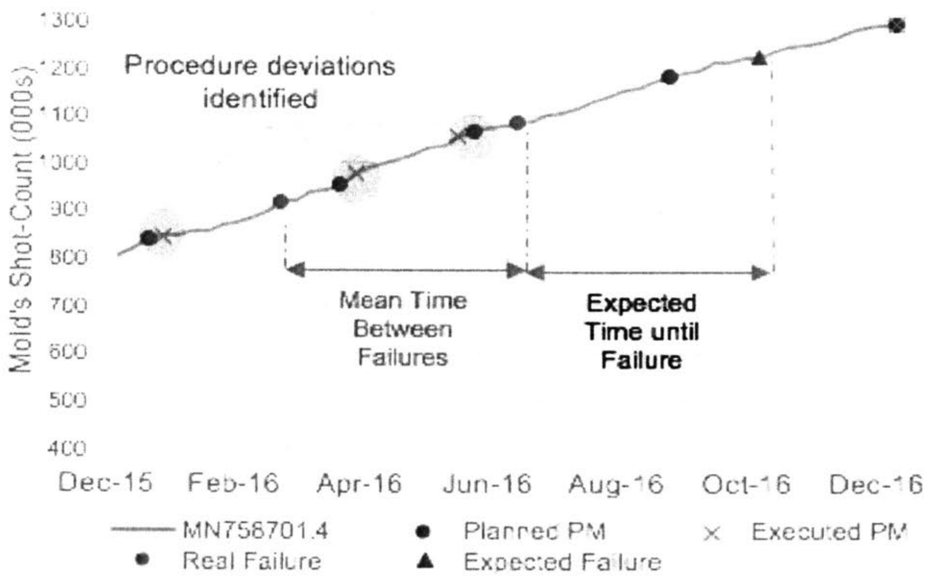


Figure IV-2. Shot-count timeline with different events indexed to it (elaborated by the author)

2. Features and capabilities of the proposed system

After the assets' inherent characteristics are entered into the system, the system is able to track their life-cycle, show leading and lagging indicators, and add events that index to it.

a. Indicators

Indicators available by default

Besides the inherent characteristics mentioned before, the system offers three additional indicators and one graph that are always displayed without any additional input required:

- Current Shot-Count (counts): Indicates the most up-to-date shot-count of the asset.
- Average Interval (days): Indicates the average interval between every batch received in which the asset was involved. In other words, it tells us how often we get an updated shot-count for that asset.
- Average Shot-Count Rate (counts/day): Indicates the average manufacturing rate, expressed in shot-counts per day, of the asset. This is calculated using the 180 days previous to the last item received from the asset.
- Shot-Count timeline: a time series of the accumulated shot-count of the tool. It can help the user identify periods of inactivity or unusual patterns of the asset's activity. Additionally, the graph also plots the occurrence of maintenance or failure events, when the user enters this information. The data input for these events will be explained later in this chapter.

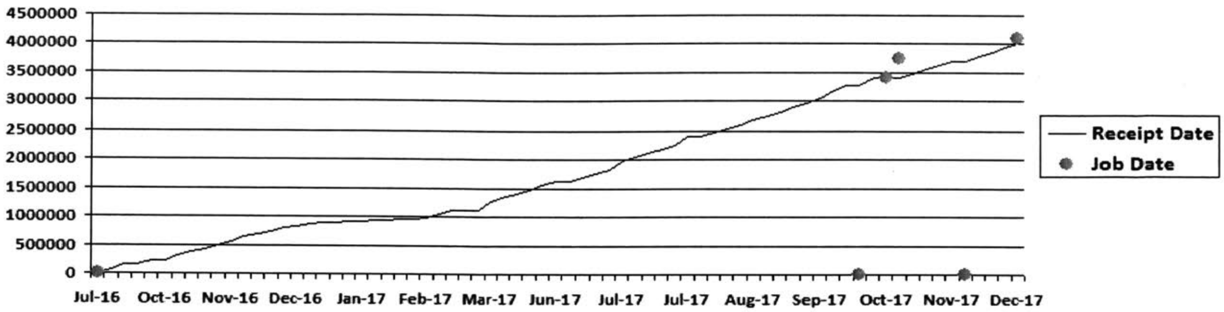


Figure IV-3. Sample of shot-count timeline displayed by the system (Source: Beckman Coulter's Asset Management System)

OEE estimation and graph

As mentioned in previous chapters, the OEE is a major leading indicator that would allow to evaluate the success of maintenance initiatives or strategies, re-negotiate the price of parts, or justify a new capital investment. The way the system calculates the OEE is as follows:

$$OEE_{(Asset;\,month)} = \frac{Sum\ of\ QTY_{RECEIVED\,(Triad;\,month)} \times\ Units/EACH_{Asset}}{Designed\ Capacity_{(Asset)} \times\ Scheduled\ Hours_{(Asset;\,month)}}$$

Where:

- $OEE_{(Asset;\,month)}$: Overall Equipment Effectiveness for a specific asset in a specific month
- $Sum\ of\ QTY\_RECEIVED_{(Asset;\,month)}$: The accumulated QTY_RECEIVED (from the internal receipts info) of a specific asset in a specific month
- $Scheduled\ Hours_{(Asset;\,month)}$: The number of hours that were scheduled for the asset to operate during the specific month. This is entered manually by the user but is only required for the OEE estimation.

The numerator of this formula is the product of the Total Received Quantities from the asset in one month and the Units/EACH indicator, which would result in the total good units effectively produced by the asset. The denominator, on the other hand, is calculating the maximum possible number of units manufactured by the asset during the scheduled hours. That is, in essence, equivalent to the classic OEE definition of Availability × Performance × Quality Rate.

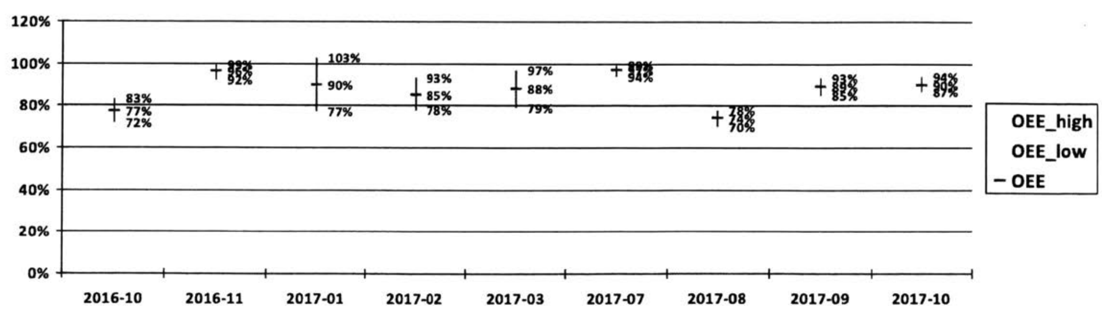


Figure IV-4. OEE graph displayed by the system (Source: Beckman Coulter's Asset Management System)

The graph shown by the system (see Figure IV-4) is an estimation of the asset's OEE. The middle point is the expected value assuming no month-to-month change in the finished goods' inventory levels at the CM. The high and low points are the values that correspond to a change of one standard deviation of the month-to-month inventory change. This graph requires some minor additional information ("Monthly Scheduled Hours" and "S.D. of inventory change") to be entered manually on a monthly basis.

b. Tracking dependencies between elements in the system

The system allows to easily track and visualize the dependencies between the finished goods and the raw materials (and vice versa), passing through the work-in-progress parts, processes and manufacturing assets. This feature also allows to aggregate and disaggregate diverse indicators such as the specific shot-count of an asset's component, or the consumption of a specific resin. We can even assign specific causes to a low OEE cross-checking with the maintenance event durations, or periods of use of a new type of resin.

Initially, the first dependency that is created in the system is between the PNP and PNM, listing all the PNMs that are required to assemble a specific PNP. After that, the PNMs are referred to the assets that are used to manufacture them via the asset's information sheet. PNMs are also referred to the resins that are currently validated to be used for their manufacturing processes.

Optionally, the user can feed in information about the usage of a resin for manufacturing process during a period of time, including quantities per unit that allows to calculate consumption and set alerts for potentially running out of stock. Even if this task is usually performed by the Direct Procurement team, with their own specialized tools for this purpose, having an estimation of the availability of a raw material allows the engineering team to evaluate if a change (or unavailability) in the resin is the cause of an asset's downtime.

The relationship between the components of an asset (inserts, wear parts) and the asset is also captured by the system. The components information is entered through the asset's information sheet, and allows the user to enter the period on which the component was being used. Based on this, the system calculates the shot-count for the components as well. It also allows to enter maintenance and failure events regarding to the components, similarly to the asset's maintenance events, including all the additional features.

c. Maintenance and failure events

The system allows to record maintenance events for tools and critical components. These records can be used to set alerts, plan for future maintenance, analyze performance, or set the basis for predictive analytics.

The main form of the system allows to enter maintenance events for each of the assets being tracked by a user. The maintenance record was designed to maintain a simple way to record these events, but at the same time to make it relevant and granular enough for further analysis and decision making. The main fields to enter are the type of event (Failure, Repair, or Preventive Maintenance (PM)), the type of issue (General PM, Mechanic, Electric, Human Error, Parameter Calibration, or Software), and the notes (an open-text field where the user should enter the most relevant keywords to filter or to cluster). Additionally, the user should specify the shot-count and date at which the event happened (or will happen, in the case of the PMs). The system also allows to mark a PM or event pending for action as "Done", and to set e-mail alerts to people in the organization, for scheduling or warnings. All the events entered here will be plotted in the shot-count graph, for visualization.

To facilitate the manual input of these events, the system has some degree of automation. One of these features involve the possibility to import maintenance events from an Excel form. This comes useful when the company needs a CM or a non-authorized user to enter the information in the system and there is reluctance to share with them all the system's interface. The system also allows to easily enter recurring tasks repeating the event for a specified number of times and for a specified "shot-count frequency" or "time frequency". It also sends automatic e-mails using a template that includes the event information and gives notice of required further action.

d. Calculating the Mean Time Between Failures (MTBF)

In the current system, there is no condition-monitoring variables. Given the nature of the system and the different types of ownership philosophies in every different CM, monitoring operating conditions has not been put in place yet.

For this reason, the calculation of the Mean Time Between Failures (MTBF) needs to be done under the assumption that we are in the IP region of the asset (i.e. we have not entered the P-F curve, as we do not have any signal from the system that we could use as our Alarm Limit. See Chapter II4.).

The system filters similar type of issue (Mechanical, Electrical, etc.) as per indicated by the user. The user can also filter by a "keyword" that is searched in the notes field for each maintenance event entry. After the event criteria is set, the system calculates the mean time between the events.

The statistical definition of MTBF is the inverse of the parameter λ, which is the rate of occurrence of an event in an exponential distribution. Consequently, the probability of a failure to occur is represented by the cumulative probability function of an exponential distribution, as in:

$$F(t \leq t_0) = 1 - e^{-\lambda t}$$

Since λ is $1/\text{MTBF}$, then the same probability function can be expressed as:

$$F(t \leq t_0) = 1 - e^{-t/MTBF}$$

This function allows us to calculate the probability of a specific failure to occur during the next period of *t* duration.

An alternative way to express these functions is in terms of shot-counts instead of time (*t*). The system actually uses the variable shot-count as the input for the calculated MTBF (outputs in shots instead of a time unit) and requests the user to enter a number of shot-count to calculate the probability of the type of failure to occur before the indicated number of shot-counts.

3. Technical limitations of the proposed system

Since the system relies on the information available in the receipts report and the manual input of the user, it is limited to the granularity and the quality of such. There are two main limitations that relate to this condition, which we will describe and propose alternatives to solve in the short-term. We will also propose a longer-term solution in Chapter V and in the Future Work chapter.

a. Predictive analytics based on available data

When calculating MTBF, it is important to notice that the exponential distribution assumes events with no memory, which is not exactly the case when it comes to failures (i.e. a repaired component will not behave the same way as a new component). Additionally, the exponential distribution assumes a constant rate of occurrence. However, the real rate of occurrence will increase as the component or asset has performed more shot-counts, as the asset deteriorates over time. As explained in Chapter II4. , in order to correct for these discrepancies, we need to include condition-monitoring variables into the model, which are not being measured in this pilot.

b. Different notations for same location

Since the location name is crucial to establish the triads, having different notations for the same location cause the system to account for different assets when it is actually only one. This situation can occur for specific situations (e.g. the procurement team decides to maintain a separate record for different shifts at the same location, and call them "ABC1" and "ABC2"). Even though this is an unusual situation, the user needs to verify that it is not arising from the tracked assets. The system provides a sub-form where the user can define the location names that are equivalent to prevent this from misleading outcomes.

c. Multi-stream processes at the same location

The system is not able to differentiate which specific asset is accountable for the manufacturing of a part number, when a supplier's location has two or more assets performing the same task. The receipts report does not separate nor identify batches from different production lines, therefore the available information to overcome this issue is insufficient. If the user needs the system to keep track of the shot-count of these multiple assets independently, the system will require some way to differentiate them, either by PNM, by Supplier, or by Location. The latter is strongly recommended.

The methods to execute this depend on the specific conditions under which these multiple assets work. For instance, the user could know that all the parts received from DayX to DayY correspond to AssetA, from Supplier1 at Location1, and the parts received after that date range correspond to AssetB, from Supplier1 at Location1. The system provides a separate sub-form called "Multiple Assets Conflict" where the user can specify the conflicting triad (PNM, Supplier and Location) and specify the dates in which the receipts should be allocated to two artificial locations, to which the conflicting assets would be assigned when they are created in the system. In a similar case, if the multiple assets actually run simultaneously, the user specifies a percentage of the receipts that should be allocated to each asset. This is, of course, only a partial solution because it assumes that the proportion of the production coming from each stream will remain constant for the notated period of time. This is definitely a very wishful assumption. More systematic and rigorous alternatives are explored in Chapter V.

Chapter V

Definition of ideal system's characteristics towards a Smart Factory

The current state of the manufacturing structure at Beckman Coulter accounts for some limitations to implement a more complete asset management system, in line with current developments and available technology that are in the domain of Industry 4.0 standards. Most of these limitations are originated in the fragmented and diverse nature of contract manufacturers in their network, which use different manufacturing and information systems that make any standard solution to be intrusive and, therefore, unlikely to be implemented.

Oppositely, the proposed solution in this thesis is absolutely applicable across the different type of CMs, even without their collaboration, and it sets a platform for more sophisticated features that will drive higher value to the CM and the OEM. The current chapter describes how should an ideal asset management system work with Industry 4.0 standards, proposing implementations to the manufacturing floor that are required to advance to such a state, and describes the potential predictive capabilities that such a system could reach.

1. Description of an Industry 4.0 CM-based manufacturing network

The integration of new information management and communication technologies into the manufacturing operations has put in place the foundations for the next industrial revolution, called Industry 4.0 [26]. Even if this concept is vastly discussed among manufacturing gurus and experts, and also a top priority for most companies, feasibility of implementation is generally regarded as difficult and the understanding of its term is usually vague [2]. This section attempts to present the ideal description of an Industry 4.0 environment, applied to a CM-based plastic manufacturing network, leaving aside the existing barriers for implementation. The objective is to set a reference point to which a manufacturing system should aim its decisions.

Marr [27] argues that for a factory to gain the value of an Industry 4.0 environment, it must follow these design principles:

Interoperability: Refers to the capacity that machines, devices, sensors and people have to connect and communicate between them. Wireless communication technologies play a prominent role in the increasing interaction as they allow for ubiquitous internet access [26]. The interconnection allows objects, such as actuators, RFIDs, sensors, and computers to interact with each other and act according to a decision-tree lined-up to an objective function.

Information transparency: A virtual representation of the real world needs to be collected and stored in the system at the highest degree of detail possible, to allow analysis of past events and informed decision making. Context-aware systems is the coined term for systems that can create a reliable representation of the reality in a data form. Context-aware systems combine the information that comes from the physical world (e.g. the position of a robotic arm, or inventory levels) with the information from the virtual world (e.g. electronic documents, drawings, and simulation models). Data coming from sensors are usually in raw format and needs to be cleaned, aggregated and interpreted by a data analytics service, and make it accessible to all the participants. Depending on the criticality of a process, the processing speed of real-time information becomes more crucial [26].

Technical assistance: The systems are designed to support humans, shifting their roles from machine operators to strategic decision-makers and flexible problem-solvers, assisted by the higher information processing speed and data storage capacity of artificial intelligence. The systems are designed to display information in a comprehensive way for humans, enabling them to react quickly and reliably. Interconnection with wearable electronic devices (e.g. phones, tables) facilitate this assistance [28]. Additionally, the current advances in robot technologies allow physical assistance to humans, with tasks that are challenging, unsafe, or exhausting for humans.

Decentralized decision-making: An Industry 4.0 system has the ability to make a baseline of decisions without human intervention or supervision, and this baseline is subject to a decision hierarchy. Combining different decision-makers is an advantage of the system because it allows to utilize local and global information to achieve a better optimal state in terms of economic performance. However, the system must allow local systems to perform their tasks as autonomous as possible and identify decisions that might significantly affect external outcomes or be affected by external factors. In these cases, the tasks or decisions are delegated to a higher level. This automation level allows humans to take on more complex tasks and reduces the need for repetitive and simple supervision [28].

In plastic manufacturing, the implementation of these principles needs to be studied in detail to decide which ones are critical, and which ones are not. However, it is known that in order to achieve Industry 4.0 capabilities, a minimal level of implementation of each principle is required. A smart plastic manufacturing system will enable several useful operational skills, such as ability to reject parts based on quality observations, stop and start processes based on inventory levels and demand projections, or set an asset for maintenance when a condition-monitoring variable is observed to pass the alert threshold.

2. Improving asset effectiveness with Industry 4.0 principles

The specific conditions about the political, cultural and organizational environment in the CM and the OEM needs to be taken in consideration for an implementation of this nature. To implement such a system, Hermann et al. propose a project roadmap [26]. First, a common understanding of Industry 4.0 needs to be created, especially among upper management of both organizations, illustrating exemplary scenarios and success cases. After this, project owners and bilateral members are assigned to the implementation team. Together with upper management, the teams identify and specify what are the Industry 4.0 scenarios that the organization can implement, guided by the four design principles listed above. *Table V-1* shows the scenario description for improving the asset effectiveness.

Scenario: Improving asset effectiveness
Description: - Failure and wear prediction for mold spare parts - Autonomous anticipation of part requirement and order placed to supplier - Automatic setting and calibration of operating parameters - Production plan modification and finished product inventory levels alerts set
Current Situation: - Run-until-failure or preventive maintenance - Manual update of production plan - Risk of out-of-stock

Table V-1. Scenario identification and description [26]

After this, all the described scenarios are evaluated through a ranking of factors. The factors usually relate to three topics: compliance with Industry 4.0 design principles, contribution to strategic objective, and feasibility. Each topic has sub-topics and each sub-topic is given a weight and the scenarios are assessed on these, as seen in Table V-2. With these results, the scenarios are prioritized based on the total sum of the final scores, and are re-evaluated in terms of risk and cost-benefit analysis. Finally, the selected scenarios are taken to a detailed execution plan that includes technical and organizational actions.

		Improving asset effectiveness	
Factors	**Relative Weight (%)**	**Assessment (0-5)**	**Final Score**
Industry 4.0 principles			
Interconnection	100%	4	4.0
Information transparency	100%	4	4.0
Technical assistance	80%	4	3.2
Decentralized decision-making	40%	4	1.6
Strategic objective			
Cost reduction	80%	4	2.4
ROIC improvement	80%	4	3.2
On-time delivery	80%	4	3.2
Feasibility			
Technical feasibility	60%	4	2.4
Economic feasibility	60%	2	1.2
Legal feasibility	40%	5	2.0
Operational feasibility	80%	3	2.4

Table V-2. Factor analysis for scenario (adapted from [26])

The scenario for improving asset effectiveness described and assessed above shows us that the design principle factors with the most relevance are the information transparency and interconnection, followed by the technical assistance. This provides guidance in the allocation of resources required to fulfill these principle with the most importance.

From a general perspective, this analysis embodies the integration of computation and physical processes where digital assets monitor and control the physical assets, using feedback loops that constantly inform the exact condition of the assets and acts on them. The first step is to have proper identification of the physical assets, most commonly done by RFID technology, that is accompanied by information storage and processing provided as a centralized service. Installing sensors and actuators allows to capture more information about reality and execute actions given by the centralized data processing service.

3. Ideal future-failure predictive model

To enable an appropriate and effective future-failure prediction model in the plastic manufacturing floors of the CMs, the right information needs to be collected (Information transparency) and shared

(Interconnection). As mentioned in Chapter II4. additional variables should be used to improve the accuracy of a predicting model. Only the time between failures is included as a variable in the current state of the system's failure prediction model. In plastic manufacturing, there are various types of condition-monitoring variables that are useful to explain machine behavior and potentially predict failure events or anticipate wear patterns. According to the analysis provided by Selcuk [17], different condition-monitoring techniques are useful for different types of processes. The following were found to be adequate for an injection molding plastic manufacturing process:

Process parameter measurements: temperature and fluid pressure are one of the most important operating parameters in injection molding. These are measured to monitor health of the system, trying to detect abnormal changes. Production rate and product quality can also give information about the machinery condition. A large advantage of this technique is the fact that most injection molding presses currently measure these parameters. A CM would only require to add the data processing and communication module. The disadvantage is that this type of variables need to be carefully corrected to dismiss operational changes [30].

Thermal analysis: thermography is useful for injection molding failure prediction because it can detect nozzle clogging, un-even temperature distribution, and unusual friction (or lack of) between components. The disadvantage is in the complexity of the image data processing and combination with discrete value data.

Acoustic analysis: changes in sound patterns (audible and non-audible) can indicate wear and deterioration of components. Ultrasonic analysis can be used for leak detection in seals and gaskets, and for detecting hidden flaws in the metallic materials. These two aspects make acoustic analysis a very appropriate method for molds and presses. Similar to thermal analysis, acoustic waveforms require additional data processing to include in a statistical analysis.

Oil analysis: can usually provide information about the machine condition and the oil condition. Analyzing the size, shape, composition and amount of debris can provide relevant information about the type of wear in the components.

Vibration analysis: is one of the most popular PdM techniques. However, in the case of injection molding tools, the low speed of the moving parts make this method ineffective to promptly detect defects. Even if false alarm rate is in the order of 8% only, this is mostly applicable to high-speed, non-reciprocating rotational machinery.

In accordance to Selcuk [17], it should be noted that this PdM model is being designed under the assumptions that:

- Deterioration rate is low enough to allow time to detect and analyze the failure signs and then to intervene
- Leaving the system to fail is not affordable in terms of safety and/or cost

Having chosen the appropriate parameters and techniques to measure, the sensor location needs to be defined. Then, the inspection interval is determined, either continuously, on regular intervals, or at condition-based intervals. Lastly, a computerized maintenance management system (CMMS) needs to be put in place. Sensors that monitor these variables would provide valuable data points to construct a predictive model using the Weibull hazard function, as explained in Chapter II4. . The collected data is used to fit the curves and determine the function coefficients.

The resulting model formulates a time to failure prediction in the form of a cumulative density function. However, the full function will not be necessarily valuable to the user, and its interpretation could even be confusing and time-consuming. For this reason, this model can be converted into a simpler high-low chart, as seen in *Figure V-1*, that provides discrete values that are easier to interpret [20].

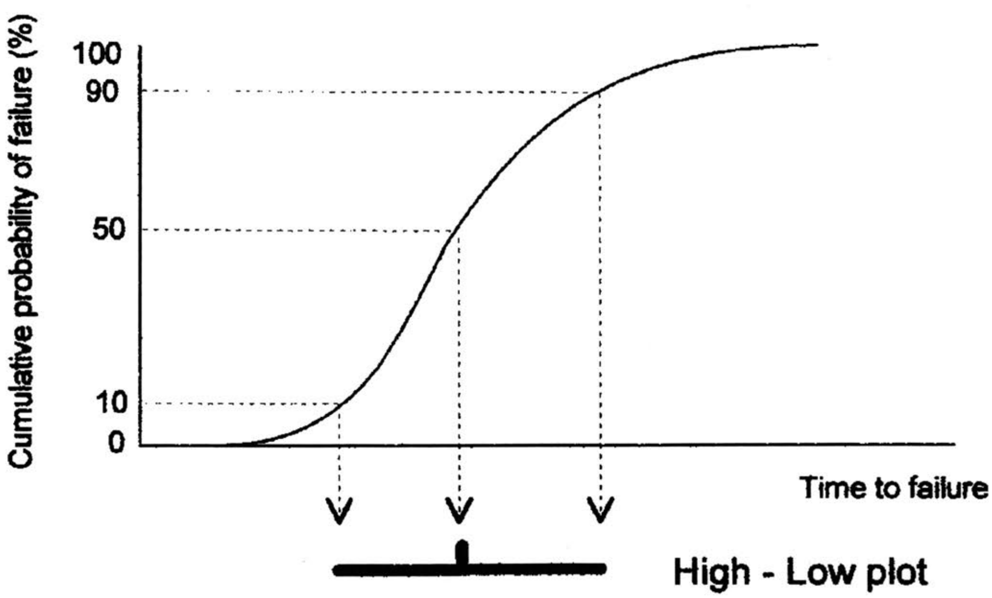


Figure V-1. High-Low probability chart for time to failure estimation [20]

Conclusions

This thesis demonstrates the possibility of creating a manufacturing asset management system, particularly through life-cycle tracking and assets' interdependencies, in a complex and fragmented manufacturing network. Given the low likelihood of having CMs in the network to change their current operating and information sharing processes, and the limited budget available to create a comprehensive and relevant solution, the results are very positive. The system allows to track the life-cycle of hundreds of assets in a matter of minutes, and only requires the user to input the assets' specifications the first time that the asset is recorded into the system.

1. Impact to the business

The impact to the business is reflected in three different core-value drivers, the main success indicators used by Danaher Corporation. The first one and more obvious is the on-time delivery. As the OEE of the assets starts to improve, the risk of running out of stocks is reduced. This is achieved through different means, from just having clear visibility of interdependencies of assets, materials and products, to a more efficient schedule of maintenance plans and spare parts stocking.

Current safety stock levels can also be reduced, without surrendering desired service levels, only by having a more stable OEE, since the manufacturing lead-time variability is the major contributor to the current safety stock levels.

Additional impact is delivered through improving the ROIC of the assets. The Synchron Cartridge example, shows that if the process OEE improves to the industry standard, the effect on NOPAT would drive a significant improvement of current ROIC. More importantly, this could be replicable to other assets, given the similitude of the Synchron Cartridge process to other injection molding processes.

2. The path to operational excellence

Tracking the right data is crucial for exceptional decision making. In the previous state, tracking the results of a change in an asset management procedure or policy was virtually impossible, since neither the current nor the future OEE value was measured. The current system lets the user visualize the OEE of the assets on a monthly basis, and therefore see the effectiveness of the decision previously taken.

Additionally, combining the information obtained from tracking the shot-count of the assets with condition-monitoring variables should increase the accuracy of the predictive model, which will also allow the user to simulate future states of the asset condition, without necessarily reaching that state.

3. Engaging internal and external users

Engaging internal users and the CMs is crucial to the success of this project. To achieve this, the system started from a basis that required very low additional effort from the internal users and almost no commitment from the CMs, but that advances them quickly to a better state. This basic level consists in providing an efficient way to track mileage, interdependencies, and a place to deposit historic information. More complex features like predictive analytics were included as add-ons that provide incremental value but are not required to initiate the system. This way, both the internal users and the CMs see the value generated even at this basic level, increasing their willingness to provide additional information in the longer term, or to collect and provide the data that is required for the predictive features.

Future Work

1. Economic evaluation of assets

It is recommended that Beckman Coulter includes an economic valuation to the assets, and to the maintenance actions that are performed on them. This information can be combined with the OEE indicators to evaluate the current economic value of an asset given a condition, and simulate the effect of difference decisions, such as repairing versus retrofitting versus disposal, to achieve a local optimum.

2. Use RFID information to solve for multiple streams issue

Even if the company is not willing to take the path towards converting their processes into Smart Factories, or to follow Industry 4.0 design principles, implementing RFID tags in the most critical assets is a valuable next step. These devices will primarily improve the accuracy of the shot-count tracking, especially for parts that have constant variations in the finished goods inventories, and for parts that are manufactured by multiple manufacturing streams at the same location.

Implementing RFIDs will also push the CM's operational environment towards an asset management-based culture that will be more receptive to the latest Industry 4.0 trends.

3. Use the data collected by the system deployed to create a predictive model based on real data

It is recommended that Beckman Coulter continues to use the Asset Management System delivered to the Value Engineering and Plastic Manufacturing teams. This is recommended not only for the immediate benefits derived from its current information status and capabilities, which are mostly limited to shot-count tracking, but also because its constant use will facilitate the collection of valuable maintenance and failure information. This will ultimately serve as the training and testing sets to create the predictive model for each asset.

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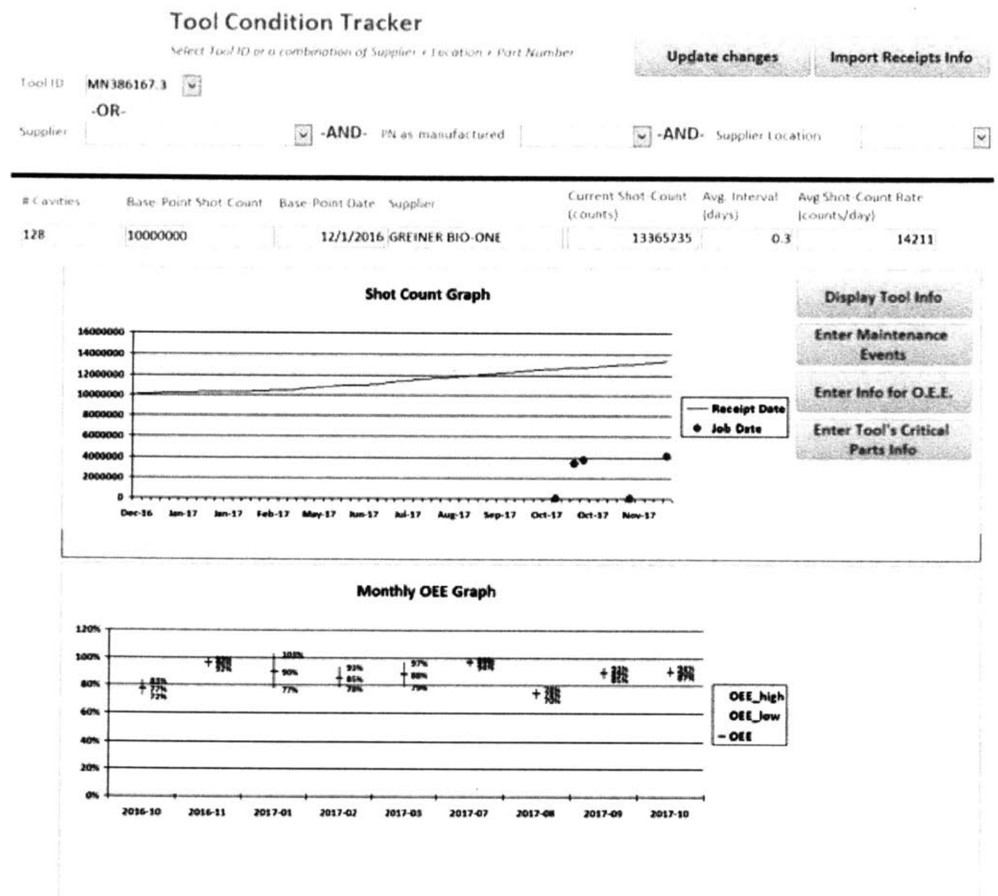
Appendices

Appendix I. Main page of tool condition tracker. User interface.



Appendix II. Maintenance event record

Maint Job

Maint Job ID	Job Description	MoldID	Plan or Real	Event Shot-Count	JobDate	Job Notes
1	PM	MN386167.3	Scheduled	1090000	05/16/2016	PM planned for 11000000 shots. Change seals and ga
2	PM	MN386167.3	Executed		06/08/2016	Changed water seal in hot water in-flow
3	PM	MN386167.3	Scheduled	1205000	01/01/2017	PM planned for 12050000 shots. Change seals and ga
4	PM	MN386167.3	Executed	1208000	01/26/2017	Changed water seal in hot water in-flow
5	PM	MN386167.3	Executed	1235000	03/15/2017	Joint
6	FLR	MN386167.3	Executed	1330000	03/30/2017	Broken Insert
7	REP	MN386167.3	Executed		07/15/2016	Welding
(New)		MN386167.3		0		

Appendix III. Example of downtime report from contract manufacturer

Downtime Log Report

Contract Manufacturer Plastics
[Region], CA

Mach	Down Code	Down	Start Date	End Date	Down Time	Up Time
113	Unknown	Unknown	10/5/15 14:19	10/5/15 14:20	0.02	
113	Unknown	Unknown	10/5/15 14:21	10/5/15 14:28	0.12	0.02
113	Unknown	Unknown	10/6/15 6:25	10/6/15 6:32	0.12	15.95
113	Unknown	Unknown	10/6/15 16:34	10/6/15 16:35	0.02	10.03
113	Unknown	Unknown	10/6/15 16:35	10/6/15 18:11	1.60	0.00
113	AuxEquipProb	Auxiliary Problem	10/6/15 18:11	10/7/15 9:43	15.53	0.00
113	WaitTech	WaitTech	10/7/15 9:43	10/7/15 9:49	0.10	0.00
113	IDLE	Idle	10/7/15 9:49	10/7/15 12:08	2.32	0.00
113	Unknown	Unknown	10/7/15 12:09	10/7/15 12:11	0.03	0.02
113	Unknown	Unknown	10/7/15 19:16	10/7/15 20:07	0.85	7.08
113	AuxEquipProb	Auxiliary Problem	10/7/15 20:07	10/8/15 8:30	12.38	0.00
113	WaitTech	WaitTech	10/8/15 8:30	10/8/15 11:15	2.75	0.00
113	Unknown	Unknown	10/8/15 11:15	10/8/15 11:16	0.02	0.00
113	Unknown	Unknown	10/8/15 11:17	10/8/15 11:18	0.02	0.02
113	Unknown	Unknown	10/8/15 11:21	10/8/15 11:29	0.13	0.05
113	Unknown	Unknown	10/8/15 11:30	10/8/15 11:30	0.00	0.02
113	Unknown	Unknown	10/8/15 11:31	10/8/15 11:32	0.02	0.02
113	Unknown	Unknown	10/8/15 14:17	10/8/15 18:00	3.72	2.75
113	Unknown	Unknown	10/8/15 18:01	10/8/15 18:05	0.07	0.02
113	Unknown	Unknown	10/9/15 10:49	10/9/15 17:33	6.73	16.73
113	Unknown	Unknown	10/9/15 17:34	10/9/15 17:38	0.07	0.02
113	Unknown	Unknown	10/9/15 17:40	10/9/15 17:42	0.03	0.03
113	Unknown	Unknown	10/10/15 22:12	10/10/15 22:13	0.02	28.50
113	IDLE	Idle	10/10/15 22:13	10/10/15 22:15	0.03	0.00
113	Unknown	Unknown	10/10/15 22:15	10/11/15 3:50	5.58	0.00
113	Unknown	Unknown	10/11/15 10:26	10/11/15 10:28	0.03	6.60
113	IDLE	Idle	10/11/15 10:28	10/12/15 12:46	26.30	0.00
113	Unknown	Unknown	10/12/15 12:47	10/12/15 12:48	0.02	0.02
113	Unknown	Unknown	10/12/15 12:48	10/12/15 12:56	0.13	0.00
113	Unknown	Unknown	10/12/15 12:56	10/12/15 12:57	0.02	0.00
113	Unknown	Unknown	10/12/15 12:59	10/12/15 13:01	0.03	0.03
113	Unknown	Unknown	10/12/15 22:36	10/12/15 22:36	0.00	9.58
113	AuxEquipProb	Auxiliary Problem	10/12/15 22:36	10/12/15 22:38	0.03	0.00
113	Unknown	Unknown	10/12/15 22:39	10/12/15 23:41	1.03	0.02
113	IDLE	Idle	10/12/15 23:41	10/13/15 6:13	6.53	0.00

Appendix IV. Example of production report from contract manufacturer

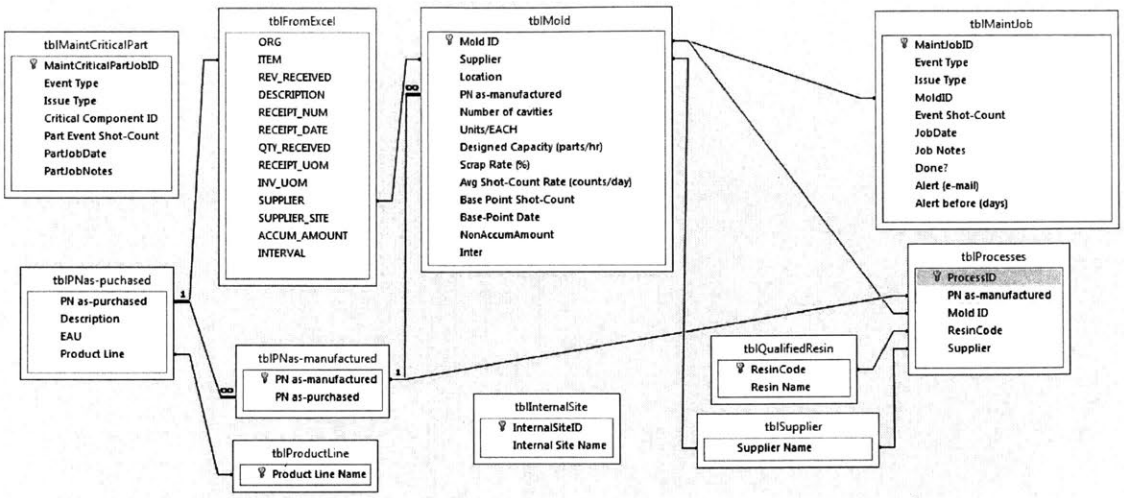
Daily Job Production Report

Contract Manufacturer Plastics
[Region], CA
Job Number: 9287738
All Machines

Department: ONE - Injection Molding

Mach	Date	SH	Job Number	Part	Run Time	Down Time	Percent Down	Good Prod	Packed Prod	Scrap Prod	Percent Scrap	Cycle Eff	Yield Eff
113	12/12/2016	3	924720	A79239	6.84	1.17	14.6	8,179	8,179	8	0.1	4,209	4,062
113	12/13/2016	1	924720	A79239	8	0	0	8,768	8,760	8	0.1	91	91
113	12/13/2016	2	924720	A79239	8.01	0	0	8,712	8,712	0	0	91	91
113	12/13/2016	3	924720	A79239	8	0	0	8,656	8,656	16	0.2	90	90
113	12/14/2016	1	924720	A79239	8	0	0	8,672	8,672	8	0.1	90	90
113	12/14/2016	2	924720	A79239	8.01	0	0	8,680	8,680	0	0	90	90
113	12/14/2016	3	924720	A79239	7.62	0.38	4.7	8,296	8,296	16	0.2	91	86
113	12/15/2016	1	924720	A79239	8	0	0	8,696	8,704	8	0.1	91	91
113	12/15/2016	2	924720	A79239	8	0	0	9,104	9,104	0	0	95	95
113	12/15/2016	3	924720	A79239	7.78	0.22	2.7	8,824	8,824	0	0	94	92
113	12/16/2016	1	924720	A79239	3.29	4.72	58.9	3,688	3,696	8	0.2	94	38
113	12/16/2016	2	924720	A79239	0	8.01	100	0	0	0	N/A	N/A	0
113	12/16/2016	3	924720	A79239	0	8.01	100	0	0	0	N/A	N/A	0
113	12/17/2016	1	924720	A79239	0	0	0	0	0	0	N/A	N/A	N/A
113	12/17/2016	2	924720	A79239	0	0	0	0	0	0	N/A	N/A	N/A
113	12/17/2016	3	924720	A79239	0	0	0	0	0	0	N/A	N/A	N/A
113	12/18/2016	1	924720	A79239	0	0	0	0	0	0	N/A	N/A	N/A
113	12/18/2016	2	924720	A79239	0	0	0	0	0	0	N/A	N/A	N/A
113	12/18/2016	3	924720	A79239	0	0	0	0	0	0	N/A	N/A	N/A
113	12/19/2016	1	924720	A79239	1.99	6.01	75.1	2,200	2,240	56	2.5	94	23
113	12/19/2016	2	924720	A79239	8	0	0	9,024	9,024	0	0	94	94
113	12/19/2016	3	924720	A79239	8	0	0	8,976	8,976	16	0.2	94	94
113	12/20/2016	1	924720	A79239	4.34	3.67	45.8	4,768	4,800	56	1.2	93	50
113	12/20/2016	2	924720	A79239	8	0	0	9,008	9,008	0	0	94	94
113	12/20/2016	3	924720	A79239	8	0	0	8,968	8,968	16	0.2	94	93
113	12/21/2016	1	924720	A79239	8.01	0	0	8,944	8,664	8	0.1	93	93

Appendix V. Dependencies from the Asset Management System



Appendix VI. Mold Maintenance Checklist

MOLD PREVENTIVE MAINTENANCE CHECKLIST

(To be performed on molds at the pre-determined number of cycles. Evaluation of the condition of mold should be made after inspection to determine if number of cycles between Preventive Maintenance intervals should be increased or decreased.)

Mold MP# ________

1. ☐ Open parting lines and inspect surface.
2. ☐ Disassemble mold and clean all components
3. ☐ Inspect condition of all components, including:

- ☐ Lifters / Floaters for signs of wear (inspect last shots for flash)
- ☐ Cavities and cores
- ☐ Leader pins and bushings
- ☐ Ejector pins and sleeves
- ☐ Core pins
- ☐ Slides
- ☐ Angle pins
- ☐ Any other moving parts

4. ☐ Install new o-rings, water test for leaks, completely drain and blow out all residual water.
5. ☐ Replace any worn components (ejector pins, standard core pins, angle pins, leader pins and bushings, springs)
6. ☐ Repair minor cavity, core and component wear issues (scratches, dings, polish etc.).
7. ☐ For molds with hot runners: Check "L" dimension for uniformity between the drops.
8. ☐ Ohm out all drops. MAINTENANCE SIGNATURE:____________________________
9. ☐ Zero out corresponding codes in MATTEC.

Comments: ____

____

Appendix VII. Work request form for mold maintenance or repair

WORK REQUEST FORM SUBMIT

[redacted]

TO: TOOL ROOM

DATE:	8-28-15
COMPLETION DATE:	9-1-15
CONTROL JOB#	35819

CUSTOMER:	[redacted]	REQUESTED BY:	EVAN G.
MP MOLD #	1064	PHONE:	EXT:364
CUSTOMER MOLD #	758701.4	PART NUMBER:	758701
DESCRIPTION	CATRIDGE,BOTTOM REGENT	# CAVITIES:	8
		AUTHORIZED BY:	[redacted]

CHARGE ☐

INTERNAL ☐

IS THERE MOLD DAMAGE/FAILURE: YES ☐ NO ☐

THE MOLD DAMAGE/FAILURE REPORT SECTION MUST BE COMPLETED WHENEVER THERE IS DAMAGE OR FAILURE.

WORK TO BE PERFORMED	WORK DONE BY:	HOURS
1) PM	STEVE	9.2
2)		
3)		
4)		
5)		
6)	TOTAL	9.2

DATE	P.O.#	VENDOR	WORK/PART REQUESTED	COST
	N		LABOR	$736.00
		A	OUTSIDE COST	$

WORK DESCRIPTION: OPEN PARTING LINES AND INSPECT SURFACE,DISASSEMBLE MOLD AND CLEAN ALL COMPONENTS,INSPECT CONDITION OF ALL COMPONENTS INCLUDING CAVITIES AND CORES,LEADER PINS AND BUSHINGS,CORE PINS,ANY OTHER MOVING PARTS,INSTALL NEW O-RINGS,FOR WATER LEAKS.