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# Development of Testing Metrics for a Decision Model for the Replacement of Medical Equipment at a Large County Health System

By

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This thesis is submitted as a partial fulfillment for the degree of Master of Science in Offshore technology, specialized in industrial asset management

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## Abstract

The medical revolution that has occurred in the last one-hundred years has truly been remarkable. With this amazing growth as well as the continued development come many aches and pains that are exhibited in any rapidly developing technology sector. A major concern is focused on the maintenance and replacement of these technologies. When is the right time to continue to hold onto existing technologies and products and when is it right to cut your losses and invest in new devices? This is a question that plagues hospitals and clinics worldwide. And it can be a costly question to answer.

This thesis seeks to formulate and test several metrics to indicate the proper points of replacement for a large fleet of medical equipment. There have been several publications attempting to quantify this risk, but most apply a complicated series of scoring criteria at a single timepoint and provide a recommendation to move forward. This thesis will pull in historical work order and cost data from the computerized maintenance monitoring system of Harris Health to test each designed metric and apply it to nearly 20 years of operations. The goal is to identify proper points of replacement and gauge performance of each metric. The metrics sought are simple and easily calculable with existing data from the CMMS.

The thesis will then make a recommendation of the metric that performed the best and review the past budgets of Harris Health to determine feasibility.

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## List of Abbreviations

AHA – American Health Association

BCG – Boston Consulting Group

Biomed – Biomedical Engineering Department

CMMS – Computerized Maintenance Management

CT – Computed Tomography

GAAP – Generally Accepted Accounting Practices

ICT – Information and Communication Technology

IT – Information Technology

MRI – Magnetic Resonance Imaging

NBV – Net Book Value

SWOT – Strengths, Weaknesses, Opportunities, & Threats

# 1. Introduction

## 1.1. Background

Harris Health represents the county health system in Harris County, Texas in the USA. It is the third largest county health system in the USA to only Los Angeles and New York counties. It manages an annual budget of $1.4 billion and operates nearly fifty distinct facilities (www.HarrisHealth.org, 2015). It provides care for anyone who walks through its doors, regardless of ability to pay. In fact, roughly 70% of all services performed are uncompensated (www.HarrisHealth.org, 2015).

It is able to continue to operate in this environment through property tax revenues in Harris County. This accounts for roughly $700 million of Harris Health's annual budget (www.HarrisHealth.org, 2015). This means that every property owner in Harris County, roughly 5 million people, has a vested interest in Harris Health, even if they don't receive health services in a Harris Health facility. Because of this, there is great concern for spending money wisely at Harris Health. Much time and effort is put in place to ensure that this is reflected throughout the organization.

The Medical Capital Group is born out of this necessity. The Medical Capital Group is a department at Harris Health that is responsible for the planning, purchase, installation, and start-up of new medical equipment for the organization. Every new equipment request or replacement is vetted through a rigorous process to ensure that the equipment is needed and that a cost-effective model is purchased that meets all of the requirements of the clinical staff. The Medical Capital Group works in conjunction with the Biomedical Engineering Department (Biomed) to accomplish these goals. Biomed is responsible for repairing broken equipment and performing periodic maintenance on specific items. Together, the Medical Capital Group and Biomed formulate a list of equipment annually comprising of equipment that is to be replaced in that fiscal year.

This is in addition to the new requests that must be reviewed for additions to the total portfolio. This creates a complicated budgeting scenario as the system juggles life critical devices, major devices such as MRIs and CTs, and on-going equipment failures throughout the year. Finding the appropriate budget figure can not only be daunting, it can also be risky. Too low of a budget results in unplanned costs or an inability to replace vital equipment in a timely manner. Too high of a budget could result in less concern for a good value and it removes dollars from other services where it may be more needed. This presents the problem.

## 1.2. Problem Formulation

Aging equipment is a constant challenge in all health systems. Determining which items to replace and which to continue to repair and maintain is an annual conversation that often leaves more questions than answers while the backlog tends to grow each year. There is a real struggle to not only make this determination but to implement an on-going replacement cycle to make replacement costs as predictable and repeatable as possible. At Harris Health, existing equipment data including purchase date, age, expected lifetime, maintenance costs, repair costs, and replacement costs, etc. are kept in a detailed database. While there is a wealth of information available, very little of this information is used to determine how much money should be spent replacing equipment. Currently, the primary means of formulating a budget for the next year is to use depreciation values of existing equipment. This poses several challenges that will be reviewed later. But given that more than seventeen years of data has been collected, there is an opportunity to use the data to create a long-term strategy that serves both the financial and operational needs of the organization.

What is a suitable metric for measuring the necessity of replacing medical equipment? While preventative maintenance and repairing equipment on failure can extend the lifetime of a particular device, this comes at a cost. And worst of all, repair costs are often unpredictable and can topple budgets to the detriment of all. This evaluation hopes to identify a suitable metric that leads to more predictable budgets and a stable average age of equipment. For this analysis, the terms maintenance and work orders will refer to both preventative and corrective maintenance.

## 1.3. Main Objectives & Sub Objectives

### 1.3.1. Main Objective

This project seeks to define and test six metrics to indicate the proper time to replace each piece of medical equipment. The metrics, calculated from the current asset data, will be analyzed to identify which is best able to demonstrate a reasonable balance between replacement and maintenance costs while optimizing the useful life of equipment.

### 1.3.2. Sub Objectives

This analysis will be carried out and supported based on five sub-objectives. First, some gaps in the database must be reconciled. This involves populating blank fields with the appropriate values. Fields to be reviewed include purchase year, purchase cost, and replacement cost among others. Ensuring this data is accurate and imported properly is a crucial step to the accurate completion of this analysis.

Next, the formulation of the metrics to test has to be determined. This was done with the guidance of the program director of the Medical Capital group. It defined what will be analyzed and what will be deemed as peripheral information. It focused on the equipment life and operability given different replacement and maintenance considerations.

Third, a strategic planning effort will be completed to evaluate the effect of different replacement metrics. This will include a detailed analysis of the impact each metric will cause on the system at large including staffing and financial concerns along with the changes to existing processes that must occur.

The fourth phase will involve the prototyping and testing of the proposed parameters. These parameters will be tested using real data from the biomed database to evaluate their effectiveness of keeping replacement and work order costs affordable while balancing an average fleet age that indicates a strong performing system of equipment.

Finally, a metric will be chosen to propose a strategic effort to effectively utilize these results. The end goal is to establish a long-term vision for a successful equipment replacement program. This program should exhibit characteristics that help produce predictable and sustainable annual budgets while maintaining an acceptable average equipment age.

## 1.4. Research Method

Harris Health is well suited to be able to conduct this sort of analysis. It has been collecting data on medical equipment repair and maintenance costs for well over twenty years. It also stores accurate purchase costs as well as replacement costs of all currently active assets. It has invested heavily in systems to collect and store this information. In addition, data collection is a job function at many points of the institution. If there were an ideal scenario for data collection and processing, this would be it. This is also a challenge. While Harris Health has collected massive amounts of data, not all of it is quality data. This can produce a hindrance to data processing methods when dealing with an amount of data on this scale.

## 1.5. Scope & Limitations

For this analysis, the main focus will be on system assets as well as the work orders that have been completed to keep these devices functioning. These assets include medical equipment only and items range from large complicated systems to fairly minor and small equipment. Examples of large items include MRI machines and operating room lights and booms. Small items could be bedside patient monitors or simple hand-held laboratory analyzers. This study specifically does not include equipment that would fall under building systems such as air handlers, chilled water distribution units, and electrical service equipment. These types of equipment are managed and maintained by the facilities department at Harris Health and truly exhibit their own dynamics and processes in terms of maintenance and replacement.

Specific details pertaining to the nature of repairs that have been conducted over the years will not be presented within this study due to the sensitivity of the information. Where specific items are presented, such as section ‘4.6 Analysis Process’, the identifying characteristics of the item have been replaced with a sample asset identification number.

The assets included in this study total over 50,000 individual units and more than 500,000 work orders have been executed in the timeframe of interest; 2000-2017. Processing this amount of data has produced a range of challenges. First, reaching back to the year 2000 approaches the timeframe of the implementation of the current system. Some data points may have been less than complete from that time. Many fields in the database are blank. For sake of simplicity, any records where fields of interest, such as purchase year or manufacturer and model, are blank have been omitted. Also, any work orders that show a cost of $0 due to an error or an actual $0 work order was omitted. No parameters tested rely solely on the number of work orders so these provide no value to the task at hand. Finally, the focus has been placed on current assets. These assets contain the most accurate and up to date information. This still provides data back to the year 2000 as many devices in the system are approaching 18 years of age. With these assumptions in place, our sample data is reduced to 25,000 devices and roughly 170,000 work order line items.

# 2. Literature Review

The general literature would indicate that health care maintenance models are unique to each hospital and cannot be applied broadly. This section will begin with a general introduction to medical equipment in hospitals. It is followed by a review of models that are available in the academic field of reliability analysis. These are usually component specific and are useful when looking at one piece of equipment. The final portion of the review is of other hospitals attempts at formulating a repair/replacement model. There is yet to be a simple replacement model that is applied successfully in a large fleet of equipment though the ideas at the individual level are useful to inform analysis for this paper.

## 2.1 Medical Equipment in Hospitals

As defined by the Harris Health System, medical equipment refers to any equipment purchased by the medical capital group, maintained by biomedical engineering department, and used by physicians, nurses, and technicians to aid in patient care. Medical equipment is regulated, follows an identification system, and requires specialize technicians to maintain and repair. This equipment is different from typical building system capital assets, IT systems, or supplies. The following section seeks to provide an overview of what makes medical equipment unique.

### 2.1.1 Types of Equipment

Medical equipment covers a broad range of equipment types. An item can be as simple as a gas meter measuring the oxygen content delivered to a patient or as complicated as an entire hybrid surgical suite that is fully integrated to dynamically position the operating table, lights, booms, and imaging equipment. The range of complexity between these devices is vast and these two equipment types illustrate the span from one extreme to the other. However, there are countless other devices that fall in the middle. In fact, ECRI Institute, a popular third-party benchmarking and major research company for medical equipment identifies over 10,000 unique medical equipment categories (ECRI Institute, 2017). And it is estimated that there are over 20,000 different vendors selling items that would categorize as medical equipment in the United States (ECRI Institute, 2017).

There are many types of equipment in a hospital that do not qualify as medical equipment. Building systems such as air handlers or water chillers are one example. These would typically fall under facilities engineering. In addition, there are many information technology systems that support hospital operations. These include computers, servers, and general software, etc. While some medical equipment does run specialized software within these frameworks, this infrastructure does not classify as medical equipment. Finally, many medical equipment devices also utilize supplies or consumable items in order to operate. The device itself is medical equipment but the supply or consumable would be distinctly tracked apart from the device.

### 2.1.2 Specialized Team to Maintain

A unique characteristic of medical equipment pertains to the team of technicians that maintain and repair the equipment. These technicians are typically trained through formal education systems prior to finding employment within hospitals. They then often receive technology specific training through medical equipment vendors on how to work with equipment present at the hospital where they are employed. They must understand the inner workings of a hospital system as well as the impact the equipment has on patient care.

### 2.1.3 Governing Authorities

In order to qualify for certain funding as well as achieve a proper level of accreditation, several governing authorities have emerged in the healthcare industry to provide a framework of rules and guidelines to increase safety and patient outcomes in the hospital. There are two common organizations that deliver these sort of guidelines; DNV and The Joint commission. Each of these institutions have their unique rules and guidelines. In the United States, in order to qualify for reimbursement for Medicare and Medicaid Services, this accreditation service is a priority (Review of Medicare's Program Oversight of Accrediting Organizations and the Clinical Laboratory Improvement Amendments of 1988 Validation Program, 2016). The rigorous rules touch many parts of a hospital and medical equipment is no exception. For instance, special attention is put on medical equipment and specifically the strategies employed to set preventative maintenance frequencies (HCPro, 2011). It also has a heavy impact on the type of record keeping that is instituted for asset tracking and work order data. This has a direct impact on how these processes are setup.

### 2.1.4 Identification

Medical equipment in the hospital is tagged in an effort to identify equipment as well as ensure preventative maintenance is properly performed. The tags vary from institution to institution and generally contain the asset number assigned to that device as well as the last date in which maintenance was performed. They are also typically color coded so a clinician can quickly ascertain whether to call the biomed department or facilities engineering when a repair is required. These asset tags must be thoughtfully designed with consideration of not only placement but also the environment the tag will be exposed to. A large institution does not want to face changing tags. A sizable effort would be required to change tags for a system the size Harris Health which could easily equate to over 25,000 tags.

### 2.1.5 Service Models

In most cases, an institution can choose to purchase service packages from individual manufacturers or they can opt to perform maintenance and repairs in-house. Each of these options pose varying challenges. Maintaining service contracts come at a cost but are typically governed by a contract to hold the manufacturer accountable to repair times, loaner units, and repair costs. The downside is scalability. If you need to focus resources in a short period of time, there may be a limitation since those resources are out of the control of the institution. The opposite choice is to service and maintain the equipment through in-house technicians. This effort requires hiring qualified personnel, continuing training, maintaining parts inventory, and providing all of the necessary tools and workspaces to complete the appropriate tasks (Strauss, 2006). These tasks require quite the undertaking but some types of medical equipment, such as large radiology systems, have been shown to save up to 30% by handling maintenance in-house (Rossi, 1989). Harris Health, as well as many large institutions, chooses to operate a hybrid version of this models. Service contracts are typically acquired for large and expensive systems that require highly specialized personnel. The biomed technicians tend to maintain and service items that are part of a large fleet. For instance, it makes sense to have a dedicated technician on patient monitors as the system carries a fleet of greater than 500 similar units. The investment required for keeping replacement parts in an in-house inventory is much more justifiable when you have many devices to maintain. The mix of service packages employed varies widely from facility to facility depending on capabilities, resources, and space.

## 2.2 Replacement Models

The portion of reliability analysis that deals with repair/replacement modeling attempts to evaluate when the proper replacement time is and when it is sufficient to continue repairing. It seeks to calculate the optimal maintenance interval (Arild, 2016). Several common replacement strategies emerge.

- Age Replacement Model
- Block Replacement Model
- Minimal Repair Block Replacement Model
- Group Replacement
- Condition-Based Replacement

### 2.2.1 Age Replacement Model

The age replacement model is one of the simplest models to be employed. The piece of equipment is either replaced at failure or when it attains a particular age, whichever comes first (Arild, 2016). Under this model, it has been established that the expected time between replacements can be represented by the following formula:

$$E(\min(T,u)) = \int_0^u tf(t)dt + \int_u^\infty uf(t)dt = \int_o^u tf(t)dt + u\big(1 - F(u)\big) = \int_0^u R(t)dt$$

(Arild, 2016)

Where: E(min(T,u)) = expected time between replacement
u = age of replacement
T = lifetime of component
t = current time
f(t) = failure function
F(u) = probability distribution
R(t) = survivor function

As such, when the cost of corrective replacement (at failure) and the cost of preventative replacement (at specified age) are known, the expected cost per replacement is easily attainable (Arild, 2016). Further, these equations can be combined to find the expected replacement costs per unit time and finding the age that minimizes this value provides the optimal maintenance interval for this method (Jiang, 2015).

As stated, this is a fairly simple model that produces a clear result in the optimal maintenance interval. One downside is the information that must be known at the beginning to employ it. Failure distribution data must be collected and applied to find meaningful results. In the setting of maintaining a large fleet of medical equipment, this poses practicality issues. This calculation would need to be completed for each device type. Dealing with many manufacturers to establish the baselines and apply failure probability distributions would be a very difficult task.

### 2.2.2 Block Replacement Model

In the block replacement model, the item or component is replaced at both failure and at fixed times; u, 2u, 3u,…etc. (Arild, 2016). These fixed timeframes are established ahead of time and remain in place regardless of when actual failures occur, as illustrated below (Jiang, 2015). This means that if a failure occurs just before reaching the fixed time frame, the unit will be replaced both at the failure and immediately again at the time interval.

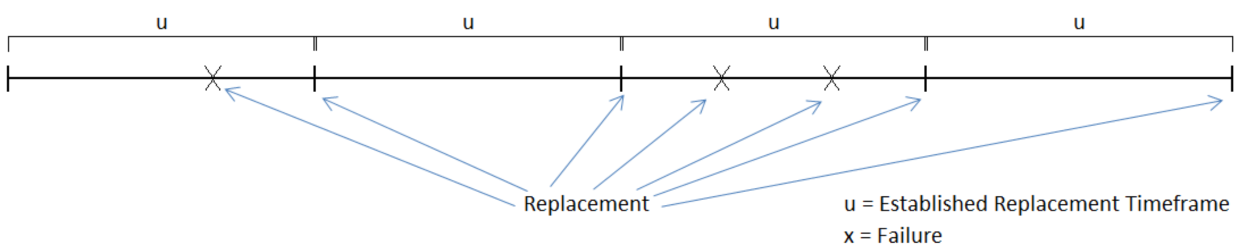


*Figure 1 - Block Replacement Model*

The same calculations are possible with this method; expected time between replacements, expected cost per replacement, and the expected cost per unit time (Arild, 2016). Of course, the goal is to find the time frame, u, that minimizes the cost per unit time. Again, to apply this to the repair/replacement scenario at Harris Health, there are some probability distributions that must be applied to wide range of equipment. There would also be institutional pushback which may see this model as wasteful in the fact that equipment can be replaced multiple times when it is not necessary, as described above. In addition, the block replacement model may be challenging to implement in an environment where devices are in constant use (Dekker and Smeitink, 1991). When the timeframe, u, is reached, there is no guarantee that the unit would be able to be made available for replacement immediately. This would drastically impact the ability to test this model and apply the results effectively. Alternatively, there has been much research into opportunity based block replacement. In this sort of model, items can only be replaced preventively when maintenance opportunities arise (Dekker and Smeitink, 1991). This further complicates the simple block replacement model and due to the same inherent issues mentioned above, it too fails to meet the requirements sought after in this replacement model.

### 2.2.3 Minimal Repair Block Replacement

The minimal repair block replacement model is a variation of the block replacement model. However, when using this method, the equipment would not be replaced on failure, it would simply be minimally repaired to allow it to reach the next replacement interval, u (Jiang, 2015). Applying the probability distributions does not become any easier but it does eliminate some of the perception of wasteful spending. When using this method, the occurrence of failures between the replacements can be described by a non-homogeneous Poisson process. (Arild, 2016)

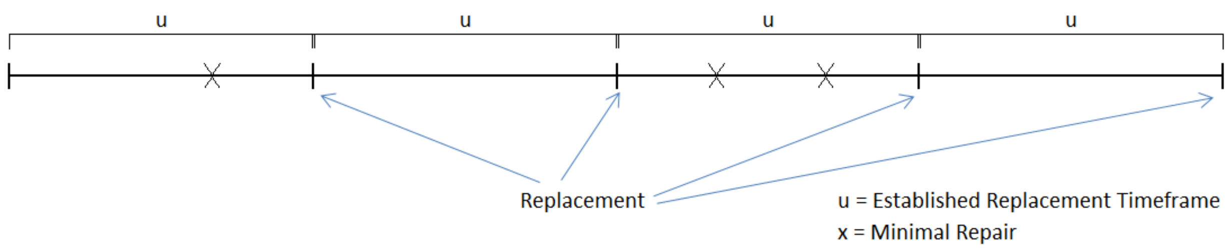


*Figure 2 - Minimal Repair Block Replacement Model*

### 2.2.4 Group Replacement

Group replacement represents a model where the main idea is to leverage economies of scale to secure better pricing for products (Manzini et al., 2009). For this system to be effective, there should be a large costs savings on a per item basis when the entire group is replaced. The goal of the mathematical analysis would be to determine the optimal time, t, which produces the most cost-effective time to replace the entire fleet. If a single unit fails prior to time t, it is replaced individually at the increased price (Manzini et al., 2009). Regardless of how new the unit is, under this model it will be replaced again with the group (Manzini et al., 2009). This sort of replacement model is popular for units that fail completely (Popova and Popova, 2017) such as light bulbs, valves, and electronic parts. The are some categories of medical equipment in a hospital may benefit from this, such as gas flowmeters or suction regulators but the vast majority would not. These types of assets are relatively inexpensive and only make up a small portion of the total portfolio. Simply put, most equipment can be repaired at failure and not necessarily require immediate replacement.

### 2.2.5 Condition Based Replacement

In a condition based model, a collection of variables are used to measure a system's state and arrive at a replacement decision based on these variables (Popova and Popova, 2017). These variables can be of a technical or financial nature. Condition monitoring from a technical standpoint can be quite costly and complicated due not only to the testing equipment but the also the expertise required to formulate baselines and analyze the results (Lifetime Reliability Solutions, n.d.). On the contrary, condition monitoring from a financial standpoint it is quite feasible and simple to implement when used in conjunction with a computerized maintenance management system. This method shows promise for a large healthcare setting. When you consider that there are roughly 4,800 device types at Harris Health, it is unlikely to find a technician that can understand the mechanics of every one of them to effectively predict failures. Each device would be different and respond differently to varying stimuli. However, financial indicators are more universal. Tracking equipment repair and maintenance costs is a fairly standard process in the healthcare setting. Identifying trends and basing a replacement cycle tied to maintenance costs could provide a standardized set of parameters to institute an effective program.

### 2.2.6 Review of Replacement Models

When attempting to apply these models to the current situation at Harris Health, these is no one size fits all solution. The population of equipment is simply too complex. Repair and replacement abilities vary greatly between equipment types and the number of equipment types is simply too great to choose any one solution. In fact, in 1992, Larry Fennigkoh contended that "although capital equipment planning and replacement models are well established, they have yet to find widespread use in healthcare" (Fennigkoh, 1992, p.43). This is largely still true to this day. There are no general norms in the healthcare industry. And it would prove exceptionally difficult to establish these norms. Every healthcare facility is vastly different in their abilities to maintain and replace equipment. In addition, the tools they have to monitor information range from highly sophisticated online systems to simple datasheets. Finally, purchasing practices, priorities of the facilities, and complex political environmental simply add to the confusion. While the data presented here hopes to establish a defined and successful program for equipment replacement, it should be stated upfront that this system is designed for use at the Harris Health System. As Fennigkoh (1992, p.43) contends, "a model that is usable in one hospital may not be usable in another". However, the hope is that the information and capabilities are scalable to other institutions who can use this analysis and provide some value to their capital maintenance/replacement programs.

## 2.3 Industry Based Repair Replace Models

Several studies have been completed over the years that have established replacement models. They are thorough in their analysis yet their implementation or even testing may prove difficult to establish. This is because they include some scoring categories that are either difficult to collect, expose the political environment of a healthcare setting, or are simply unfeasible to update and track for a fleet of 25,000 devices. For example, Fennigkoh established a total of 7 criteria in his 1992 analysis which are listed below:

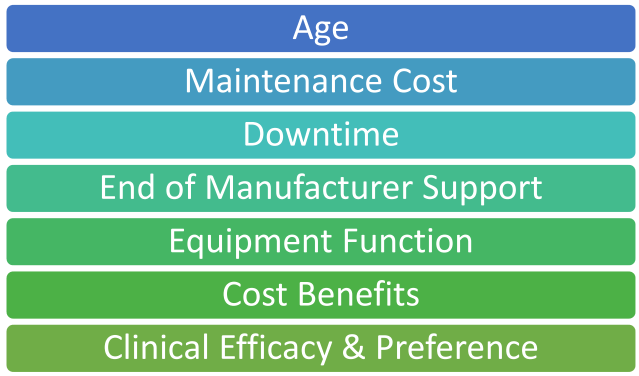


*Figure 3 - Replacement Strategy Characteristics (Fennigkoh, 1992)*

Some of these are straightforward and will be used in the analysis of this report such as age and maintenance cost. Others may prove difficult to collect. For instance, upon examining downtime for use at Harris Health, this type of characteristic is hard to pin on either an operating or failed state as Fenningkoh suggests (Fennigkoh, 1992). Equipment may lose some functionality but still be able to be operated. Does this qualify as downtime? In addition, downtime is composed of several components that do not necessarily indicate the value of the equipment. For instance, a repair may be very minor and only require 30 minutes of labor but waiting for the parts to be shipped could take two weeks if not longer if items are on backorder. Yet, the device may be down for this entire time. Institutions must circumvent this in order to effectively implement this. And further, their systems must be able to differentiate between these types of downtime categories to provide an effective analysis. Fennigkoh's (1992) solution looked at the number of unscheduled service calls and compared this total to the mean number of calls for all devices in this category.

In general, subjective fields should be avoided to protect the system from outside influences and personal opinions. Fennigkoh (1992) attempted to accomplish this by utilizing a "yes-no" (0,1) scoring system to provide decision makers an alternative to conventional deterministic techniques. This came at the suggestion of Chan Park and Gunter Sharp-Bette (1990). Other techniques have addressed the problem a little more head on by assigning intensity values indicating the importance with respect to the criterion (Taghipour, Banjevic and Jardine 2010).

Harris Health seeks to simplify this task in the overall analysis by focusing on hard cost data produced and stored by the computerized maintenance management system (CMMS) which biomed maintains. This practice removes subjective scoring fields from the entire process. It is acknowledged that certain subjective fields may add value but due to the current scope and scale of this analysis, cost data related to work orders and replacements will take priority as the primary characteristic of interest.

Another fault exposed by the parameters utilized is ‘Clinical Efficacy & Preference’. As admitted by Fenningkoh (1992), this is the most subjective parameter but this almost makes it not usable. As mentioned above, healthcare settings are highly political. There is only so much money to go around and who you are and who supports you is a highly competitive and political environment when it comes to equipment replacement. There is not anything stopping a clinician from adjusting the clinical efficacy of a particular device to portray a piece of equipment in a different light and either indicate replacement or retention. It could be argued that when the efficacy of a device is established it cannot be changed but this is unrealistic as well because new and improved devices on the market skew the perception of what ‘Clinical Efficacy & Preference’ mean. When a new and shiny device hits the market, suddenly the everyday product we currently employ begins looking worse and worse even though the functionality has not changed at all.

Finally, updating and tracking these fields for a fleet of 25,000 devices poses its own challenges. If these categories are not part of an existing process or job function, a significant expense would have to be realized in order to begin testing if this parameter truly adds value overall. For this reason, Harris Health hopes to seek parameter based on existing data that is collected by existing job functions and processes utilized by the system today.

The majority of available publications on equipment replacement models for medical equipment focus on a small subset of a couple hundred devices to serve as a test case. Each device is labelled based on the composite scores of the parameters they seek to monitor. The study either recommends to replace, monitor closely, or review in the future. None of the studies apply the system they have established to an entire fleet. In addition, none of the studies tie in financial data to test the efficacy of the parameters.

With that said, the previous studies are valuable in formulating a repair/replacement decision model but the analysis of this project seeks to not only develop a model, but to test the model on historical data and define steps for implementation that will persist into the future. How can these tools be used to identify an appropriate level of spend to get the system on track to produce a sustainable medical equipment budget? That is the intent of this paper. To not only identify a feasible calculated parameter to help identify when equipment should be replaced, but also detail an implementation strategy to set the system up for sustainable and predictable budget levels.

Another point to consider is the amount of time and investment that goes into implementing this process. A health system cannot simply decide that they plan to implement this and expect results immediately. Harris Health is very fortunate to have years of data pertaining to maintenance costs of devices and accurate estimated replacement costs. By leveraging this data, and back testing several parameters over an 18-year timeframe, the hope is to identify the most useful parameter. This knowledge can then be utilized by any institution but they will still need to begin collecting their own maintenance cost data to effectively extract useful information.

## 2.4 Technology and Information Systems in the Healthcare Setting

Technology has changed the way organizations have operated. Innovations continue at a blistering rate and organizations must accept these innovations or be left behind. When discussing computerized databases of information, many organizations and industries have made that leap and keep most, if not all information in some digital form. But the healthcare industry has provided an interesting environment for this implementation to occur. The electronic patient record is now widely available through a series of companies. The major challenges that still arise are due to patient privacy and interconnecting software systems between cooperating institutions. There are more than 1,000 different platforms available for this service and very few communicate with each other (Patel, 2017). Now a computerized maintenance management system employed by the biomed department typically does not house the type of patient critical data that comes under the scrutiny as an electronic medical record but the environment and industry within which it operates generates some unique challenges that may not apply to more traditional engineering settings.

A computerized maintenance management system (CMMS) serves as the central repository for maintenance information for an engineering department (Elatewiki.org, 2017). CMMS systems came into large use during the 1980s and early 1990s and this generated a drastic shift in the maintenance world as large complex systems suddenly had a digital format to store and retrieve maintenance records (MicroMain, 2017). For a large healthcare institution, such as Harris Health, being able to closely monitor equipment, schedule preventative maintenance, and store and recall key information provides clear evidence of the drastic improvements to the efficiency of the biomed department. As the systems evolved and improved, more functionality was added. The system that Harris Health utilizes can even streamline the entire service process. It has the capability to have a clinician submit a request for a repair and this request automatically generates a work order in the CMMS. The work order can then be reviewed and routed to the appropriate technician and work can commence. The man hours required to complete a work order along with all associated costs of parts and labor are tracked in detail and stored in the record. This enables a very thorough analysis to be able to pinpoint total cost of ownership of each device in real time. This detail is vital to the following analysis.

## 2.5 Challenges of CMMS Systems in Healthcare

While the CMMS system itself does not directly store patient information or communicate with partner institutions, it shares some of the same challenges as the electronic health record. First, the system will live on the same network as the electronic health record. As the technology advances enabling these great benefits to productivity and efficiency, the capabilities of hackers and criminals become more advanced to access desirable and valuable information. The potential for back-door access into patient records is never overlooked and a long vetting process with any software vendor is required. This analysis spends a great deal of time reviewing what systems this software touches, where data is stored, and the type of access the vendor is provided when period maintenance on the system requires a remote login.

A second challenge is the shear amount of information. Each record of equipment can easily store 100's of specific data points related to that item. The system becomes even more complicated when items are tied through component relationships and interconnectivities. Thoughtful consideration must be given to how the data is stored, displayed, and recalled to truly optimize the productivity and workflow of all parties that interact with the system.

A final challenge that builds on the previous is simply the massive amounts of data involved. Any system that sits on an ICT network must provide considerations to how it manages its data. While the cost of data has declined in recent years for a variety of reasons (LaChapelle, 2017) that does not mean that a high level of organization should be applied to data storage. System performance and response times can be drastically increased if the proper due diligence is not performed. In addition, storage lifetimes must be considered. Will the organization keep information indefinitely or archive data after a set number of years? All of these questions should be addressed at the up-front implementation of a CMMS in a healthcare setting.

# 3. Harris Health in Practice

As a large county institution that operates on public funding, Harris Health takes great care to ensure that it spends the tax dollars allocated to it wisely. To accomplish this, it seeks to invest in systems that provide a great deal to value, such as the CMMS described below. In addition, through the Medical Capital Group and Biomed Department, it staffs several teams of individuals to repair equipment and ensure equipment purchases are thoroughly vetted in the marketplace. Harris Health also remains open to process improvements to increase the efficiencies of their operations such as this project. The following section delves further into the employed by Harris Health and how it currently prioritizes equipment for replacement.

## 3.1 Current Replacement Model / System

The replacement of equipment is currently monitored based on a series of indicators. But before any replacement is even considered, the amount of funds allocated to both replacements and the purchase of new equipment must be established.

Before detailing this process, a moment will be spent reviewing how Harris Health calculates Net Book Value (NBV). NBV represents the value that a piece of equipment adds to an organization's financial valuation. In the United States, organizations track this figure on every asset they own for tax purposes. Equipment loses value over time. Pinpointing an accurate figure on this value can be a complicated process as many variables factor into the value of an asset. But keeping an accurate figure on the books is important because when an asset loses value, it can be reflected as a financial loss. Because of the tax system in the United States, an organization never wants miss an opportunity to apply a loss. However, the complicated process of existing equipment valuation would make this task nearly impossible. To accommodate this complicated situation, Generally Accepted Accounting Practices (GAAP) allows that capital assets can be depreciated over their estimated lifetimes. This is demonstrated by the yellow straight-line depreciation depicted below. As can be seen in the figure, there are several other means for depreciating capital assets. Harris Health has chosen the straight-line depreciation model to accommodate the large and diverse inventory of equipment it maintains.

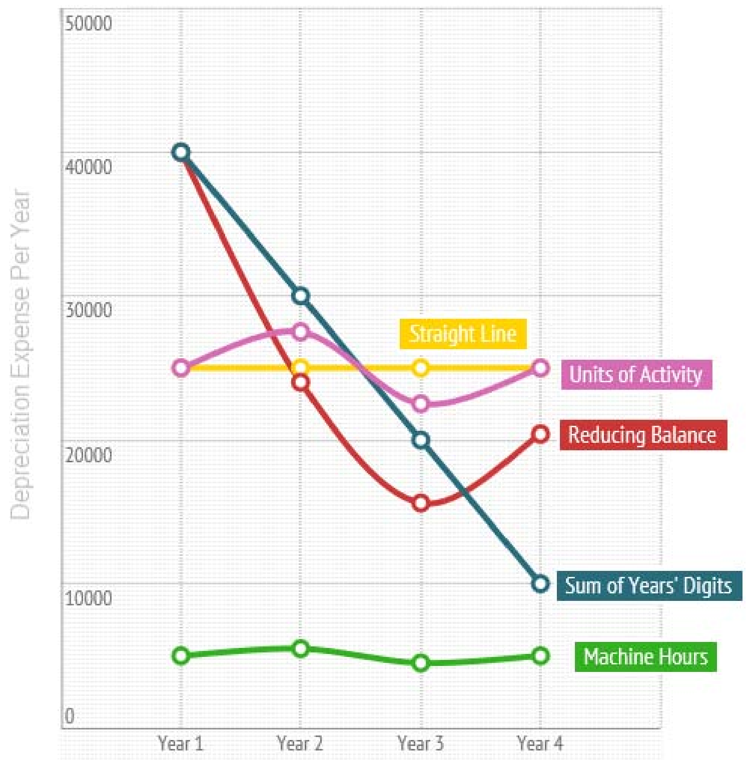


*Figure 4 - Depreciation Methods (Accounting Simplified, 2017)*

So why is this value important to Harris Health? Harris Health currently attempts to maintain a stable Net Book Value across all medical capital equipment assets on a year to year basis. Therefore, if it is able to write off a loss on existing capital assets, it seeks to maintain a stable NBV by purchasing an equivalent dollar value for that year.

From an accounting perspective, it is a simple way to define the budget and maintain a stable valuation of the existing assets. However, this process does pose some significant challenges. First, if an asset has depreciated to zero and the depreciation value has not been spent effectively, the asset cannot be depreciated any further. To replace this asset would mean taking money that should be technically spent on another asset. Second, this budget is also used for the purchase of new assets. This refers to a completely new item for the system and not a replacement. If the intent is to fund replacement projects with depreciated dollars, new equipment purchases take money directly out of this pool. Finally, this method makes no consideration for medical inflation. Medical inflation consistently outpaces general inflation (Patton, 2015). In 2015, the medical inflation rate of 8.75% was 5.5 percentage points higher than general inflation (Aon, 2016). Because of these significant challenges, determining the budget in this manner runs the risk of creating a deeper and deeper hole of aging and problematic equipment that is not being replaced in a timely manner and the funding to do so is being allocated elsewhere.

The previous process provides the budget but the current replacement process is even more complicated when investigating how replacements are initiated. There are four groups that can identify when equipment is to be replaced; the biomedical engineering department, the medical capital group, the clinical users, or executive leadership.

Biomed is responsible for maintaining the system's maintenance database of all medical equipment assets. They have access to equipment age, purchase data, and work order costs over the lifetime of equipment. They are also responsible for handling work orders by repairing equipment or arranging for a vendor repair. The main mode of replacement initiation that comes through biomed is based on the ability to repair. This comes in two forms. First, a piece of equipment may be unable to be repaired. This can be due to a malfunction that deems the equipment dead or if a repair is simply too expensive to be the economical decision. There is currently no set formula to define this level. The decision is largely subjective and not based on real data calculations. The second way biomed can initiate a repair is based on support. When vendors release new product lines and end sales or production of older models, eventually these vendors will cease either producing or even maintaining a stock of replacement parts. Should a piece of equipment fail that is defined by this scenario, the biomed department would find themselves unable to complete the repair as required. If this is a life critical asset, a real problem could develop as the system waits for a new asset to be purchased. The main focus of replacement initiated by biomed is based on the ability to repair.

The next group that has the ability to initiate a replacement is the medical capital group. The Medical Capital Group is responsible for completing purchasing projects for both equipment replacements and new equipment acquisitions. They monitor the lifetime of assets from initial purchase and generate a list annually of which assets have reached the end of their expected life. They meet periodically with clinical staff to gauge the urgency required in replacing assets that fall under that department's responsibility. From here, they are able to produce a prioritized list of replacement projects. Another point of oversight that is carried out by the medical capital group is the management of strategic projects. It may be economically advantageous to replace all of the items in a particular category even though 20% may not qualify for replacement individually. The benefit of replacing early could be from economies of scale to safety concerns of mixing devices. These strategic projects are the second manner in which the medical capital group can directly initiate the replacement process of a unit.

The clinical users also have a say in the process of replacing equipment. In addition to meeting with the medical capital group regularly to review their needs, they also have the ability to initiate a review of the particular item. Sometimes the needs and requirements of a department change over time. It is possible that new research has led to a change in a process that requires a change in equipment or change in functionality. New employees or doctors can also influence the equipment that a department requires. Also, if equipment has simply increased in age and it was not adequately tracked via other existing mechanisms, the users have a say. Finally, newer equipment with more advanced features may simply be available now and that may not have been the case when the equipment was originally purchased. All of these scenarios can factor into when equipment is put into the replacement process. It should be noted that there are controls on users simply requesting brand new equipment year after year. If an asset has not fully depreciated prior to a replacement request being submitted, the department is responsible for paying down the remaining NBV from their operational cost center. Not only does this produce equality on the accounting balance sheet, it can be a deterrent for a department to continually request items to be replaced year after year without any real justification.

A final group that occasionally drives equipment replacement is executive leadership. This is handled by the execution of system wide endeavors. It may be that executive leadership puts an extra focus on catching a particular disease early and doing so may require an equipment upgrade. Or maybe new research has proven a particular process to reduce patient falls and leadership wants to make this a priority. If existing equipment does not allow this, equipment may be replaced system-wide. It is not common for this to happen but the mechanism is allowed under the current circumstances.

Now, while all four groups have a voice in the process, they all must work together to prioritize which projects are put forth. Once they are able to compile a prioritized list that fits within the budget that has been approved, the entire plan is presented to the medical capital committee on a quarterly basis. The medical capital committee reviews the lists and has final approval power on the compiled plan.

The current system and process is very robust and does well to replace older assets but in general it is reactive and not necessarily proactive to equipment failures. It is mostly based on equipment failing or growing older and simply responds to these characteristics. This can catch a lot of problematic items but it can also put a strain on existing systems when equipment is life critical and goes down suddenly without prior notice. As a government entity, the county attempts to be as transparent as possible in terms of replacing equipment and dealing with vendors. As such, replacing equipment does not happen overnight. It is not uncommon for a project to take over two months from the time it was approved for replacement. If a device is critical to operations, two months of downtime is a real problem. This analysis seeks to provide insights on more proactive indicators to enable replacement before approaching or reaching catastrophic failures.

## 3.2 Current CMMS

Harris Health currently utilizes an advanced CMMS database to track existing assets and the maintenance work orders that they generate. It is a commercial product commonly used throughout the industry. This system enables Harris Health to do several major tasks.

First, the system provides a means for tracking inventory. At its most basic roots, the CMMS utilized by Harris Health is a database to store a list of existing assets. It is quite easy to run a report of all available equipment in the system and filter it by a myriad of fields including Building, Department, Cost Center, or Pavilion, etc. The lines can be grouped and subtotaled by any field as well. This enables a quick calculation of device types, asset status, manufacturer, model, or any combination of stored parameters. The system is populated when a new piece of equipment arrives in-house and items are retired when they are taken out of service.

A key aspect of the system is the ability to manage and track work orders. The system integrates with an online support interface where clinical users can initiate a request to have a piece of equipment looked at that is giving the department problems. This automatically generates a work order in the CMMS. The work order is routed to the appropriate technician and work can immediately begin to look into fixing the problematic device. Quick access to past service history or existing service contracts can be quickly cross referenced and reviewed. Should replacement parts be required, the details and cost of these items can be stored within the record itself. In addition, the man hours and labor costs are captured and tallied for each for order. This information was vital to the analysis of this report. When the work order is completed, it is closed out and archived in the system. Similar to the asset inventory, work orders can be queried, filtered, totaled, and exported in any report format. The system is highly flexible and information is easily gathered.

Another key feature of the CMMS is that it is a web based system that is hosted internally on Harris Health servers. This means it is accessible from any available terminal in the Harris Health System without requiring any software downloads or installation. Harris Health owns the data and manages the data itself. The CMMS company simply provides the interface and the tools to store the data.

The CMMS is also flexible enough to store custom fields of information. This can be any data point deemed necessary by the system ranging from equipment age to group purchasing organization affiliations. These fields provide some very useful functionality. Harris Health uses some of these fields to denote particular characteristics about the equipment. For instance, what year is the anticipated replacement year. This is currently solely based on estimated lifetimes. Another custom field tracked is whether a piece of equipment has been funded for replacement. Having this value denoted allows the medical capital group to quickly export a list of existing assets that will be replaced in the coming year. These can be grouped by manufacturer or distributor to leverage pricing and increase efficiencies. Some custom fields have the ability to tie into other technology driven databases. For instance, Harris Health utilizes real time location tracking software to identify the locations of many high value assets. When the sensors are pinged, the location of the unit is updated in a custom field in the CMMS. Any combination of external data can be interfaced and incorporated into the CMMS. Overall, custom fields provide the flexibility to incorporate new ideas and cross reference other existing databases with the system.

Finally, the system tracks historical data. As mentioned above, items can be designated as retired in the system. This does not remove them from the database. They are simply denoted as retired in one field. This is useful because a report can quickly be generated that is only concerned with currently active assets. In addition, those items may provide some very useful data for future analysis projects. This project was only concerned with existing active assets so retired assets were not part of the overall analysis.

Because the system is so flexible allowing a range of field datatypes including long text or memo fields, special care must be taken to ensure that patient information does not get captured in the database inadvertently. It is unlikely for patient health information to end up in the database but it is possible for a technician to document that a particular doctor validated the completed repair on a particular patient. Because the field may be defined as a free form text field, the technician can document any text he wishes related to the repair. It is possible that the technician could even name the patient in this short narrative. If this happened, it would be a serious privacy issue. Special care must be taken to ensure that information such as this is not documented in this manner. The system is equipped to store a large amount of data but it can suffer from a reduction in performance as more data is compiled. The current database houses over 50,000 active and retired assets and over 500,000 work orders. This spans nearly 20 years of data. While Harris Health has not experienced any serious performance issues with the system, it will need to make decisions in the future related to data archival or organization in order to reduce lag times. However, the custom fields and varied filtering capabilities would provide ample functionality to keep system performance high and also maintain the ability to recall archived data as required.

Overall, the CMMS utilized by Harris Health is great tool. It is hard to imagine the system functioning efficiently without it. The ability to keep an accurate inventory of equipment along with the associated work orders tied to that equipment is simply a tool that the benefits cannot be overlooked. In addition, the flexibility of the system allows it to adapt to new ideas and processes and keep Harris Health performing at a very high level as new technologies and improvement processes are implemented throughout the system.

## 3.3 Disclaimer

Larry Fenningkoh (1992, p.43) provided a general disclaimer to the implementation of his analysis at St. Luke's of Milwaukee and it is worth mentioning here.

> "This model should not be used as an absolute measure of a hospital's replacement needs. As with all models, its primary value is derived from establishing a framework within which an issue can be further and rationally evaluated. In essence, a good model forces decision-makers to think about – or to rethink – what they are doing." (1992, p.43)

# 4. Strategic Planning

## 4.1 The Metrics

The six metrics were formulated with the assistance of the director of the Medical Capital Group at Harris Health. They are a combination of current practices in the system and new ideas worth testing the efficacy of. All required data is either currently tracked/collected or easily incorporated into the existing work flow.

The six testing metrics can be broken down into three major categories. The first category is time based. This would mean the main determining factor for replacement is the age of equipment or the amount of time it has been owned. Several different metrics can be produced in this category. A popular one is a percentage of the AHA estimated lifetime. One-hundred and twenty five percent (125%) of the estimated lifetime was used in this analysis. The second major category is cost based. Using existing parameters where data has been reliably collected, led to four parameters to test. The first is that the total cost of equipment and work orders surpasses the original predicted total. The second is that the cost of work orders surpasses fifty percent (50%) of the equipment purchase price. Third, the cost of work orders surpasses the remaining Net Book Value. And finally, the cost of the next work order exceeds the remaining Net book value. The third and final category to investigate combines time and cost. In this category, we look at replacement occurring at 125% of the total cost of ownership analysis. This covers time and cost because the total cost of ownership is estimated because any equipment is purchased. This estimation is determined by looking at the estimated lifetime and existing work order data of similar current asset. Therefore, this metric combines both the age of the equipment as well as the work orders it generates as it compares to the original estimations.

| Metrics |
| --- |
| 125% of AHA Lifetime |
| Total Work Order Cost Exceeds Estimated Upfront Total |
| Total Work Order Cost Exceeds 125% of Estimated Upfront Total |
| Total Work Order Cost Exceeds 50% of the Original Purchase Price |
| Total Work Order Cost Exceeds the Remaining Net Book Value |
| The Next Work Order Cost Exceeds the Remaining Net Book Value |

*Table 1 - Testing Metrics*

## 4.2 Scenario Planning

Scenarios represent a list of alternate futures that could conceivably occur. An infinite number of variables influence everyday life and the idea of scenarios is based on there is being a set of ‘possible futures’. Oftentimes, it is easy to determine which ones would be considered desired futures and sometimes it is even clear which is the most probable future. Scenario planning is a process to review a handful of possible scenarios and determine the implications and options they present to the current situation. In fact, scenario planning has become quite popular in recent years. Jay Ogilvy, a Forbes contributor, cites a poll conducted by the Corporate Strategy Board and found that more than 30% of respondents representing 183 corporations consider scenario planning as one of their favorite tools (Ogilvy, 2015). Further, scenario planning was the most popular of all of the tools chosen in the pool. Other tools included BCG growth-share matrix, SWOT analysis, and Porter's five forces analysis (Ogilvy, 2015). In my opinion, this is not a real surprising result because this is how we, as humans, make decisions in everyday life. Although often done subconsciously or quickly using prior knowledge, our brain runs through a list of probable outcomes for each action and typically we choose the most favorable or enticing to us and make a decision that leads us towards that scenario. Also, thinking about alternate scenarios can challenge our minds. There is a popular book genre referred to as game books. Every so often, a decision for the main character arises and then two or three scenarios are presented. The reader makes a decision and turns to the page corresponding to that decision. Then the book carries on as normal until the main character is presented with another decision. Scenarios and scenario planning in organizations is really not that different. It "attempts to imagine or calculate the effects of alternate decisions" in the business environment (Lindgren & Banhold, 2009, p.23).

First, it is important to not confuse scenarios with forecasts. Although forecasts can be quite useful, it is based on quantitative data. Attempting to forecast in the long term can be quite challenging as the amount of uncertainty has detrimental effects on the success of the forecasting effort. Scenario planning provides an alternative. "Through skillfully crafted scenarios, we can reduce a large amount of uncertainty to a handful of plausible alternative directions that together contain the most relevant uncertainty dimensions" (Lindgren & Banhold, 2009, p.25). Therefore, scenario planning is found to be quite useful for medium to long-term planning with uncertain conditions (Lindgren & Banhold, 2009).

There are several activities where scenario planning has proven to be useful. The most obvious is strategy and planning but others include innovation, where scenario planning may help shape new ideas, and evaluation, where it can be used to test existing conditions. Scenario planning also allows us to understand the causes influencing the alternative actions. In this case, it is a very effective learning tool. Whichever way scenario planning is used, a key aspect is to always use good scenarios. Lindgren & Banhold present seven characteristics of good scenarios (2009). One; each scenario must provide useful information for the question be tested. Two; each scenario should be realistically plausible. Three; each scenario in the set should be roughly equally probable. Four; each scenario should be internally consistent. Five; each scenario should be different. Six; scenarios should be easy to remember. Lindgren & Banhold recommend 3-5 scenarios (2009). Others recommend staying away from three as it could lead to a decision simply towards the most moderate (Ogilvy, 2015). And seven; the final criterion is that scenarios really challenge the organization's perceived wisdom about the future. (Lindgren & Banhold, 2009)

This is all great information on what scenarios are and how to put together good scenarios but unless we are able to use this information in a practical way, it is not a very effective tool.

Scenario analysis must be applied to generate a strategy. A scenario itself does not determine the strategy. A strategy must be developed from the scenarios. Jay Ogilvy presents scenarios as different sets of hands you may be dealt in a card game and the strategy is the way you would play a particular hand (Ogilvy, 2015). Of course, scenarios can also be developed after a strategy is chosen to test the strategy. If a company has decided to finance a large project through an issuance of new stock, they may use scenario analysis to determine what sort of market conditions might arise that could cause this to be a very poor decision. Overall scenario analysis offers organizations a very powerful tool to help navigate an uncertain future. It relies on both qualitative and quantitative data but only evaluates possible or often probable outcomes. Most modern business strategies have evolved from the world of change we live in and scenario planning is no different. It is a very robust tool when evaluating changes due paradigmatic or non-liner change. Modern organizations can benefit greatly from the implementation of such a system.

## 4.3 Activity

The scenario planning for this research helped expand on the global effects of implementing each replacement schedule proposed.  This is slightly different from traditional scenario analysis where a particular scenario would develop and the ideal replacement metric in that scenario would reveal itself.  In this project, all of the metrics are able to implemented independent of what scenario develops at the organization.  In short, there is no external factor in the organization that would require one metric over another to be used.

The planning effort established general questions to help identify key players and stakeholders in both the analysis and implementation.  In addition, a series of questions were posed to evaluate the effectiveness and difficulties of implementing each metric.  A worksheet was completed for each metric.  While planning such as this often involves a qualitative review with little data and specific calculations, it has the ability to highlight some key areas of concern.

## 4.4 Planning Process

The first step of the planning effort dealt with the general implementation of the analysis.  Who has access to the information and historical data was addressed as well as who is responsible for generating and saving new data.  At Harris Health, several key groups were identified including the Medical Capital Group, the Biomedical Engineering Department, and the Healthcare Systems Engineering Department.  Further, key stakeholders in this effort were identified.  Due to some of the metrics, this also brought in Asset Management along with the groups already mentioned. This formed of core group of information providers to this effort.  Weekly meetings were established to convene this group and discuss ongoing issues and developments.

As part of the planning efforts, a series of questions were established to further examine each metric and to delve deeper into the effects that the implementation of a metric would pose.

These questions were formulated through brainstorming efforts by the core group mentioned above and finalized with the director of the Medical Capital Group. This exercise produced a total of seven questions outlined in Table 2 below.

| Questions |
|---|
| 1. Is this metric calculable with current collected data? |
| 2. What changes to data collection method must be realized to implement this metric? |
| 3. What groups would be required to change their process to institute use of this metric? |
| 4. Would there be an added cost to instituting this metric? |
| 5. Would this metric address cost, performance, and age of equipment? |
| 6. Are there any side effects that are less obvious to implementing this metric? |
| 7. Does implementing this metric lead to any other interesting analysis tools? |

*Table 2 - Planning Questions*

Next, each proposed metric was put under the test of the various metric specific questions. How they would affect current processes, the costs involved, and potential setbacks were key areas of interest. In general, the effort brought to light some key points of information that will prove vital in the interpretation of the analysis results. In addition, several concepts were established that would need to be considered in the implementation of a metric. All seven questions were answered for each metric but the following table provides a summary of these planning efforts and lists specific details of a few points that were relatively unknown before this exercise.

| Metric Specific – Metric 1<br>125% of AHA Lifetime |
|---|
| 3. What groups would be required to change their process to institute use of this metric? |
| If all groups are performing as expected for the time being, no changes would be necessary. However, there are times when the life expectancy may not be determined for a new piece of equipment and the item is entered into the CMMS with the field blank. This process would require the Medical Capital Group to provide this information and for Biomed to leave the incoming technical inspection open until the information has been provided in the event of it not being initially provided. |
| 5. Would this metric address cost, performance, and age of equipment? |
| This metric is merely based on age. Cost and performance are not reflected in the calculation. Theoretically, this metric says that all repairs should be completed, regardless of the cost and current status of the equipment. In practice, this is not feasible as there are certain repairs that would be too costly and equipment too old and outdated to continue supporting. |

*Figure 5 - Strategic Planning Metric 1*

| Metric Specific – Metric 2<br>Total Work Order Cost Exceeds Estimated Upfront Total |
|---|
| 5. Would this metric address cost, performance, and age of equipment? |
| This metric addresses cost and performance as presumably the accumulated work order costs would continue to increase as more work orders were completed over the lifetime. However, age is neglected in this analysis. Should a piece of equipment require very little maintenance, and in some scenarios none, it could conceivably grow to an very old age without accumulating a large work order cost. With this metric, there is no indicator of replacement for these assets. While this doesn't create a large financial burden, the system could be missing out on newer technologies that would typically replace this item. Now, it should be noted that this metric uses the estimated lifetime to establish to estimated upfront total. The annual estimated costs are multiplied by the estimated lifetime to find this value. However, the current age of an asset is not reflected in the replacement model. |

*Figure 6 - Strategic Planning Metric 2*

| Metric Specific – Metric 3<br>Total Work Order Cost Exceeds 125% of Estimated Upfront Total |
|---|
| 6. Are there any side effects that are less obvious to implementing this metric? |
| This metric is less susceptible to changes in inflation than Metric 2. The 125% is somewhat arbitrarily set but this could be tweaked to help offset inflation for future years. |

*Figure 7 - Strategic Planning Metric 3*

| Metric Specific – Metric 5<br>Total Work Order Cost Exceeds the Remaining Net Book Value |
|---|
| 1. Is this metric calculable with current collected data? |
| Yes. Currently, work order costs are tracked and able to be subtotaled for each asset in real time. In addition, asset management maintains a detailed account of the net book value of each price of capital equipment. This is an accounting practice to allow a depreciated amount of value to be written off of taxes as a loss. This is typically done over the course of the lifetime of a piece equipment. |

*Figure 8 - Strategic Planning Metric 5*

| Metric Specific – Metric 6<br>The Next Work Order Exceeds the Remaining Net Book Value |
| --- |
| 6. Are there any side effects that are less obvious to implementing this metric? |
| From an analysis standpoint, this metric is useful however it poses some flaws. Should a very simple work order that may only total a cost of $5 be able to indicate replacement for an asset that is otherwise performing well but the net book value is depreciated. What if this asset would cost $50,000 to replace? Some controls would need to be in place account for this. Work orders are generated for all sorts of reasons. Some are $1, some are $10,000. There should be some relevance given to this scenario. With that said, this scenario could be covered by some controls being put in place. Some percentage of net book value could be used as an alternative. Or limits could be instituted as well. For instance, there could always be a lower limit to the net book value. When an asset's net book value hit zero, the next work order could have to exceed $100 to indicate replacement. However, there is always but those outlier questions. Why would $101 indicate replacement when $99 does not? |

*Figure 9 - Strategic Planning Metric 6*

## 4.6 Analysis Process

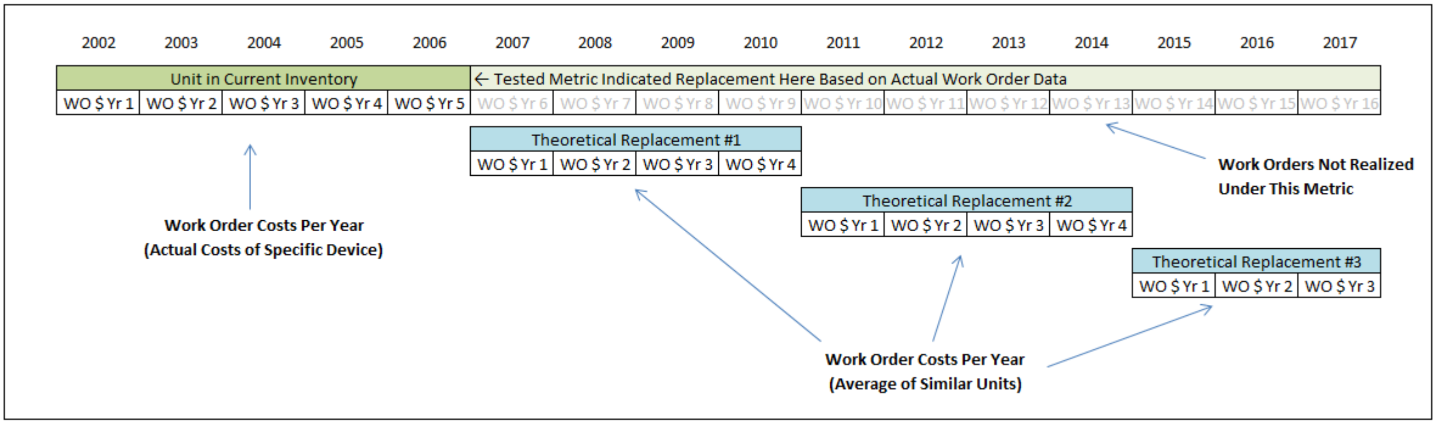


*Figure 10 - Analysis Process*

| Date | Work Order Cost | Running Total |
|---|---|---|
| 5/24/2002 | $ 234.50 | $ 234.50 |
| 7/1/2002 | $ 217.00 | $ 451.50 |
| 1/27/2003 | $ 8.75 | $ 460.25 |
| 2/4/2003 | $ 52.50 | $ 512.75 |
| 11/1/2003 | $ 17.50 | $ 530.25 |
| 2/6/2004 | $ 29.75 | $ 560.00 |
| 1/6/2005 | $ 164.27 | $ 724.27 |
| 2/1/2006 | $ 36.75 | $ 761.02 |
| 5/15/2006 | $ 1,885.25 | $ 2,646.27 |
| 8/1/2007 | $ 17.50 | $ 2,663.77 |
| 8/1/2008 | $ 26.25 | $ 2,690.02 |
| 3/6/2009 | $ 12.25 | $ 2,702.27 |
| 8/1/2009 | $ 17.50 | $ 2,719.77 |
| 8/1/2010 | $ 17.50 | $ 2,737.27 |
| 8/1/2011 | $ 254.50 | $ 2,991.77 |
| 7/24/2012 | $ 87.50 | $ 3,079.27 |
| 8/1/2012 | $ 17.50 | $ 3,096.77 |
| 10/25/2012 | $ 35.00 | $ 3,131.77 |
| 8/1/2013 | $ 17.50 | $ 3,149.27 |
| 10/29/2013 | $ 118.23 | $ 3,267.50 |
| 7/28/2014 | $ 21.00 | $ 3,288.50 |
| 9/8/2015 | $ 478.00 | $ 3,766.50 |
| 11/29/2015 | $ 966.75 | $ 4,733.25 |
| 4/2/2016 | $ 227.25 | $ 4,960.50 |

*Table 3 - Actual Work Order Costs for Patient Monitor B02704*

The following section details the process of how the analysis was conducted. For explanation purposes, we will focus on one piece of equipment to define the workflow; in this case, patient monitor B02704. Patient monitor B02704 was purchased in the year 2002 and still exists as a functioning asset in the inventory today. Since 2002, work order dates and costs for patient monitor B02704 have been captured in the CMMS (see Table 2)

With this data, each of the 6 tests are applied. To continue the explanation, we will follow the Metric 2 specifically. When any piece of equipment is purchased, an estimate is made on the total cost of work orders that will occur in the equipment's lifetime. The premise of Metric 2 is to replace the piece of equipment when the true work order costs exceed this estimation. For Patient monitor B02704, this estimate was $1,386.15. Had Harris Health used Metric 2 to manage their equipment repair/replacement schedule, then they would have replaced patient monitor B02704 in 2006, which would be the fifth year after the initial purchase. This is demonstrated in both Figure 10 and Table 2 by the lightened shade of text. In this particular test, even though there is work order data from 2007 to present day in the CMMS, this data will be omitted from the further analysis of Metric 2. Now when this unit would have been retired in 2006, a new unit would have been purchased to replace it; this can be referred to as patient monitor B02704-2. For Metric 2, the theoretical work orders attributed to Patient Monitor B02704-2 have been estimated based on the average annual work orders of all patient monitors of the same model in the CMMS. So, the theoretical work order costs for patient monitor B02704-2 are shown below:

| | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 |
|---|---|---|---|---|---|---|
| Annual Work Order Cost | $ 262.25 | $ 139.08 | $ 113.67 | $ 914.58 | $ 38.50 | $ 55.42 |
| **Subtotals** | **$ 262.25** | **$ 401.33** | **$ 515.00** | **$ 1,429.59** | **$ 1,468.09** | **$ 1,523.50** |

*Table 4 - Average Annual Work Order Costs for Patient Monitors*

Once the estimated work order costs have been determined, the suggested life of Patient Monitor B02704-2 is recalculated using Metric 2, as indicated by the blue box in Figure 10 labeled 'Theoretical Replacement #1'. In this case, a Patient Monitor B02704-2 would have a lifetime of four years. This would suggest that the original Patient Monitor, B02704, may have been on the higher end of quality/reliability as its work order data suggested five-year cycle as opposed to the four-year cycle of all similar units. The four-year cycle is used for all future replacements in an attempt to level off any quality fluctuations among specific units. In this example, 'Theoretical Replacement #3' only shows a three-year cycle because we have arrived to the current year, 2017.

Now from this demonstration, several pieces of data can be calculated. The original cost of the equipment is known as well as the replacement cost. If Harris Health were following Metric 2 in their equipment repair/replace program, Patient Monitor B02704 would have been replaced three times from 2002-2017. The total cost of ownership is the sum of the original cost, three times the replacement cost, first five years of actual maintenance costs, then the theoretical work order cost based on the average maintenance cost of the fleet of patient monitors. It can also be seen that if this metric were followed, the current age of the item would only be 3 years as opposed to the age of 16 years that the actual unit has been in service.

For the overall analysis, this calculation was completed for all line items. This then provided more in depth trend data to be reviewed. For instance, how many total replacements occurred under this metric? How many items were never replaced? And how much money was saved on work orders that would have never occurred? Finally, the age of all equipment line items can be averaged to find the average age of the entire equipment fleet. This is very important in the fast-paced world of healthcare because devices are being invented and innovated constantly. If you are holding onto to aging technologies for longer than necessary, you are most likely missing out on new developments and innovations. Also, older devices characteristically produce more work orders and devices and often become unsupported after a replacement has been brought to market and proven viable. This means repair parts and technical assistance is reduced, drastically reducing the ability to maintain and repair older equipment. When it comes to medical devices, a continually aging fleet of equipment would be a poor indication of the health of the maintenance/replacement program (Clark, 1991).

This analysis was then repeated for all six metrics and these calculations provided the data points to determine which method performed the best.  Some metrics exhibited lower purchase costs and this led to an increase in work order costs.  This indicated that more money was being spent on maintenance and equipment may not have been replaced when it should.  Other metrics showed an increase in purchase costs with maintenance costs remaining relatively low.  This indicated that equipment was being replaced more frequently than it was being repaired.  The overall recommendation is based on identifying a unit that remained balanced in replacement and maintenance costs while also reducing the average age of the fleet.

# 5. Testing Results & Analysis

## 5.1 Method 1

The first method tested was to replace assets when they have reached 125% of their estimated lifetimes as dictated by the American Health Association (AHA). The AHA publishes estimated lifetimes for various device types annually. This information is tracked and the replacement timeframe can be easily calculated based on the current age. This method focuses on age rather than performance which shows up in the results.

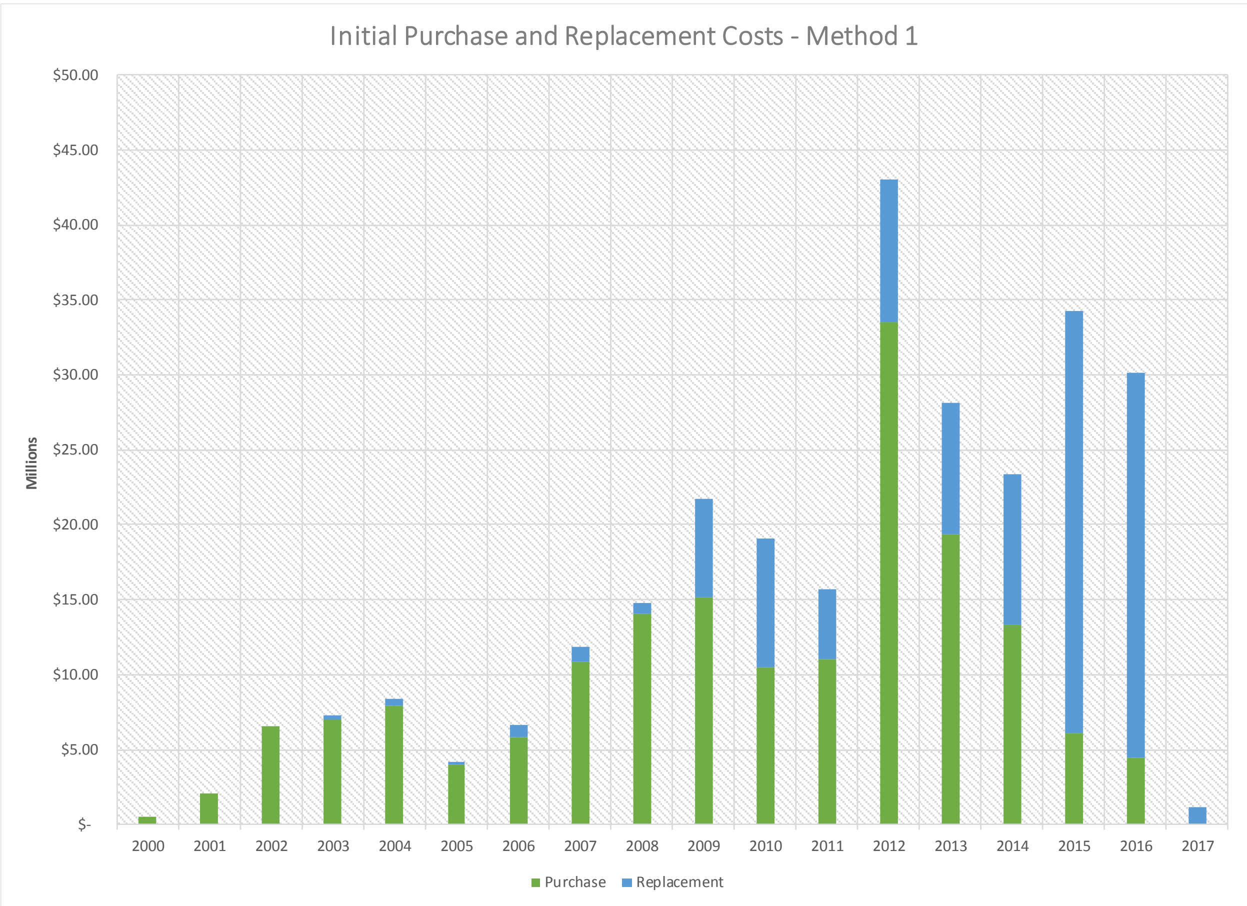


*Figure 11 - Initial Purchase and Replacement Costs - Method 1*

### 5.1.1 Replacement Costs

Compared to the entire field, this method performed very favorably in terms in number of replacements. It came in at about 7,500 replacements over the eighteen-year period. But a total of 18,446 units were never replaced. As will be described below, this adds implications to the work order costs that are incurred in this method. It should also be reiterated that the inventory is made up of currently active devices. It is more likely for a device that has been purchased in the last five years to be in the inventory than a device that was purchased fifteen years ago. Therefore, this method somewhat skews the replacement costs because older problematic devices are no longer included in the inventory and there is a larger proportion of newer devices that simply have not approached their estimated end of life. This leads to the device inventory analyzed being composed of newer devices with less money spent on replacements. The total of replacement costs for this method was $107,000,000. This does not include the initial costs of devices in the inventory. Similar to the quantity of replacements, this replacement cost is low compared to the other metrics.

In terms of the major contributing factors to the overall costs, the original equipment purchases truly dominate the field making up 56% of the costs. Replacement costs contribute 35% to the over spend as indicated in Figure 12 below.

### 5.1.2 Actual Work Orders

The actual work orders produced an interesting result in this method. Due to the fact that more than 18,000 units were never replaced, the actual work order cost to maintain these units was tremendously high; exceeding $21,000,000 when the average of the entire group was $14,000,000. This is due to two reasons. First, this method was the least stringent in terms of replacement. It does not rely on cost or performance metrics of the devices to indicate that replacement is necessary. Units are replaced when they reach a specified age, regardless of performance. This means the replacement metric is high predictable. You know on the day you buy a device, when you will replace it.

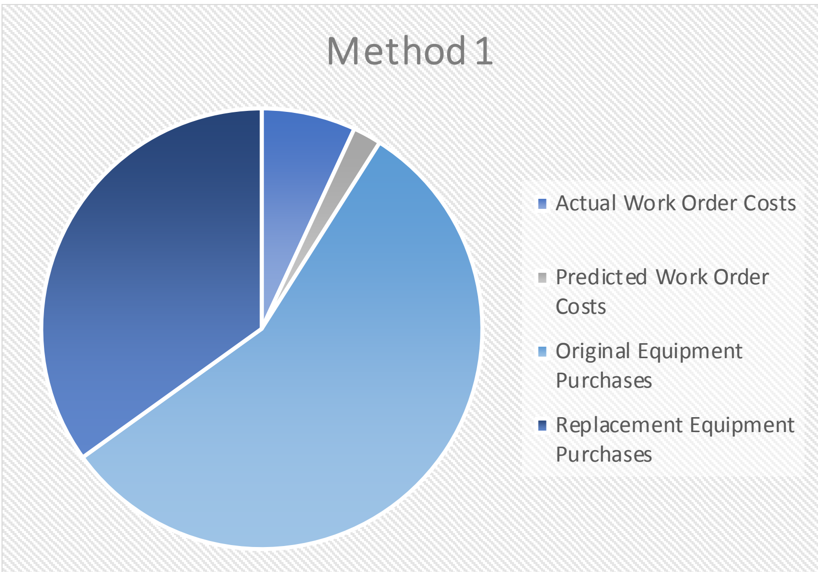


*Figure 13 - Cost Breakdown - Method 1*

However, there is an unpredictable component as well. And that is the work order costs. If you have committed to only replace a device when it reaches a certain age, you do not allow any leniency to replace early. This means that you have committed to maintain that device over its lifetime, regardless of the work order cost. For obvious reasons, this is not practical in the real world. You would not continue dumping money into a device without some sort of further analysis. This leads to the second reason for the high number for actual work orders. This analysis was only completed on assets that are currently active. Older assets that performed very poorly from a maintenance perspective would have been replaced a few years after exhibiting problems. Those assets would not have been in the inventory when this analysis was completed. A large portion of the 170,000 original work orders analyzed would be present in this analysis if a similar metric was being followed. In this metric, 66% of the actual work orders that Harris Health incurred were realized.

### 5.1.3 Estimated Work Orders

This method was fairly straightforward for calculating the estimated costs of future work orders. As explained above, this estimate covers the costs of maintenance for new hypothetical devices that are purchased after an existing unit should be replaced. Since this method is not dependent on cost or performance, each newly purchased unit follows the same work order cost cycle of the device it replaced. This means if a particular device was projected to be replaced three times in the 18-year window, each of those 4 devices (1 original and 3 replacements), would exhibit the same work order cost pattern in this metric. Therefore, the estimated lifetime and the work order costs incurred over that lifetime are same for each iteration of device. This is the cost that was used to predict work orders for replacement devices.

It should make sense that since a large proportion of devices were never replaced, the estimated work orders after the first replacement would be relatively low. This was the case for this method. Estimated work orders came in at roughly $6,400,000. This can be compared to the average of all metrics being $7,240,000.

### 5.1.4 Equipment Age

As can be seen in Figure 14, this method produced an increasing accumulated age of the entire fleet. This was typical for all methods. However, Method 1 did produce the lowest accumulated age in the entire group after 18 years of use. The average of all methods was 5.37 years and the accumulated age under Method 1 was 4.68. This is a very favorable result. The current fleet has an average age of 6.94 years. This method provides an improvement of 2.26 years or 33%.

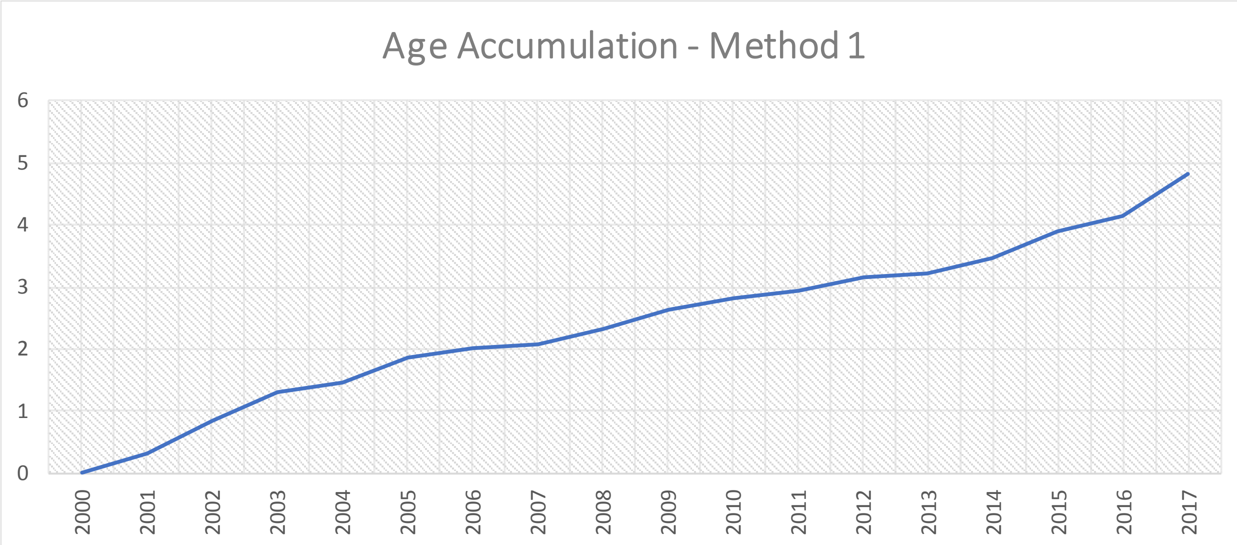


*Figure 15 - Age Accumulation - Metric 1*

### 5.1.5 Method 1 Conclusions

Method 1 performed excellent in terms of quantity of replacements and average equipment age. However, it exhibited poor performance in regards to work order costs. Overall, it provides a very simple indicator of replacement and is highly predictable as the parameters are fixed and not subject to a complicated process of determining the proper replacement timeframe. As demonstrated, this ease of use comes at a cost of higher work orders to maintain equipment until reaching the replacement age.

## 5.2 Method 2

The second method tested was to replace assets when the total cost of work orders attributed to the asset is greater than the total that was predicted at the time of purchase. The predicted total at the time of purchase is based on the average of existing work orders for similar devices in the fleet. If on average, the Harris Health spends $100 annually to maintain a unit of this type, then $100 is multiplied by the expected lifetime to estimate the total work order costs. Like all of the metrics, after the first replacement, the analysis seeks to estimate work order costs. Since this was also estimated using existing work orders costs for similar devices, the lifetime of future replacements was equivalent to the upfront estimated lifetimes.

It should be mentioned that when the next work order would ass the replacement threshold, that work order was not included in the subtotal. This is equivalent to a device that would be sent off for repair and when the estimated cost of repair was produced, the owner would opt to replace the unit instead of pay for the repair. The labor attributed to the work of determining the cost of repair is assumed to be negligible and is excluded.

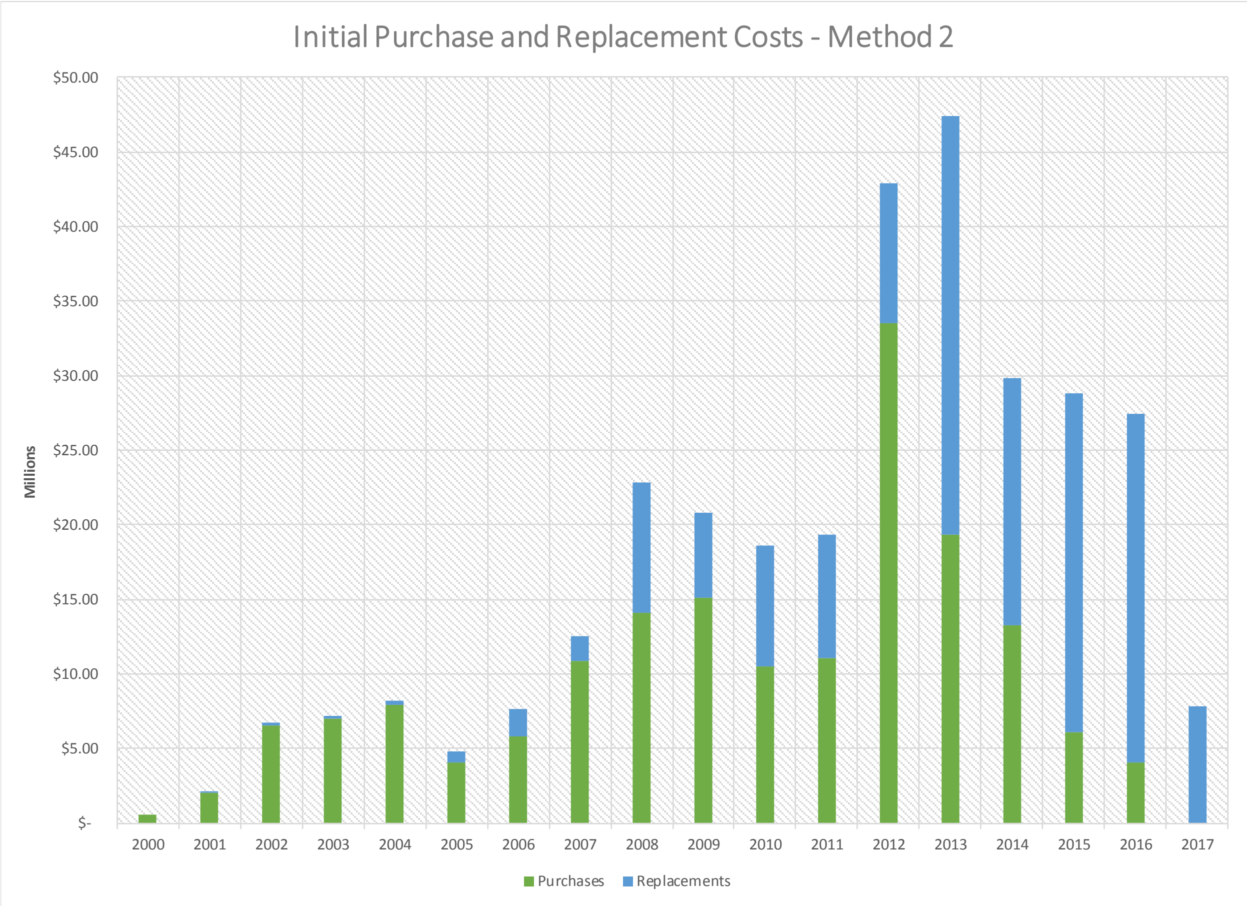


*Figure 16 - Initial Purchase and Replacement Costs - Method 2*

### 5.2.1 Replacement Costs

This method produced quite a few replacements compared to the other methods tested. In total, it produced 10,000 replacements over the eighteen-year period. This is an increase of 30% compared to Method 1. Roughly 17,000 units were never replaced. This is less than Method 1 but it is still not an insignificant number. This accounts for greater than 65% of the existing assets. The total of replacement costs for this method was $143,000,000 over the period tested. This does not include the initial costs of devices in the inventory. The replacement costs are roughly proportional to the number of replacements and reflects one of the higher totals in this category. The higher number of replacements and the higher costs attributed to replacements led to an increased overall predicted spend. Compared to the remainder of the field, this metric produced the second highest spend when considering replacements, actual work orders, and predicted future work orders. This can be interpreted in two related ways. First, the replacement criteria may be too strict. This means that replacements are occurring at a faster rate than they should be. The second interpretation is related to the first. It follows that the predicted total, which the replacement interval is based on, may be flawed. It may not make sense to use data that is 10-15 years old to estimate work order costs of future devices that could potentially live an additional 10-15 years after the initial purchase. If this metric were to be pursued further, scaling the predicted total may produce more desirable results. For instance, Metric 1 utilizes 125% of the AHA expected lifetime. A similar method could be instituted to scale the predicted total which triggers replacement. This could potentially cover increased costs due to inflation or other less foreseen risks. Overall, the amount spent on replacements was closer to the amount spent on original equipment than was exhibited in Metric 1.

### 5.2.2 Actual Work Orders

The actual work orders produced another interesting result in this method, albeit it was somewhat opposite of Method 1. Due to the fact that more than 10,000 replacements occurred, the actual work order cost to maintain these units was relatively low; less than $12,000,000. Again, the average of the entire group was $14,000,000. As was previously mentioned, this low cost of work orders was largely due to an overall strict indicator that is quick to trigger replacements. Only one metric produced less cost in the actual work order parameter.

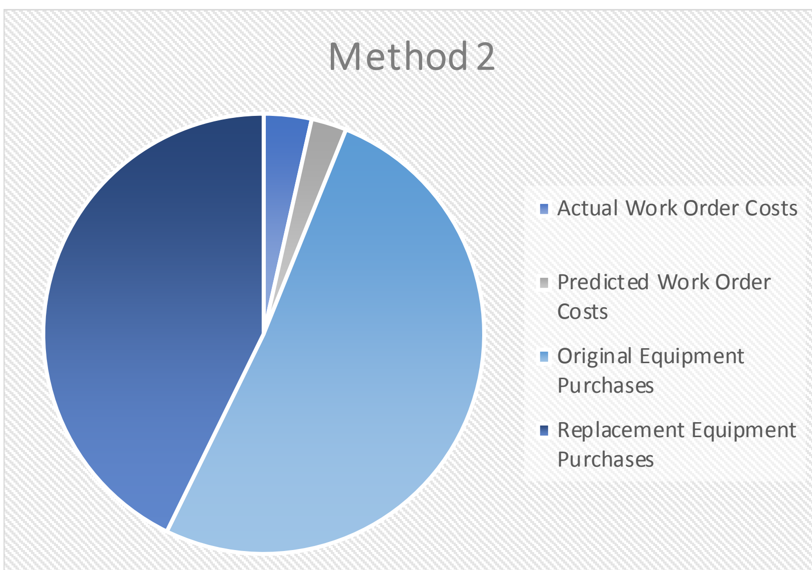


*Figure 17 - Cost Breakdown - Method 2*

One positive to note regarding the low actual work orders committed is the ability to single out poorly performing devices at an early age. Since the replacement level is based on the average work orders of similar devices, the level should reflect the average lifetime of the devices. This is especially true when a large sample size of devices is available for a particular device. Obviously, the opposite is true as well when dealing with a unique device where only a few are owned. Unit types where there are only one or two in the fleet basically produce replacement timeframe data for themselves. If one of these units happens to be an outlier in either direction, it could drastically skew when this device should be replaced.

While it has drawbacks, there are some nice benefits to this type of parameter and these were exhibited in this metric. Units that have inherent problems due to manufacturing or handling should produce more work orders earlier in their lifetime and require replacement at an earlier age. While it does increase replacement costs, problematic devices are able to be removed early and avoid late in life, high cost maintenance.

### 5.2.3 Estimated Work Orders

As can be seen in Figure 18 above, the costs associated with future purchases contribute much more to the over spend in this metric. Not only are replacement costs a higher percentage but predicted work order costs are higher as well. This is due to the fact that more replacements have occurred under this metric.

Estimated work orders under this method were calculated by taking all of the devices of the same manufacturer and model and averaging their maintenance costs for each year of an eighteen-year lifespan. Then using the estimated lifetime as predicted by AHA, a dollar value was designated as the cut-off point and this was identified as the predicted cost of equipment work orders for this device type. When this dollar value was breached, replacement would occur.

As stated above, when this calculation focused on estimated work orders as opposed to actual work orders, the equipment survived for the same timeframe as the designated lifetime by AHA. This is because the threshold was determined based on the AHA parameter and then the average data was used to track when the device should be replaced.

Estimated work orders came in at roughly $8,700,000. This can be compared to the average of all metrics being $7,240,000.

### 5.2.4 Equipment Age

As can be seen in Figure 19, this method also produced an increasing accumulated age of the entire fleet. The average of all methods was 5.37 years and the accumulated age under Method 2 was 5.08. The current fleet has an average age of 6.94 years. This method provides an improvement of 1.86 years or 27%. With a large portion of devices never requiring replacement, greater than 65%, it would be difficult to have this metric produce an age pattern that reduced over time.

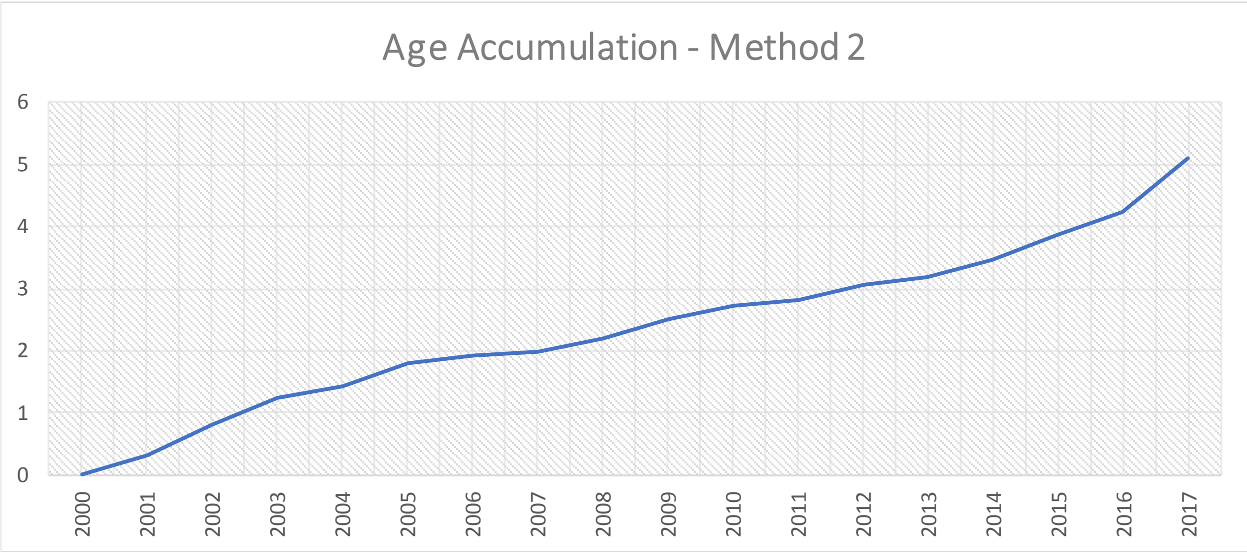


*Figure 20 - Age Accumulation - Metric 2*

### 5.2.5 Method 2 Conclusions

While Method 2 produced higher overall costs than Method 1, it exhibited some very desirable results. First, it effectively shifted costs from work orders to replacements. Now, work orders reduced by about $7,000,000 with equipment replacements increasing by $30,000,000. This is not ideal but the metric could be scaled for better performance. Again, this could help account for inflation over an 18-year testing period. The greater benefit of this shift of funds is the predictability. It is much more straightforward to predict the cost of a new device in five years than it is to predict the costs of repairing equipment over the course of five years. If a better balance can be found between these two pools of money, this metric would show promise for implementation.

## 5.3 Method 3

The third method investigated was to replace assets when the total cost of work orders attributed to the asset is greater than 50% of the purchase price of the asset. Similar to Method 2, in this scenario, the first lifetime is based on actual work orders that are attributed to the specific device. After the first replacement, the analysis seeks to estimate work order costs. Again, it should be mentioned that when the next work order would cross the replacement threshold, that work order was not included in the subtotal. This metric is straightforward and could easily be implemented in the current system. Purchase costs are already tracked and a simple calculation in the CMMS is all that would be required to implement this on a full scale.

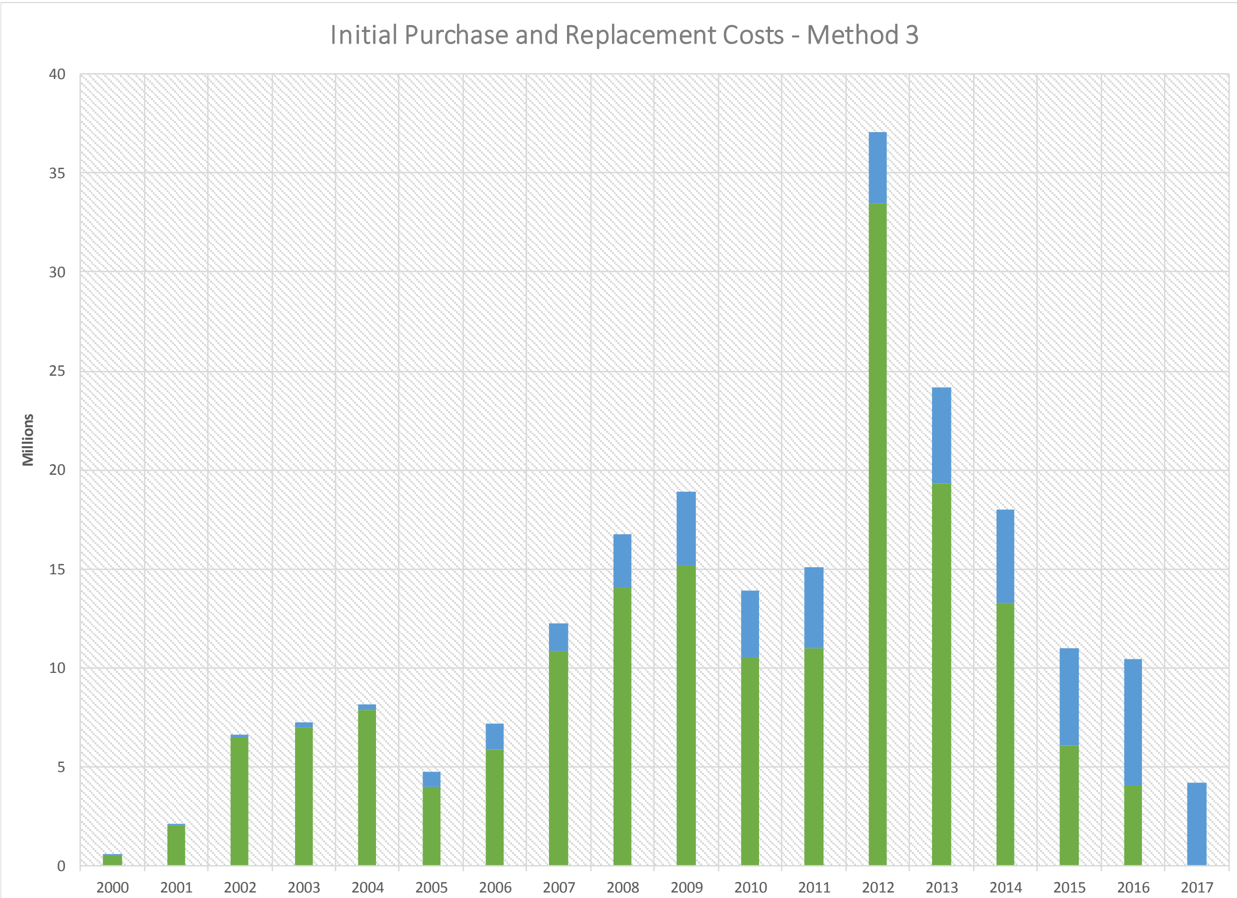


*Figure 21 - Initial Purchase and Replacement Costs - Method 3*

### 5.3.1 Replacement Costs

Compared to the entire field, this method was in the middle of the road in terms in number of replacements. It came in at about 9,400 replacements over the eighteen-year period. However, a total of 22,398 units were never replaced. This equates to nearly 90% of the devices! This was a surprising result and required a more thorough review to determine what the cause of this was. On further analysis, this was largely caused by items that were in the system that did not have a purchase cost. This was less significant with other metrics because the effect was only on the original purchase; a one-time cost. In addition, it also affected all of those metrics equally. However, in Method 3, these units would indicate that they required replacement as soon as they incurred their very first work order, which would always happen to be greater than 50% of the purchase price of $0. This resulted in the device being replaced every year.

As was explained previously, missing data was more prevalent in the early years that this CMMS was utilized. That means that often the items missing purchase prices were originally purchased in the early years of this analysis and they indicated that they should be replaced every single year. Some devices had been replaced 18 times! Now since the purchase prices were $0, they did not add to the dollar value of replacement costs. But they did record a replacement. This explains why replacement costs remained relatively low at $46,000,000, while the quantity of replacements approached 9,400. Another reason that the number of devices never replaced remained high was due to the fact that this metric did not favor replacement as it aged. It did not matter if a device was 2 years old or 10 years old, the replacement threshold remained the same. Compare this to an age based metric that is continually moving closer to the point of replacement. An item in Method 3 could conceivably continue in its life and never require any real service. As long as it does not have any major issues, it may never hit 50% of the purchase price. Referring to the pie chart below, Figure 22, original equipment purchases are the dominant cost in this method and greatly outnumber replacement equipment purchases.

Overall, this method was the least strict in replacement and it showed in the results. The dollar value indicating the replacement threshold was much higher here than in other methods. This was indicated by the fact that many devices were never replaced and the low replacement costs compared to the field.

### 5.3.2 Actual Work Orders

As you can imagine, the results have a drastic effect on how work orders were implemented in this method. Since nearly 90% of the devices were never replaced, the actual work orders of these devices were all accounted for. This was similar to the result in Method 1. This method recorded $15,500,000 in actual work orders, second only to Method 1.

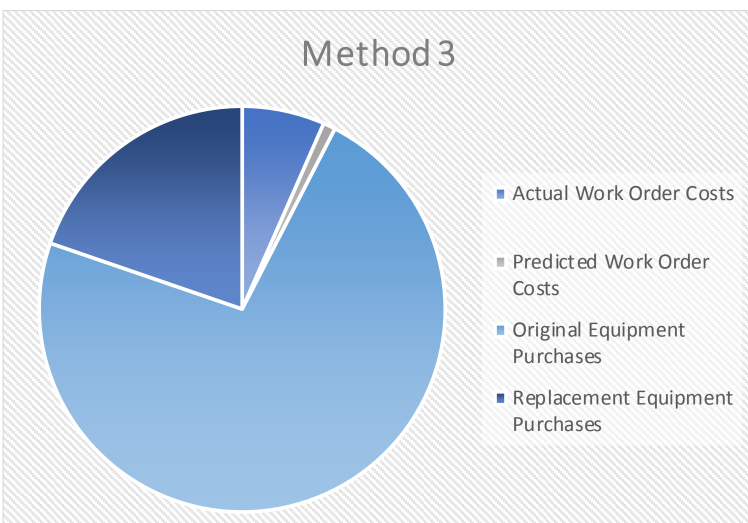


*Figure 23 - Cost Breakdown - Method 3*

As can be seen in the pie chart above, actual work orders made up a much larger proportion than predicted work orders in this method. Of the 170,000 work orders that were included in the initial data, this metric recorded the highest percentage realized of the entire group of metrics tested. This is mainly due to the conditions already described.

### 5.3.3 Estimated Work Orders

As has been the trend throughout, this method was straightforward for calculating the estimated costs of future work orders. As explained above, this estimate covers the costs of maintenance for new hypothetical devices that are purchased after an existing unit should be replaced. The annual maintenance costs of each device type were compiled and a replacement age of each device was able to be determined based on when the estimated work order costs exceeded the 50% purchase price limit. This replacement age was utilized for all devices of that device type after the original unit was replaced.

It should make sense that since a large proportion of devices were never replaced, the estimated work orders after the first replacement would be relatively low. Since this metric produced the highest percentage of devices that were never replaced, the dollar values in this category were the lowest. This method only recorded $2,300,000 in estimated work orders costs. This can be compared to the average of all metrics being $7,240,000.

### 5.3.4 Equipment Age

As can be seen in Figure 24, this method produced an increasing accumulated age of the entire fleet. Again, this was typical for all methods, but Method 3 did produce the highest accumulated age in the entire group after 18 years of use. The average of all methods was 5.37 years and the accumulated age under Method 3 was 6.23. It is no surprise that this is due to the large number of devices never replaced. The current fleet has an average age of 6.94 years. This method only provides an improvement of 0.71 years or roughly 10% compared to never replacing any devices at all.

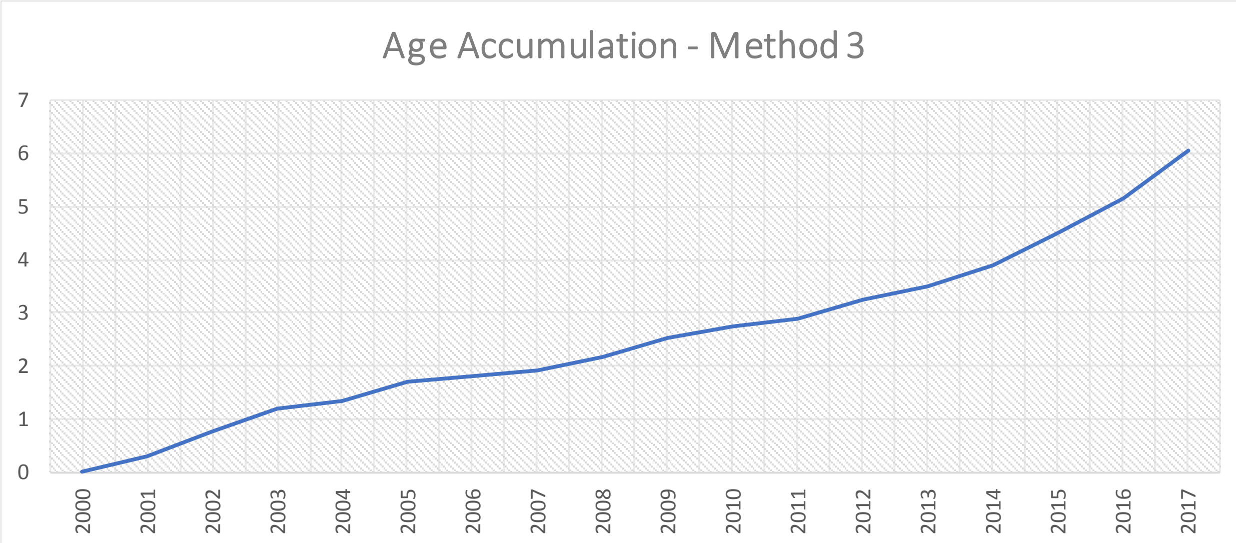


*Figure 25 - Age Accumulation - Metric 3*

### 5.3.5 Method 3 Conclusions

At first glance this Method appeared to produce very favorable results from the standpoint of total dollar value. It also is a very straightforward calculation that utilizes data already tracked. Overall, it would be a very simple implementation to use. However, on further review, it included some severe flaws. The replacement limits were very relaxed and many devices, close to 90%, were simply never replaced. Actual work orders for these devices were high and replacement costs across the board were low. An anomaly due to missing data also reflected a high quantity of replacements that were all recorded as $0. This severely skewed the quantity of replacements but had no effect on the replacement dollar value of this metric.

For a future analysis of a metric of this type, it would be beneficial to reduce the 50% of the purchase price to somewhere in the range of 25-35% and review the change to the results.

## 5.4 Method 4

The fourth metric recommended replacement when the total cost of work orders exceeded the NBV that the item had remaining. Harris Health does not calculate NBV on non-capital assets. Generally, these are assets whose purchase price is less than $5,000. However, this metric is able to be easily applied to non-capital assets by factoring in the purchase year, expected lifetime, and purchase price. Since Harris Health utilizes straight line depreciation, calculating the NBV becomes a fairly trivial task. Then, while looking at all assets, both capital and non-capital, the remaining NBV can be calculated at the time of each registered work order. Also, a running total of all work order costs for that asset was calculated. Should a work order be recorded when and the remaining NBV is lower than the running total cost of all work orders for that asset, that particular work order and all work orders that follow are excluded. This indicates the point of a recommended replacement in this metric.

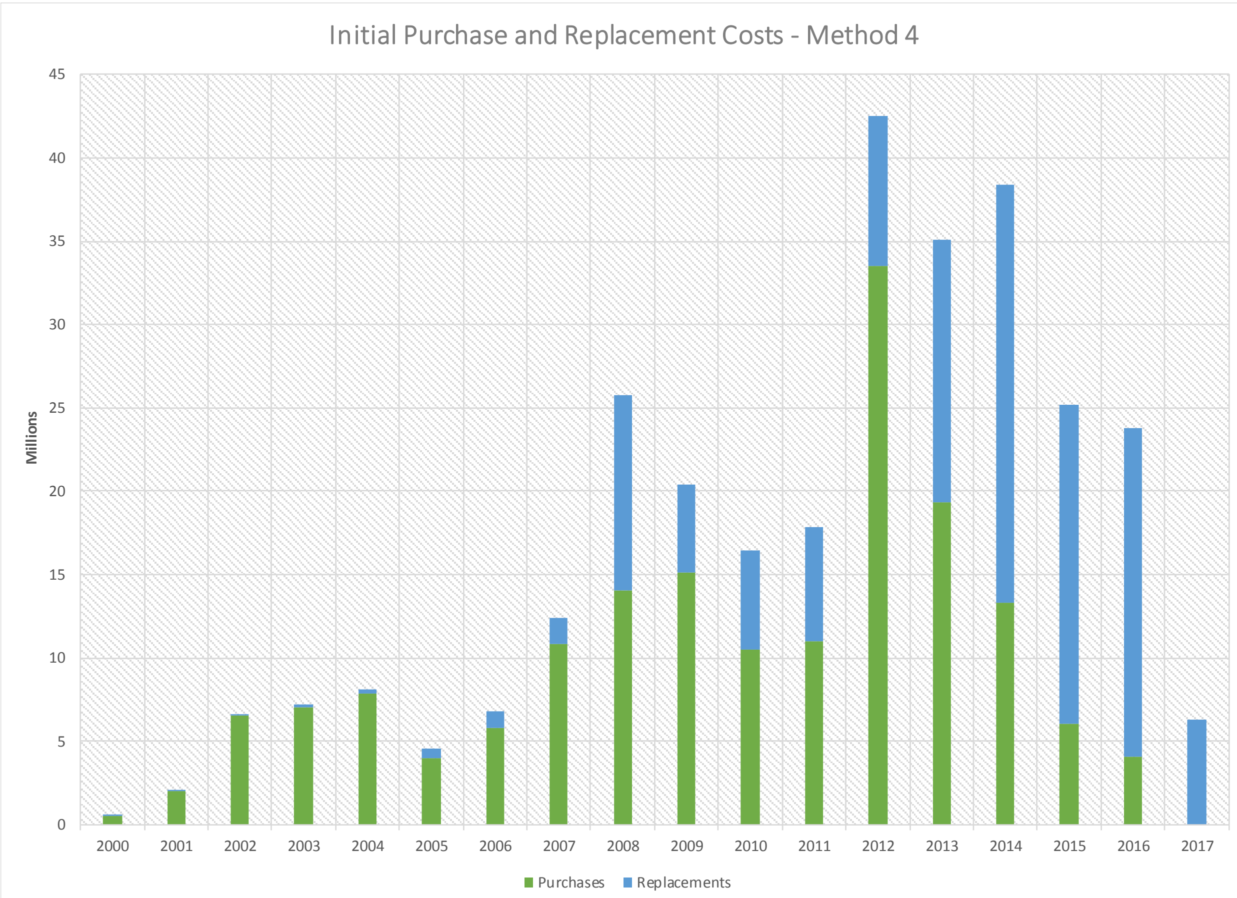


*Figure 26 - Initial Purchase and Replacement Costs - Method 4*

### 5.4.1 Replacement Costs

Compared to the entire field, this method performed average in terms of the number of replacements. It came in at about 9,000 replacements over the eighteen-year period when the average of all metrics was roughly 8,400. A total of 19,000 units were never replaced. The total of replacement costs for this method was $128,000,000. This does not include the initial costs of devices in the inventory. This method was a combination of both cost and lifetime as the threshold of replacement reduces over the equipment lifetime. This means that older equipment is replaced faster than newer equipment would be. There are advantages and disadvantages to this method. An advantage is that it leverages a natural tendency for older equipment to be more problematic. Even if it overestimates this, there is a benefit that newer equipment will be superior from a technological standpoint. This metric automatically weighs this into its process. Conversely, this poses a disadvantage as well. Eventually, the NBV will go to zero. This is simply how the accounting works. Once the equipment has a NBV of zero, any work order will initiate a replacement. This is true even if the work order only costs a few dollars. In practice, this would not be ideal as you would not want a very simple and routine repair to indicate replacement for potentially a very expensive piece of equipment that did not truly require it.

### 5.4.2 Actual Work Orders

Similar to method one, this method also had a very high number of equipment items that were never replaced. However, this method did not exhibit the high actual work order costs that were found present in method one. The method four actual work order costs came in at $11,000,000 when the average of the entire group was $14,000,000. As will be described below, these costs were transferred more to the predicted work order costs that occurred after the first replacement. The reason for this was due to how stringent to replacement rule was under this metric. Contrary to method one, it was on the higher end of stringency. It relies on cost, performance, and age.

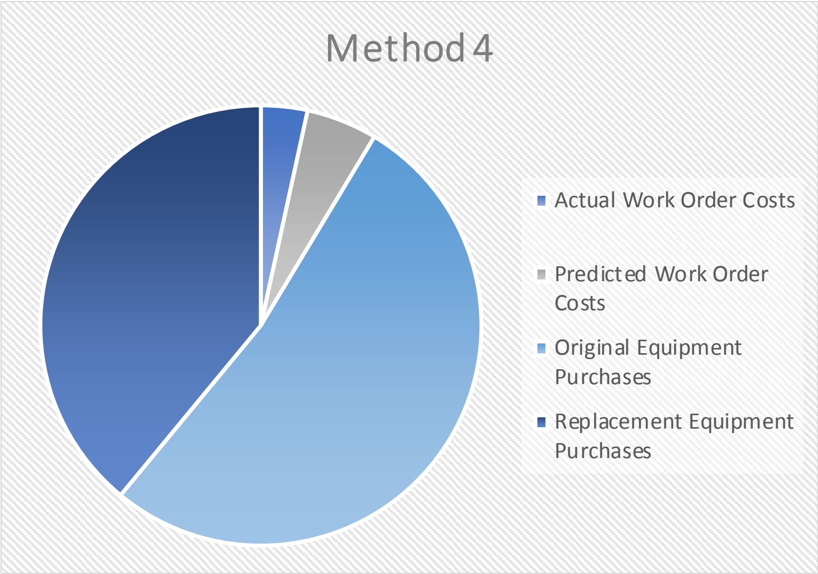


*Figure 27 - Cost Breakdown - Method 4*

In addition, a high number of the actual work orders were simply not realized under this method. In fact, only 48% of the actual work orders that were analyzed would have been included which saved about $12,000,000 on work orders but this was made up for in the equipment replacement costs.

### 5.4.3 Estimated Work Orders

This method was fairly straightforward for calculating the estimated costs of future work orders. Similar to the other methods, this estimate covers the costs of maintenance for new hypothetical devices that are purchased after an existing unit should be replaced. The average annual costs for each device type were calculated along with the NBV based on the replacement cost for the device type. The replacement price that is stored in the CMMS was used here to calculate the remaining NBV since this portion of the analysis represented devices purchased in the future; presumably close to the estimated replacement cost.

Estimated work orders in this method came in at roughly $17,000,000 and was the highest of all metrics. This can be compared to the average of all metrics being $7,240,000. As mentioned above, a large majority of actual work orders were excluded and these costs were transferred down the line to future maintenance costs. This was likely due to several reasons. One, items with high actual work order costs were replaced early in the analysis. This then left the more years for estimated work orders to occur. If the entire range of equipment averaged high maintenance costs, which is not unlikely, then the estimated work order costs will also be high along with a high number of total replacements. This method recorded a high number of replacements so this is likely the cause of such a scenario.

### 5.4.4 Equipment Age

As can be seen in Figure 28, this method produced the same increasing accumulated age of the entire fleet typical for all methods. Method 4 nearly mirrored the average of the group after 18 years of use. The average of all methods was 5.37 years and the accumulated age under Method 4 was 5.20. The current fleet has an average age of 6.94 years. This method provides an improvement of 1.74 years or 25%.

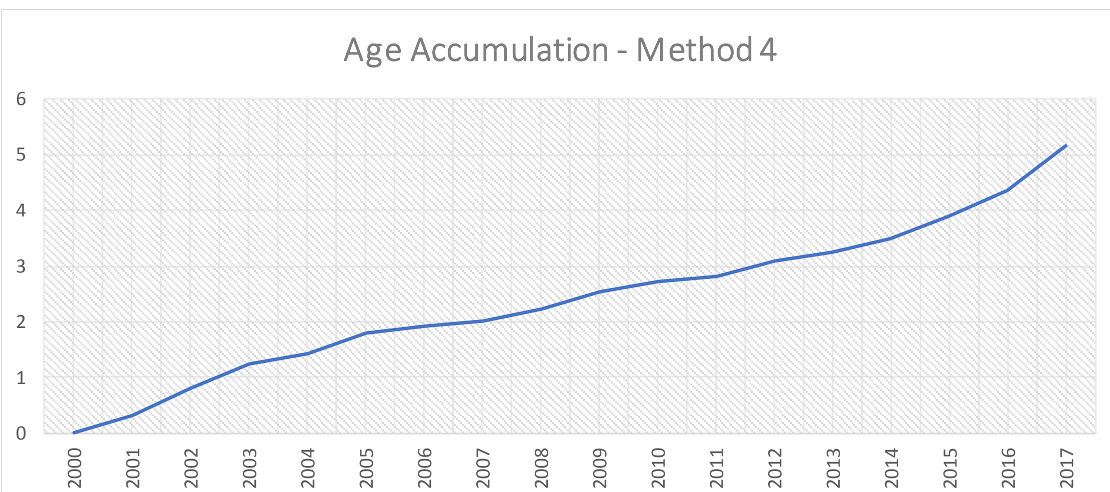


*Figure 29 - Age Accumulation - Metric 4*

### 5.4.5 Method 4 Conclusions

Method 4 performed just over the average in terms of total costs of the metric. It came in at $328,000,000 with the average being roughly $300,000,000. The overall calculation is not difficult and net book value is currently tracked on all capital assets and easily found for non-capital assets. However, the metric is very stringent on replacement leading to many replacements that may be seen as premature. It also produced high future work order costs with a limited improvement in the age of the fleet. For a future analysis of a metric of this type, it may be beneficial to set a baseline floor of the NBV value so unnecessary replacements are not triggered after a very inexpensive work order. Finally, it does not have a good solution when a piece of equipment never registers a work order. It would sit indefinitely, in the system and never be replaced. The metric did provide some very interesting results that were not predicted ahead of time. While it has not produced a winner in this analysis, the lessons learned will help shape the final implementation and success of the chosen system.

## 5.5 Method 5

The fifth method tested was to replace assets when the next repair will exceed the remaining NBV of the item. This differs from the previous metric as it is not concerned with the running total of the cost of work orders but rather it is only concerned with the cost of the current work order. When the cost of the current work order exceeded than the remaining NBV, the asset would be replaced. This metric is also easily calculable with minor modifications to existing tracking methods but it is susceptible to some of the same issues that were experienced in method four. However, overall, it is less stringent of a replacement model.

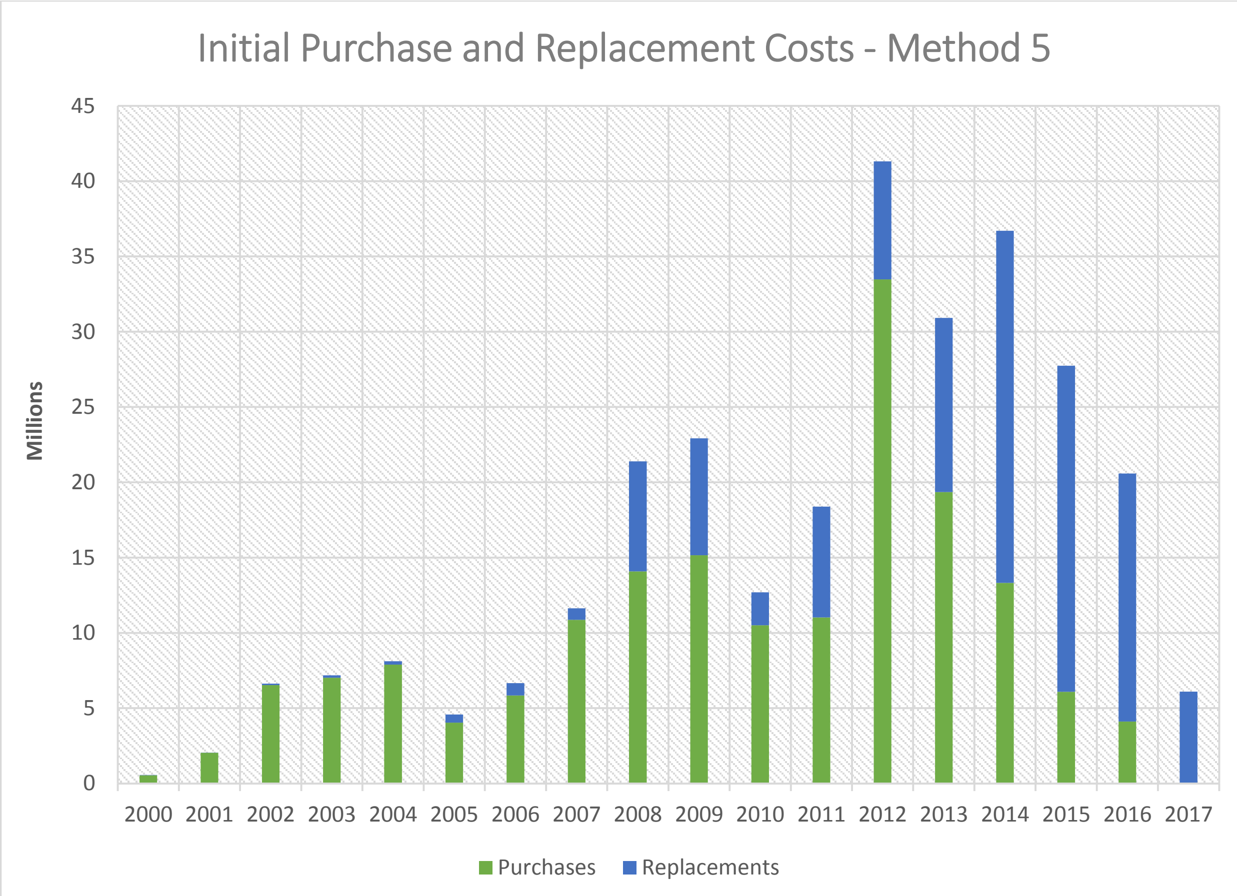


*Figure 30 - Initial Purchase and Replacement Costs - Method 5*

### 5.5.1 Replacement Costs

This method produced a low number of replacements in comparison to other metrics. It came in at about 7,600 replacements over the eighteen-year period and total of 19,800 units were never replaced. As indicated, this method was less stringent than the prior one, meaning that far fewer items were replaced.

The total of replacement costs for this method was $114,000,000. This does not include the initial costs of devices in the inventory. Similar to the quantity of replacements, this replacement cost is low compared to the other metrics. An interesting point is that this cost was not simply displaced to a different category. Actual and estimated work orders were also moderately positioned in the group.

### 5.5.2 Actual Work Orders

The actual work orders in this method came in right around $13,200,000. The metric appeared to allow assets to remain active for more time and avoided the early costly replacements. At the same time, it did not allow assets to hang around forever adding more and more to the overall cost. Just like metric four, the NBV continues to decrease over the life the equipment until it reaches zero. In fact, this process of reducing NBV is identical to method four. But when replacement is only indicated when the current work order exceeds the remaining NBV, there is less worry that small routine work orders can have a wide spread effect. This presents the moderate actual work order cost that was exhibited in this metric. It does not appear to wipe out a large portion of actual work orders and it also does not keep equipment in the system unnecessarily.

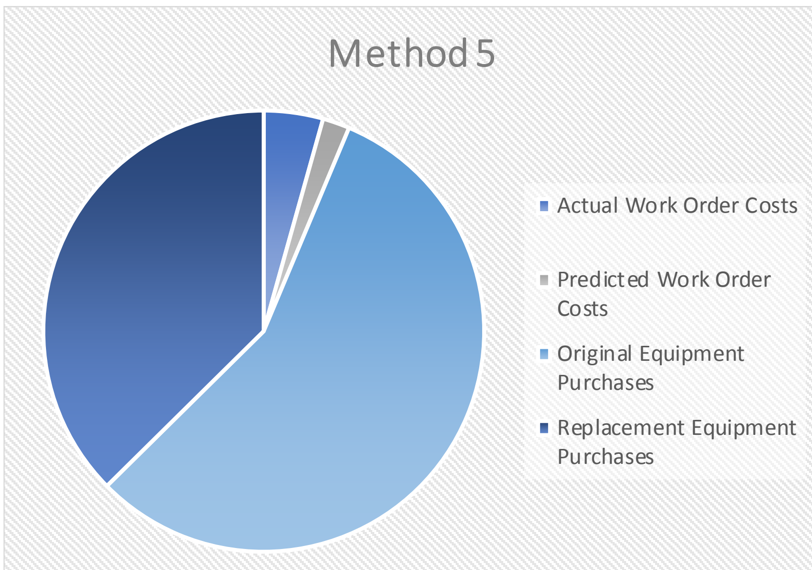


*Figure 31 - Cost Breakdown - Method 5*

### 5.5.3 Estimated Work Orders

Once again, this method was fairly straightforward for calculating the estimated costs of future work orders. It is even less complicated than the similar previous method as it is not necessary to keep a running subtotal of the average annual work order costs. Rather, it simply looks at the average annual work order costs for each year independently. Again, it is obvious how this metric provides a much less stringent threshold of replacement than it did for the previous metric.

Since metric five produced very moderate results in terms of replacements and actual work orders, it should come as no surprise that the estimated work orders were also at a very reasonable level. When devices are not replaced prematurely, it leads to a normal amount of time for future lifetimes. Also, the actual work orders make up the averages used for the estimated work orders so when the actual work orders produce reasonable results, this impacts estimated work orders positively. Estimated work orders in metric five came to a total of just over $6,000,000. This was second only to metric three which was shown to be caused by an anomaly.

### 5.5.4 Equipment Age

Referring to Figure 32 below, it can be seen that this method once again produced the same increasing accumulated age profile. Method 5 was also very close to the group average after 18 years of use. The average of all methods was 5.37 years and the accumulated age under Method 5 was 5.32. The current fleet has an average age of 6.94 years. This method provides an improvement of 1.62 years or 23%.

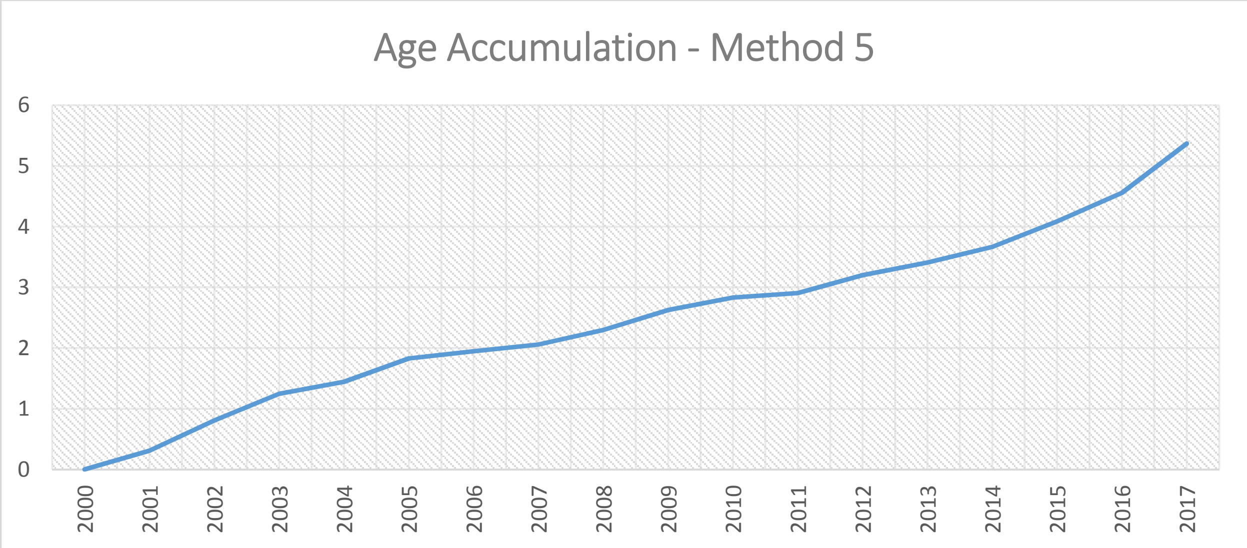


*Figure 33 - Age Accumulation - Metric 5*

### 5.5.5 Method 5 Conclusions

Method five has shown to be a strong performer in quantity of replacements, actual work order costs, and estimated work order costs. It produced lessor results in terms of the number of devices never replaced and the average age of the fleet. Several of these characteristics are obviously related. The less you spend to replace equipment, the longer devices will live in the system and this raises the average age. The interesting point is that this did not have a strong impact on the cost of work orders as would be expected. Method five appears to have struck a very sensible medium to the replacement / work order balance. It did produce a less than ideal average fleet age but it was still an improvement over the current situation.

## 5.6 Method 6

The final metric tested was to replace assets when they have reached 125% of their estimated total cost of ownership. Total cost of ownership is calculated by adding the purchase price with the estimated service costs. As the name implies, this represents an estimate of the total cost to be incurred while owning this device. This metric is very similar to metric two but only scaled to a higher replacement threshold.

As expected, this metric produces results similar to metric two with slight variations that would result from a less stringent replacement rule. This metric is based on both age and performance.

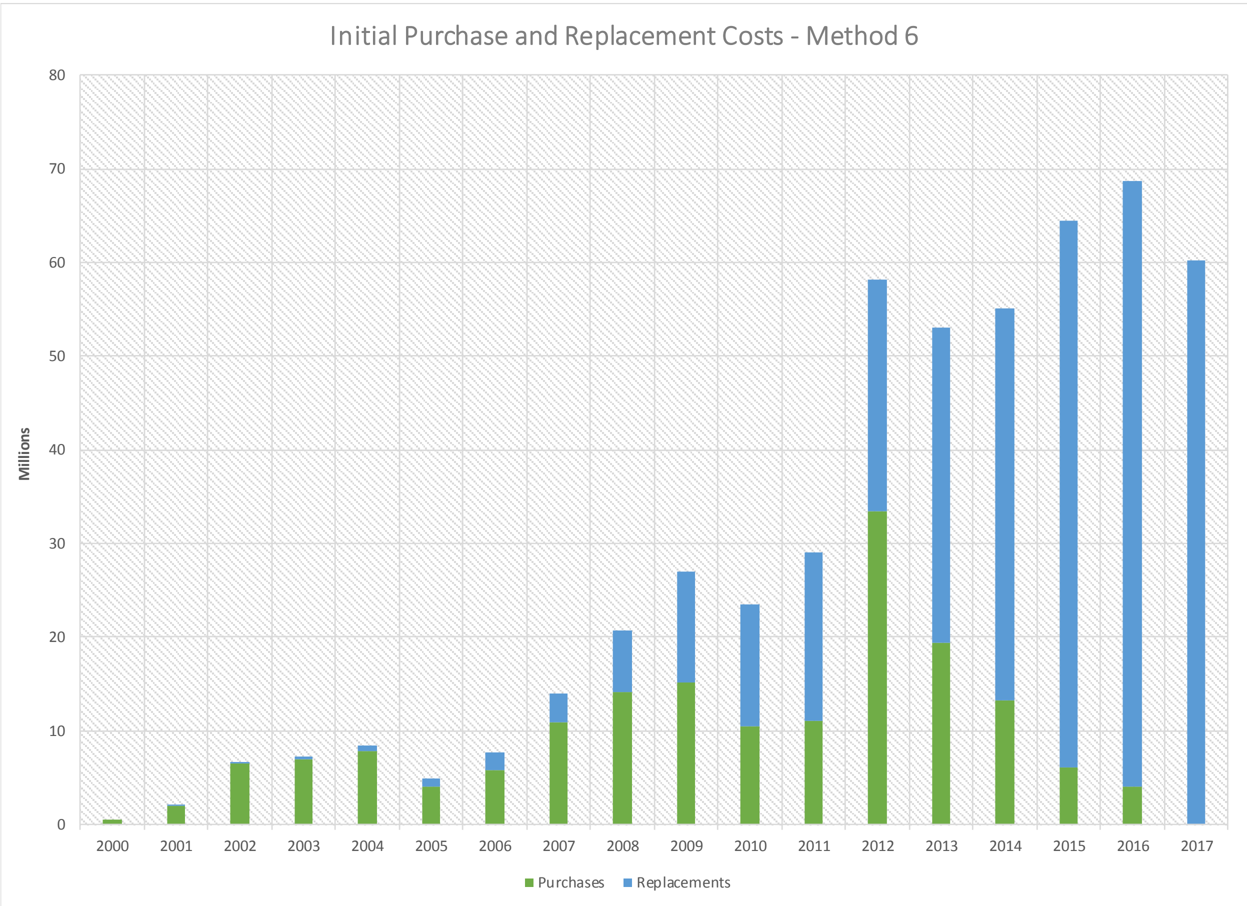


*Figure 34 - Initial Purchase and Replacement Costs - Method 6*

### 5.6.1 Replacement Costs

This final metric produced a replacement cost that was slightly lower than the average. It came in at $92,000,000 while the average was $105,000,000. Being less stringent than metric two, a very similar indicator, the replacement cost was less in comparison. As a reminder, metric two registered a replacement cost of $143,000,000. This is due to the face that items were kept in use for an additional 25% of work order costs before replacement was initiated. This metric also produced the least amount of total replacements in the entire field. It came in at about 6,700 replacements over the eighteen-year period. A total of 18,962 units were never replaced. This is an increase from the roughly 17,000 seen in metric two and is expected. Overall, the replacement costs in this metric produced very little surprises. The data responded exactly as would be expected when scaling a replacement threshold on a particular metric.

### 5.6.2 Actual Work Orders

The actual work orders under this metric totaled $13,700,000. This nearly mirrored the group average of $14,000,000. Again, this was an increase in comparison to metric two due the same sort of scaling. Units were held onto longer which meant more was spent to keep those units running.

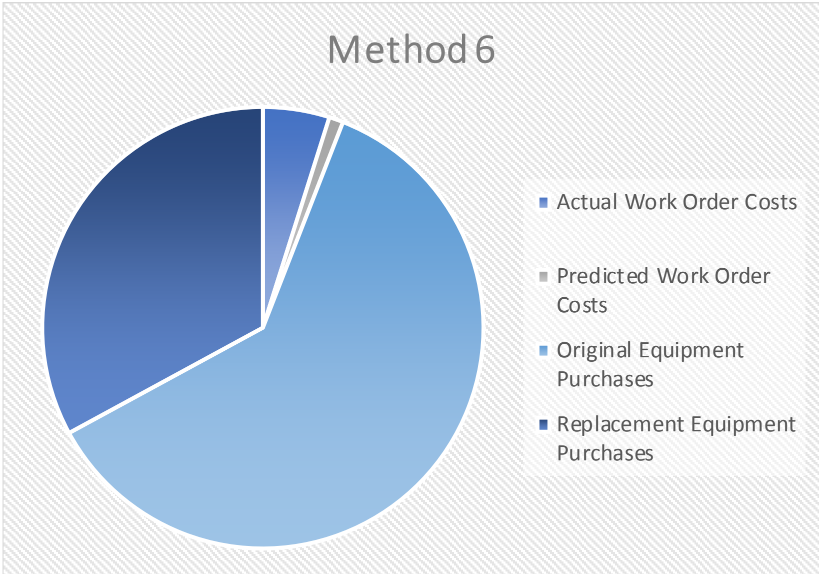


*Figure 35 - Cost Breakdown - Method 6*

### 5.6.3 Estimated Work Orders

The interesting portion of this metric was the estimated work orders. The estimated work orders were calculated exactly as it was done in metric two, only the replacement threshold was scaled. What was interesting about this metric is that while units were held onto longer and this would generally show an increase in the number of work orders. In total, there were less replacements and more units to never be replaced which completely removed those items from registering costs in the estimated work order category. This produced a substantial decrease in the work orders registering only $3,000,000 with a group average of seven million. While at first glance this sounds like a positive result, on further analysis we see that this is likely due to a large portion of devices that have not been replaced are simply units that have been purchased more recently. Due to the fact that the actual work orders produced an overall increase, this would eventually be exhibited in estimated work orders if this metric was implemented and carried into the future.

### 5.6.4 Equipment Age

As can be seen in Figure 36, Method 6 again produced the same increasing accumulated age profile of the entire fleet typical for all methods. Similar to Methods 4 and 5, Method 6 was very close to the average of the group after 18 years of use. The average of all methods was 5.37 years and the accumulated age under Method 6 was 5.68. The current fleet has an average age of 6.94 years. This method provides an improvement of 1.26 years or 18%.

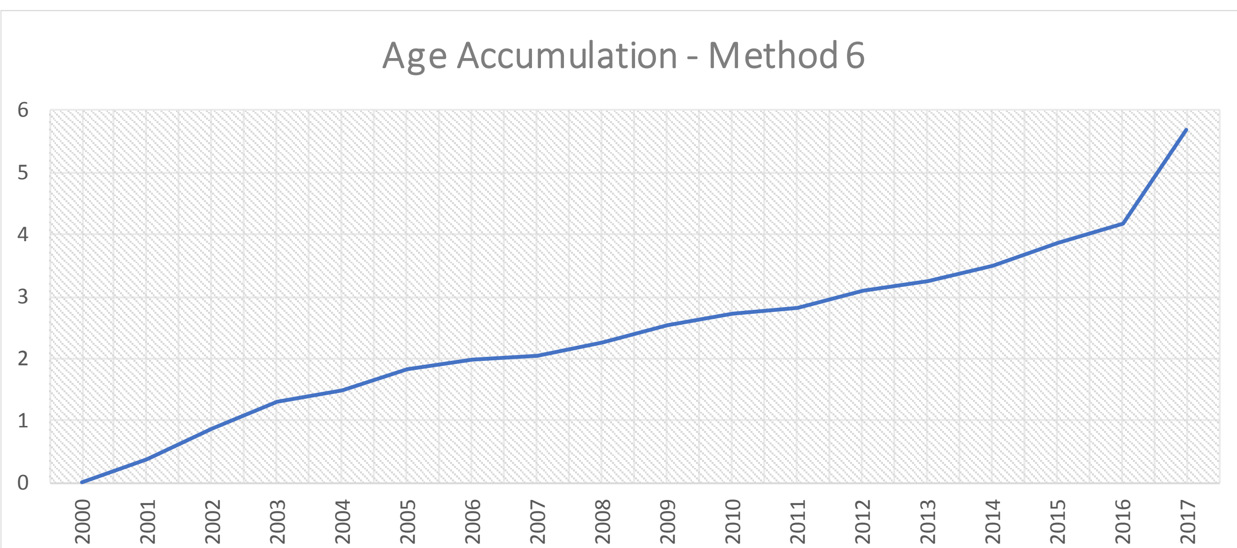


*Figure 37 - Age Accumulation - Metric 6*

### 5.6.5 Method 6 Conclusions

Overall, method 6 performed very favorably. It produced a low overall cost of the program and reasonable results in each category. It provides a very simple indicator of replacement that is not only a straightforward calculation but it also utilizes existing data and processes. It is on the high side of the fleet age characteristic but it is still an overall reduction to the current model. It also brings up a very important concept to take from this entire analysis and that is the idea of scaling these parameters. Several of these parameters can easily be tweaked by adjusting one figure in the threshold metric. For example, we went from total cost of ownership to 125% of the total cost of ownership under this metric. It did reduce overall costs but more was spent on maintenance and the fleet age increased overall. The concept proved a valuable lesson and offers an opportunity to draw more important information from this sort of analysis in general.

## 5.7 Comparison of Results

In review, all of the tested metrics are presented in Table 4 below. As can be clearly seen, Metric 3 produced the lowest overall spend. However, more than 90% of devices in this metric were never replaced. This is made evident by the average age of equipment at the conclusion of the testing period which was the highest of the entire group. Metric 6 produced the second-best numbers in terms of total spend. It also provided very respectable results in both actual work orders realized and predicted work orders. Metrics 1 and 5 were next in line in terms of total spend. However, Metric 1 totaled more than $21 million in actual work orders. This was the highest of the group in that category by a large margin. Metric 5 produced much more stable numbers in terms of work orders without any real issues being introduced into the data. The field was rounded out with Metrics 2 and 4. Each of these produced sizable replacement costs as well as work order costs. In a general review of all of the metrics, no single Metric provided a perfect solution to the presented problem. As discussed, some posed inherent problems that skewed the data and some simply performed as expected without any issues but also without impressive results. All metrics produced a seemingly low number of total replacements given there were greater than 25,000 assets included in the study. While it was not expected that every asset would be replaced, these low numbers seem to indicate that the metrics tested may not have been stringent enough to be effectively implemented in a real-world scenario.

| | Total Spend | Replacements & New Purchases* | Actual Work Orders | Predicted Work Orders | Accumulated Age in 2017 | Quantity of Replacements |
|---|---|---|---|---|---|---|
| | (in millions) | (in millions) | (in millions) | (in millions) | (in days) | (in replacements) |
| Metric 1 | $ 306 | $ 279 | $ 21 | $ 6 | 4.68 | 7500 |
| Metric 2 | $ 336 | $ 316 | $ 12 | $ 9 | 5.08 | 10097 |
| Metric 3 | $ 236 | $ 219 | $ 16 | $ 2 | 6.23 | 9406 |
| Metric 4 | $ 328 | $ 300 | $ 11 | $ 17 | 5.2 | 8972 |
| Metric 5 | $ 305 | $ 286 | $ 13 | $ 6 | 5.32 | 7658 |
| Metric 6 | $ 281 | $ 264 | $ 14 | $ 3 | 5.68 | 6712 |

*includes $172M worth of new purchases

*Table 5 - Summary of Results*

# 6. Overall Conclusions

## 6.1 Selected Metric

As stated, the best metric should be on the lower end of both replacement costs and maintenance costs. This should indicate that the metric does not disproportionately favor replacements or maintenance over the other. At the same time, it was noted that there should be an improvement in the average age of the fleet. This has been reflected and presented in the age accumulation that has occurred over the course of the testing years. The age accumulation provides a graphic representation of the average age of the entire fleet in each passing year. The accumulated age, as displayed in Figure 30, represents the average age of the entire fleet of equipment at a specific time-point; in this case, the year 2017. This value is of interest when comparing metrics as a younger fleet would indicate that equipment is being reviewed and replaced at regular intervals. Also, due to stringent requirements to bring medical equipment to market, it is generally accepted that newer models present an improvement in functionality and performance compared to the models that they replace.

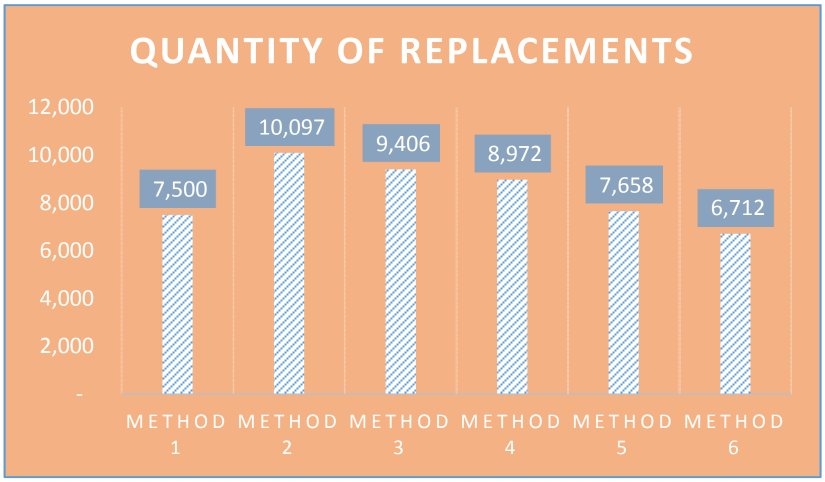


*Figure 39 - Quantity of Replacements - All Metrics*

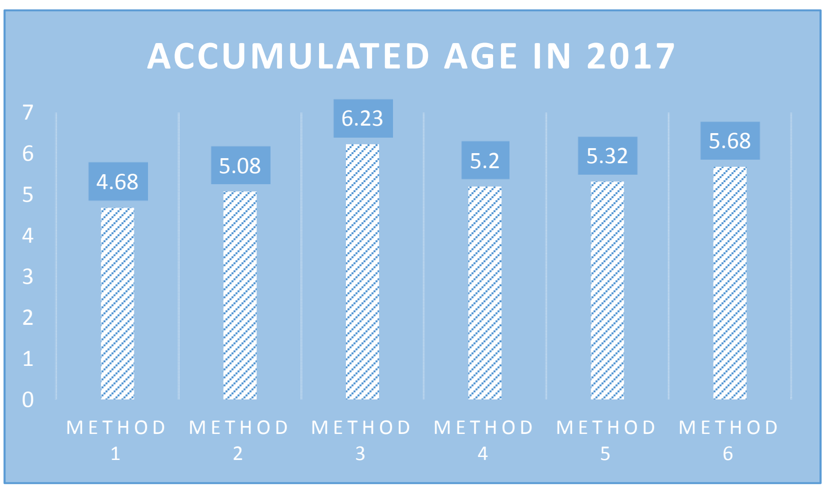


*Figure 38 - Accumulated Age - All Metrics*

The analysis produced a wide range of results. Some metrics favored replacements and some favored maintenance. In the end, two metrics emerged from the field as true contenders. These two were metric 5 and metric 6. Each of these produced the type of results we were hoping to find. These two metrics also did not exhibit any inherent anomalies that impacted their numbers. In comparing these two, metric 6 produced an overall lower spend but a large portion of this was due to a low predicted work order cost. However, the true deciding factor between these two comes down to the impact on age. While all metrics did improve the overall age compared to the existing fleet, this was expected because the analysis field was only composed

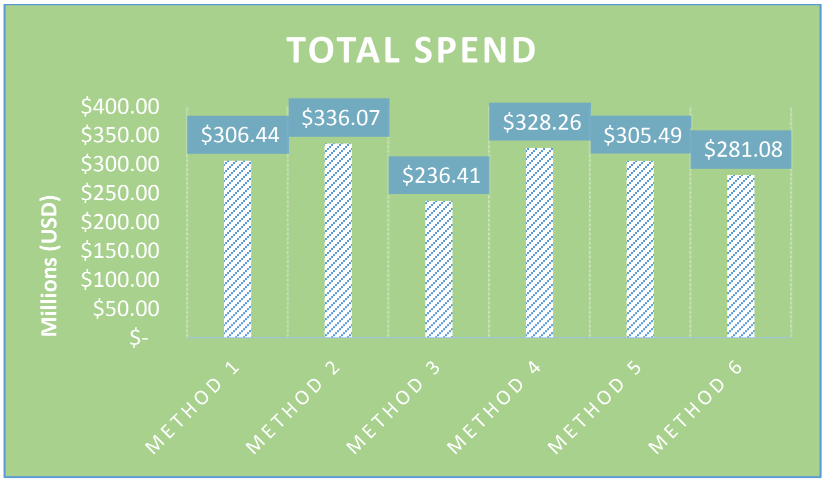


*Figure 40 - Total Spend - All Metrics*

of current assets. Even a single replacement in this regard would provide some miniscule improvement in age. However, Metric 5 did provide a sizable improvement in age over metric 6, greater than 5%. Therefore, it is identified as the best performer among the metrics tested.

## 6.2 Historical Budget Considerations

At this point a large amount of data has been reviewed and the analysis and conclusions have provided plenty of information in regards to how the metrics performed using true information from the CMMS. But this provides little insight as to whether Harris Health could actually implement such a metric. To close out this study, it is important to review the actual budgets that were available to purchase new equipment and determine if this metric is truly feasible. The annual budget data for the last five years as well as the estimated cost of equipment purchases in Metric 5 can be found in Table 5 below.

| | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|
| **Actual Budget** | $ 15,048,000 | $ 16,728,000 | $ 16,680,000 | $ 15,520,000 | $ 13,938,000 |
| **Metric 5 Cost** | $ 30,917,035 | $ 36,707,361 | $ 27,738,692 | $ 20,580,325 | $ 6,103,438 |
| **Difference** | $ (15,869,035) | $ (19,979,361) | $ (11,058,692) | $ (5,060,325) | $ 7,834,562 |
| **Balance** | $ (15,869,035) | $ (35,848,396) | $ (46,907,088) | $ (51,967,413) | $ (44,132,851) |

*Table 6 - Historical Harris Health Budget*

It is easy to see that the actual budget was insufficient if Harris Health intended to implement Metric 5. The system would have consistently fallen further and further behind each passing year. Therefore, the recommendation can only be to increase the annual budget.

At the onset of this project, the goal was not to decrease the overall budget but to put together a decision model that would lead to more sustainable and predictable budgets. The biggest problem that Harris Health has in this regard is that it currently has no set formula for any sort decision model at all. While a process is in place to identify and prioritize replacements, it is not based on data and most replacement decisions are simply from a piece of equipment receiving extra attention or a physician complaining more loudly than others. Metric 5 would provide a framework to allow Harris Health to have some semblance of a true data driven decision model. While it does not produce a consistent budget year over year, it does determine replacements from hard data. In addition, replacement decisions do not come out of nowhere in surprising fashion. While not every single replacement will be predicted a year in advance, the status of each piece of equipment can be monitored and the overall budget can be formulated based on reviewing the units that are trending towards the replacement threshold. This is a huge improvement to the current process.

## 6.3 Reflections on the Project

At the onset of this study, there was great hope that the results would lead to the perfect indicator of replacement and an obvious path forward with the best performing metric. It is now evident that this was a lofty goal for the first step of research into this sort of analysis for the Harris Health System. It is much clearer now that this study simply presented a step in the right direction of the larger effort of improving the efficiency of the decision-making process of equipment replacement at Harris Health. The search for the perfect decision model indicator should be an on-going process. Each step provides an opportunity to learn more and apply those to the work processes implemented.

## 6.4 Challenges Encountered

The biggest challenge of this project relates to the complexities of dealing with large amounts of data. Again, at the beginning of this effort, there was a general thought that as the data was analyzed and particular trends were identified, small tweaks could be made to the replacement thresholds and newer and more accurate data could be extracted with further insights. It was thought that the analysis for all metrics could be completed side by and side with instant comparison of results. This thought went out the window as soon as data manipulation and analysis commenced. This was largely due to the shear amount of data involved. The number of calculations quickly overwhelmed the available systems and the analysis process had to be completed through a series of many independent steps and calculations. Tweaking the replacement thresholds was not possible in real time and would have simply required the entire process to restart. In addition, the analysis of each metric had to be performed in individual files before combining the results into one summary file for comparison. In the end, these challenges were overcome with persistence and creativity to the calculation methods.

### 6.5 Future Studies

The conclusions generated in this report provide a great deal of information for Harris Health to apply to their current processes. While it is possible that Metric 5 has too many flaws to actually be implemented, many insights and valuable information is available from the completion of this project. It would behoove Harris Health to utilize the conclusions formulated in this report to shape future studies and decisions. Should this step be taken, some thoughtful considerations are presented in the following paragraphs.

Even though the annual spend resulting from Metric 5 would have imposed a significant increase to the historical budgets, all of the metrics tested exhibited a high percentage of devices that are never replaced. While many of these units are simply devices purchased in more recent years, this was not always the case. It is highly probable that there exists additional justifications for replacement outside of cost and age. For instance, actual utilization of devices and a thorough technological review may provide additional insights. Further, patient safety is always a consideration in a healthcare setting. These suggested parameters are not simple to quantify but may be necessary to produce a decision model that ensures all assets are reviewed and replaced if posing a risk to the system.

A second point to consider is that several of the metrics included in this study contained a threshold of replacement that was set arbitrarily. The drastic impacts of this can be seen in comparing similar metrics; for example, Metric 2 and Metric 6. These were essentially the same metric but one of them was not scaled in the calculation and the other was multiplied by 125%. This enables some issues to be resolved in the metrics by modifying these values. While a metric may not have produced a favorable result in this analysis, some small modifications could turn it into a much better performer.

Overall, the results available in this study have tremendous value. Not only was a metric identified to create an ideal balance between replacement and maintenance costs but plenty of additional information and knowledge was formulated by the completion of this project. With a few variations, minor adjustments, and possible additions there exists a ton of potential to formulate a highly reliable and predictable decision model.

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